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Genesis of the E1 Group of Iron oxide-Copper- Gold Deposits, Cloncurry District, North West Queensland

Submitted by George N.D. Case (BSci.) in July 2016

for the degree of Doctor of Philosophy from the College of Science and Engineering,
James Cook University

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3	Delineating the structural controls on iron oxide-Cu-Au deposit genesis through implicit modeling: A case study from the E1 Group, Cloncurry District, Australia; submitted to the <i>Geological Society of London</i>	Case, G., Blenkinsop, T., Chang, Z., Huizenga, J.M., Lilly, R., and McLellan, J..	Major research concepts were co-developed by the authors. Case conducted the modeling and analysis, wrote the first draft, and developed the figures. Blenkinsop and Huizenga provided substantial editorial review. Regional geophysical structural interpretations used in two figures were provided by McLellan.
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Abstract

The E1 Group of iron oxide-copper-gold (IOCG) deposits is located in the metal-rich Cloncurry District of northwest Queensland. The E1 Group contains a total resource of 47 Mt averaging 0.72% Cu and 0.21 g/t Au, and has not been previously investigated in detail. This study aims to understand the genesis of the E1 Group by characterising its geology, alteration paragenesis, ore chemistry, structural controls, and mineralising fluid properties. These features are investigated using drill core logging, petrography, whole-rock geochemistry, microprobe analysis, LA-ICP-MS U-Pb dating, 3-D implicit geological modeling, fluid inclusion studies, and SHRIMP and IRMS oxygen and sulfur stable isotope analyses.

The E1 Group comprises three distinct orebodies: E1 North, E1 East and E1 South. The orebodies are hosted mainly in marble and carbonaceous metasilstone of the Corella Formation (1750–1720 Ma). The metasedimentary rocks are intercalated with mineralised clastic metavolcanic rocks and barren meta-andesite of the Mount Fort Constantine Volcanics (~1750 Ma). These rocks were intruded by Ernest Henry Diorite, cut across by a discordant, polymictic, breccia, and then intruded by dolerite.

Drill core logging, petrography and Mineral Liberation Analysis were used to study the E1 Group alteration textures and styles. They show that E1 Group mineralisation is typified mainly by fine- to medium-grained (<500 μm) stratabound and shear zone-hosted replacement bodies. The ores are typically layer-controlled; some ores are also in veins. The discordant breccia is barren, and pre-dates mineralisation.

The alteration paragenesis was constrained with drill core logging, petrography, and Energy-Dispersive and Wavelength-Dispersive analyses. The E1 Group paragenetic sequence is characterised by three major stages. Stage 1 is dominated by albite (-hematite), with lesser quartz, actinolite, scapolite, and titanite. The second stage is broken into three sub-stages. Stage 2a is dominated by magnetite, fluorophlogopite and fluorannite, fluorapatite, K (-Ba)-feldspar and lesser quartz and pyrite. Stage 2b is a minor phase of albite (-hematite)-rutile-ilmenite alteration. Stage 2c is composed of ankeritic carbonate, magnetite, pyrite, and minor chalcopyrite. Stage 3 is the main mineralising event, and is dominated by carbonate (-Fe-Mn), chalcopyrite, barite, fluorite, pyrite, chlorite, sericite; trace amounts of monazite, bastnäsité, uraninite and coffinite are also present.

Whole-rock geochemical analysis indicates that the ores are highly enriched in Fe, Ba, F, P, and locally Mn, and are less enriched in U, LREE, Co, Mo, As, Sn, Ag while depleted in Si, Na and K. Delineation of the deposit zonation patterns shows a transition from the E1 North orebody into a barren magnetite-apatite $\pm$ pyrite zone to the southwest. Barium and fluorine are elevated over 200 m from mineralisation.

The relatively new technique of three-dimensional implicit geological and geochemical modeling was used to study the structural history and controls of the E1 Group. The deposit is hosted within a series of northwest-plunging folds that formed during regional D₂ deformation event and peak metamorphism. The E1 North and E1 South orebodies are hosted in the hinges of the E1 North Antiform and E1 South Synform, respectively, while E1 East occurs in the limb of the E1 East Antiform. The E1 North Antiform is cut by the northeast-southwest-trending brittle-ductile E1 North Shear Zone that dips $\sim 70^\circ$ northwest. The shear zone is an R-shear of a dextral Riedel structure caused by transpressional movement on the regional Mount Margaret Fault during local D₃ / regional D₄. Implicit geochemical modeling suggests that the spatial distributions of Cu, Au, Fe, U, Co, Mo, and La are controlled by the fold hinges and E1 North Shear Zone, and the highest-grade orebody occurs at their intersection. Drill core and petrographic observations indicate that ore formation took place around local D₃ / regional D₄. A later local D₄ / regional D₅ event caused brittle reactivation of the E1 North Shear Zone and formed northeast-southwest-trending reverse-oblique faults at E1 South that offset mineralisation.

Fluid inclusion analyses were conducted on Stage 2a quartz and Stage 3 barite to determine the composition of the mineralising fluids. Stage 2a quartz hosts a primary fluid inclusion assemblage, 1A, that is characterised by halite-rich, aqueous liquid-solid-vapour fluid inclusions with >50 wt% NaCl_{eq}; the assemblage was heterogeneously trapped. Stage 3 barite hosts two major fluid inclusion assemblages (2A and 2B). Assemblage 2A comprises primary, moderate to low salinity (<15 wt% NaCl_{eq}) aqueous liquid-vapour, inclusions that homogenise between 160° and 190°C . Assemblage 2B is composed of secondary, moderately saline (<9 wt% NaCl; <18 wt% CaCl₂), liquid-vapour inclusions.

In order to constrain fluid and metal sources and precipitation mechanisms, the $\delta^{18}\text{O}_{\text{VMSOW}}$ values of Stage 2a quartz-magnetite pairs, along with the $\delta^{34}\text{S}_{\text{CDT}}$ values of

and Stage 3 barite-chalcopyrite pairs, were studied; Stage 2 pyrite was also measured. For fine-grained ores, the *in-situ* Sensitive High Resolution Ion Microprobe method was used, while conventional *ex-situ* Isotope Ratio Mass Spectrometry was used for vein samples. Stage 2a quartz $\delta^{18}\text{O}$ values at E1 North have a narrow range of +12.7 to +14.8‰. In contrast, magnetite $\delta^{18}\text{O}$ values are characterised by a wider range from 0 to +8‰. Calculated isotopic equilibrium temperatures from quartz and magnetite range from 350° to 540°C, and the calculated $\delta^{18}\text{O}$ range of the fluid at these temperatures is +8.4 to +10.9‰.

Stage 3 chalcopyrite $\delta^{34}\text{S}$ values are distinct between E1 North (–5.8 to +2.7‰), E1 South (+1.7 to +17.3‰), and E1 East (+12.5 to +16.9‰). Stage 3 barite $\delta^{34}\text{S}$ values vary from +6.7 to +21.2‰ in E1 North, +19.1 to +29.5‰ in E1 South, and +5.6‰ to +26.5‰ in E1 East. Vein-hosted barite $\delta^{34}\text{S}$ values are 5 to 10‰ lower than those in fine-grained samples. Stage 2 pyrite is typically 1 to 2‰ higher than Stage 3 chalcopyrite. Calculated equilibrium temperatures for Stage 3 barite and chalcopyrite in fine-grained samples range from 230° to 340°C; vein-hosted samples did not reach equilibrium. Estimated trapping pressures of barite 2A fluid inclusions, based on these temperatures, range from 2.2 to 3.3 (± 0.5) kbar. This corresponds to a depth range of 8–12 km. The estimated values of $\delta^{34}\text{S}_{\Sigma\text{S}}$ range from $+4.9 \pm 5.3\%$ at E1 North, to $+15.9 \pm 3.6\%$ at E1 South.

The $\delta^{18}\text{O}_{\text{fluid}}$ and $\delta^{34}\text{S}_{\Sigma\text{S}}$ values at E1 North, coupled with the high salinity of 1A fluid inclusions, are consistent with those from a magmatic-hydrothermal fluid. The F-U-REE enrichment of the paragenesis suggests that the magma was an evolved, alkaline, granite. It is speculated that this granite was related to the (1550–1490 Ma) Williams-Naraku Batholith; it may have supplied some of the Cu and Au. The shifts in the values of $\delta^{34}\text{S}_{\text{mineral}}$ and $\delta^{34}\text{S}_{\Sigma\text{S}}$ at E1 South can be explained by mixing of the magmatic fluid with a shallower fluid that had equilibrated with the Corella Formation host rocks. Covariance of the $\delta^{34}\text{S}$ of barite and chalcopyrite between E1 North and South suggests that both fluids supplied SO_4^{2-} . Ore precipitation was likely caused by salinity decrease as a result of fluid-fluid mixing. Dilation in the E1 North Shear Zone and fold hinges during local D₃ / regional D₄ provided the main conduits for mixing of the mineralising fluids.

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Chapter 1

Introduction

Thesis Rationale

Iron oxide-copper-gold (IOCG) deposits constitute a significant amount of copper, gold, uranium and magnetite resources, both in Australia and worldwide. Some of the deposits in this class, such as Olympic Dam, Australia (10.1 Gt at 0.78% Cu, 0.25 kg/t U₃O₈, 0.3 g/t Au, and 1 g/t Ag; Ehrig, 2015), are gigantic in size. Other major IOCG deposits include the Prominent Hill (Australia), Salobo and Sossego (Brazil), Candelaria (Chile) and Ernest Henry (Australia) deposits. The potential size and high grade (>0.7% Cu) of these deposits continue to make them desirable exploration targets. IOCG deposits were first recognized as a distinct deposit type only 25 years ago by Hitzman et al. (1992). They vary considerably in their size, mineral assemblage, structural settings, textural styles and fluid and metal source(s). Because of these variations, a consensus on a common IOCG genetic model has not been reached, inhibiting development of useful exploration models. In some instances, geologists do not agree on the placement of some deposits into the IOCG class (e.g. Wang and Williams, 2001; Mark et al., 2006; Groves et al., 2010). Further detailed case studies of individual deposits are necessary to establish the common features and ore controlling factors of IOCG deposits.

This thesis focuses on the poorly-understood E1 Group (E1 North, E1 South and E1 East) of IOCG deposits, which are located at –20.44°S and 140°W in the polymetallic Cloncurry District. Although it is small (47 Mt at 0.71% Cu and 0.21 g/t Au; Table 1.1), the E1 Group shares some characteristics with the classic Ernest Henry IOCG deposit (226 Mt of resource at 1.1% Cu, 0.51 g/t Au, and 180 ppm Mo; Rusk et al., 2010) located only 8 km west; the two deposits, however, are markedly different.

Understanding the similarities and differences in geological features and ore genesis and controls between the E1 Group and Ernest Henry and other IOCG deposits can provide new insight into the genetic models and footprints of this enigmatic deposit class. More specifically, studying the E1 Group will help to establish what features are necessary for IOCG ore genesis, and whether or not IOCG deposits with different characteristics are genetically related.

This thesis will investigate the host rock types and stratigraphy, alteration and mineralisation paragenesis and timing, structural history, 3-D-modeled spatial and geometric distribution of ores and structural controls thereof, and the nature,

composition and conditions of the ore-forming fluid(s). The factors controlling ore formation will be presented, and a genetic model will be proposed.

Early Characterisation of the E1 Group

The E1 Group was discovered by Western Mining Company in 1995, but was not drilled out extensively until the early 2000s by EXCO Resources. Like Ernest Henry, the E1 Group does not crop out; consequently, little geological work was done in the area, aside from geophysical surveys, before drilling. Other targets around E1 were also drilled by EXCO; the closest is the E8 target, 2 km south of E1 South. The E1 Group was sold to Xstrata Copper in 2012. Open pit mining of the E1 North ore zone commenced in August 2012 and finished in March 2014. Pre-stripping of the E1 East and E1 South pits began in August 2012, but was later suspended before reaching the Proterozoic rocks.

The most recent individual resource estimates available for each orebody in the E1 Group are shown in Table 1.1. It is important to note that these estimates, which total just 38.5 Mt (Lilly, 2012), were made prior to the 47 Mt estimate stated above; no later individual estimates are available. Regardless, it is obvious that E1 North is characterised by a significantly higher Cu-Au grade, and contains more Cu and Au overall. The most recent 2015 estimate, after mining of the E1 North orebody, is much smaller at 10.5 Mt at 0.74% Cu and 0.22 g/t Au (Table 1.1).

Little work was done in the E1 Group area, except for geophysical surveys, prior to drilling. Drilling company and consultant reports are based on drill core logging and minor petrographic studies, and the work focuses on resource estimates, host rock characterisation and general alteration paragenesis interpretations (e.g. Laing, 2003; Jami, 2008; Taylor, 2012). There are no publications on the E1 Group of deposits.

The reports describe the host rocks as steeply-dipping psammites, metasilstones, and mafic to intermediate metavolcaniclastic rocks. Breccias, characterised by strong red alteration (albite, hematite, K-feldspar?), are also described, and are interpreted as being stratigraphically conformable to the metasedimentary and metavolcanic rocks (Payne, 2010). Some exploration reports (e.g. Jami, 2008) separated the coherent metavolcanic rocks into a distinct metabasalt unit that underlies the main mineralised metatuff-volcanic breccia lens and a trachyte unit that overlies the lens, and assigned both

sequences to the Toole Creek Volcanics (TC) of Cover Sequence 3 (see Chapter 2). The breccias were assigned to the Corella Formation of the regional Cover Sequence 2 (see Chapter 2, Regional Setting section; Payne, 2010) – a unit more than 100 million years older than the Toole Creek Volcanics (Foster and Austin, 2008) – and would therefore be disconformable. Much of the magnetite-laminated metasedimentary rocks are classified as banded iron formations (BIF), implying a syngenetic origin for the magnetite; no evidence for this interpretation is described. It is clear that further research is needed to fully classify the host rocks and place them in the regional stratigraphy.

Table 1.1: E1 Group Resource Estimation

	Deposit	Class	Tonnes	Cu%	Au g/t	Cu T	Au Oz
Early 2012 EXCO? JORC Estimate ¹	E1 North	Indicated (63%)	7,800,000	1.06	0.32	82,900	79,900
		Inferred	4,500,000	0.88	0.25	40,000	36,800
		Sub Total	12,300,000	1	0.29	122,900	116,700
	E1 South	Indicated (40%)	7,300,000	0.73	0.2	53,400	47,100
		Inferred	10,900,000	0.63	0.16	68,400	56,800
		Sub Total	18,200,000	0.67	0.18	121,900	103,900
	E1 East	Inferred	8,000,000	0.83	0.26	66,000	65,500
		Total	38,500,000	0.81	0.23	310,800	286,100
2013 JORC Estimate ²	E1 Group	Total	47,000,000	0.71	0.21	333,700	317,363
2015 JORC Estimate (post-E1N mining) ³	E1 Group	Measured and Indicated	10,100,000	0.73	0.22	73,730	71,447
		Inferred	400,000	0.9	0.3	3,600	3,859
		Total	10,500,000	0.74	0.22	77,330	75,305
References	¹ Lilly, 2012		² S. Harper, pers. comm			³ Glencore, 2015	

Documentation on mineralisation was preliminary. A very brief paragenesis conducted on 6 drill cores by Taylor (2012), suggested a paragenetic sequence similar to that of Ernest Henry: early albite alteration followed by K-feldspar-hematite, then magnetite ± sulfides, and finally late carbonate ± chalcopyrite veining. It is evident, however, that the E1 Group metasediment-metavolcanic rock replacement mineralisation style is substantially different from the Ernest Henry breccia-hosted style. Indeed, most of the breccia surrounding E1 is virtually barren. The fine-grained, replacive, mineralisation

texture and style of the E1 Group instead resemble the metasedimentary rock-hosted Osborne and Starra IOCGs.

The limited body of existing work leaves open many problems concerning the nature and genesis of the E1 Group:

1. The hypothesized host rocks, the Toole Creek Volcanics and Corella Formation, are interpreted as conformable yet are over 100 million years different in age, and are part of two distinct sedimentary-volcanic packages (Cover Sequence 2 and 3; see Chapter 2).
2. The alteration paragenesis has not been analysed through extensive petrography or microprobe analysis, and the spatial distribution of alterations are not known.
3. The relative and absolute timing of mineralisation and alteration – especially magnetite (epigenetic or syngenetic) – are not constrained.
4. The structures and deformation history of the deposit are not documented in detail.
5. The origin and source(s) of the mineralising fluids and metals are not constrained.

These problems will be resolved through the aims and objectives described below.

Aims and Objectives

The aim of this PhD project is to understand the geology and genesis of the E1 Group of IOCG deposits in order to improve existing IOCG genetic and exploration models. To achieve such understanding, the major objectives are as follows: 1) characterise the host rock stratigraphy, geological framework and alteration paragenesis of the deposit, 2) constrain the timing of alteration and mineralisation, especially for magnetite and chalcopyrite, 3) delineate the structural history of the deposit and the structural controls on mineralisation, 4) characterise the evolution of the mineralising fluids in the deposit, and 5) combine the geology, paragenesis, structures and fluids into a composite genetic model. These objectives are reached through a combination of geological core logging, 3-D geological and structural modeling, U-Pb geochronology, and whole-rock, mineral, stable isotope, and fluid inclusion geochemistry.

The thesis is structured such that each chapter focuses on one of the previously mentioned objectives. Chapter 1 describes the rationale and aims of the thesis. In Chapter 2, the results of characterisation of the geology and alteration paragenesis of the E1 Group (Objective 1) are presented, and the relative and absolute timings of alteration and mineralisation are discussed (Objective 2); the deposit is then placed into the context of other IOCG deposits. Chapter 3 draws upon these data and presents 3-D geological and geochemical models of the deposit; the structural history and controls on mineralisation are then discussed (Objective 3). Chapter 4 focuses on the fluid evolution of the E1 Group (Objective 4) delineated through fluid inclusion and stable isotope analyses. The possible fluid and metals sources and fluid evolution are discussed. Finally, in the Conclusion chapter (Chapter 5), the results of Chapters 2–4 are synthesised to establish a comprehensive ore genesis model of the E1 Group (Objective 5).

Chapter 2 describes the framework geology of the E1 Group deposit – the host rocks and alteration paragenesis – based on the results of core logging, petrography, whole-rock geochemical analysis, microprobe EDS (Energy-Dispersive Spectroscopy) and WDS (Wavelength-Dispersive Spectroscopy) mineral analyses, and U-Pb monazite geochronology. Drill core and thin section petrographic observations of the lithology and mineralogy of the host rocks, combined with whole-rock major, minor, and trace element geochemical analyses, are presented. The detailed alteration paragenetic sequence, derived from drill core logging and petrography, is described. The data from EDS and WDS microprobe analyses of alteration minerals are presented. The results of U-Pb dating attempts on monazite, paragenetically related to mineralisation, are also shown. The implications of these results in the genesis and classification of the E1 Group are discussed. The data form the geological groundwork and context for the remaining chapters.

Chapter 3 presents the outcome of 3-D geological modeling of the E1 Group host rocks and structures, based on drill core logging and geophysical datasets, and discusses the structural history and structural controls on mineralisation. Three-dimensional geochemical grade models of Cu, Au, Fe, P, S, U, Co, and Mo assay data are presented. The results are compared with existing work on the nearby Ernest Henry deposit, and implications for structural controls on IOCG genesis in Cloncurry and other districts are discussed.

In Chapter 4, fluid inclusion and oxygen and sulfur data from pre-ore quartz-magnetite and syn-ore barite chalcopyrite are presented. Fluid inclusion assemblages (FIA) in quartz, barite, and calcite are mapped and described. Melting temperatures and resultant salinity estimates from barite fluid inclusions are shown, along with barite homogenisation temperatures. Oxygen isotopic measurements of quartz and magnetite are shown, and are used to constrain the isotopic composition and equilibrium formation temperature of these pre-ore minerals. Sulfur isotope data from barite, chalcopyrite, and pyrite are described. Equilibrium temperature estimates of barite-chalcopyrite formation are presented, and used to place constraints on pH, f_{O_2} during mineralisation, as well as on the possible sources of sulfur and cations. The sulfur isotope temperature constraints are combined with barite fluid inclusion homogenisation temperatures to estimate true trapping pressures during ore formation. The data are combined to discuss models of fluid sources and ore precipitation mechanisms of the E1 Group. The implications of these factors in IOCG genesis in the Cloncurry District are also discussed.

The Conclusion chapter uses the results of Chapters 2–4 to establish a complete ore genesis model of the E1 Group that includes geological, structural, and fluid aspects. It is followed by a section which summarises the exploration implications of the model.

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Chapter 2

Geology and alteration paragenesis of the E1 Group of epigenetic iron oxide-Cu-Au deposits, Cloncurry District, Australia

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Abstract

The E1 Group, located 8 km from the world-class Ernest Henry iron oxide-copper-gold (IOCG) deposit in the Cloncurry District, is hosted in a package of metamorphosed clastic and coherent intermediate volcanics and calcareous and siliciclastic sedimentary rocks of the ~1750 Myr old Mount Fort Constantine Volcanics and Corella Formation. The rocks were intruded by Ernest Henry Diorite (~1650 Ma), cut across by discordant breccia, and then intruded by (meta)-dolerite. E1 Group ores are mostly laminated, stratabound and shear-hosted, and the geometry of the orebodies follows a series of north-northwest-plunging folds. The folds are cut across by northeast-southwest and northwest-southeast-trending faults and shears. The ores are restricted mainly to clastic metavolcanic and metasedimentary rocks. Mineral Liberation Analysis indicates that the magnetite-barite-fluorite-calcite-chalcopyrite ores are dominantly characterised by fine-grained (<100 µm) layer- and groundmass-controlled replacement textures.

The E1 Group formed in three major phases. Stage 1 is characterised by early albite and lesser amphibole and titanite alteration. Stage 2 is subdivided into three sub-stages that probably formed close together in time: Stage 2a magnetite-biotite-apatite-K(-Ba)-feldspar alteration, Stage 2b intermediate albite alteration, and Stage 2c early carbonate-quartz-magnetite-chalcopyrite mineralisation. Stage 3 chalcopyrite-pyrite-barite-fluorite-carbonate alteration is the main mineralising event. Stage 3 also contains minor monazite, bastnäsite, coffinite, and uraninite U-REE phases. A U-Pb (LA-ICP-MS) age of 1456 ± 44 Ma of Stage 3 monazite overlaps in error with the youngest magmatic and mineralisation phases at ~1500 Ma, but may also be mixed with younger ages related to a resetting event of uncertain cause.

Geochemical data indicate that, in addition to economic Cu, Au, and magnetite, E1 Group ores are highly enriched in Ba, F (up to 22 wt% and 15 wt%, respectively). Phosphorus (up to 7500 ppm P_2O_5), LREE (1500 ppm), U (450 ppm), Co (500 ppm), Mo (400 ppm), Sn (150 ppm), and Ag (6 ppm) are also enriched relative to less altered rocks in the area. Lead concentrations of 49 ppm in ores are anomalous, but zinc abundances are not elevated. Geochemical anomaly thresholds for Ba, F, and Mn, determined from the value of the median + $2 \times$ median absolute deviation, are much higher than average crustal concentrations; this may be the result of an alteration halo

extending beyond existing drill holes. Such extent suggests fluorine and barium can act as potential vectors for E1 Group-style mineralisation.

The E1 Group is consistent with some of the defining features of Ernest Henry and Olympic Dam-style IOCGs: Cu-Au-Fe-oxide-U-REE-Ag-Ba-F-P-Co-Mo-Sn geochemistry, strong structural controls, and spatial association with Na-(-Ca) alteration. However, E1 is characterised by higher concentrations of Ba and F. Drill core observations and geochemical data indicate a metasomatic origin of the magnetite-layered host rocks. The replacive nature of E1 ores indicates that factors such as host rock composition, and the presence of shearing, are important controls for smaller deposits that are more abundant in the Cloncurry District. The transition from Ba-bearing K-feldspar to barite alteration between stages 2a and 3, and the transition from Stage 2a fluorapatite to Stage 3 fluorite, suggest that Ba and F were present throughout much of the paragenetic sequence. It is speculated that the elevated concentrations of Ba and F in the E1 Group are a result of protracted *in-situ* enrichment of wall rocks and earlier alteration; such enrichment was limited at Ernest Henry because of volume increase caused by brecciation. The similar parageneses of E1 to the nearby Ernest Henry and Monakoff deposits suggests that these systems probably formed from a similar type of ore fluid under similar conditions.

Introduction

The E1 Group of Cu-Au deposits – E1 North, East, and South – is located in the northeast Cloncurry District of the Eastern Fold Belt (Fig. 2.1). E1 East lies 700 m northeast of E1 North, and E1 South is 1 km southeast. The closest other target is E8, 2 km south of E1 South. Like Ernest Henry, the E1 group of deposits are hosted in Proterozoic basement rocks overlain by 20–50 m of Mesozoic sedimentary rocks that form a flat, featureless plain. The Proterozoic/Mesozoic unconformity culminates in a palaeotopographic high over the E1 North orebody. The nearest basement outcrops to the E1 Group are Mount Margaret, 2 km southeast (Fig. 2.1), and Mount Fort Constantine, 18 km west-southwest.

The E1 Group has not been previously studied in detail, and there exists little understanding of the host rock stratigraphic framework, alteration and litho- and ore geochemistry of the deposit. This chapter aims to describe these characteristics, which will also provide the geological context for the structural, fluid inclusion and stable

isotope studies presented in subsequent chapters. In this chapter, the E1 Group deposit host rocks and stratigraphic position, alteration and mineralisation, paragenetic sequence, ore geochronology, ore chemistry and zonation patterns are presented. These data are based on a combination of drill core logging, optical petrography, microprobe and Mineral Liberation Analysis (MLA), and whole-rock geochemistry of fresh and altered wall rocks and ores. In particular, this study also uses MLA, which was necessary for characterising the very fine-grained (<20–200 μm) ores of the E1 Group. Based on these data, the E1 Group is placed into the regional geologic framework of IOCG mineralisation, and the classification of the E1 Group as a true IOCG deposit is discussed.

Geological characteristics and classification of IOCG deposits

The iron oxide-Cu-Au class of ore deposits was recognized by Hitzman et al. (1992) after the discovery of the super-giant Olympic Dam Cu-Au-U-Ag deposit (10.1 Gt at 0.78 % Cu, 0.25 kg/t U_3O_8 , 0.3g/t Au, and 1g/t Ag; Ehrig, 2015) in South Australia in 1975 by Western Mining Company (Roberts and Hudson, 1983). IOCGs are distinguished from other deposit types mainly through empirical geological characteristics, which have been discussed extensively in Hitzman et al. (1992), Hitzman (2000), Williams et al. (2005) and Groves et al. (2010). Although the classification is controversial, those workers generally agree that true IOCGs are characterised by the following: 1) economic grades of Cu-Au $\pm$ U $\pm$ Ag, accompanied by enrichment of REE, P, CO_3^{2-} , F, Ba, Co and Mo; 2) strongly structurally-focused hydrothermal mineralisation in breccias, veins, or replacement bodies; 3) spatial association with regional-scale (> 100 km^2) sodic (albite $\pm$ Na-scapolite) and/or sodic-calcic (albite-scapolite-Ca-amphibole) alteration; 4) abundant, low-Ti Fe-oxides in magnetite and/or hematite; and 5) temporal association with regional A- or I-type magmatism (Groves et al., 2010). The paragenetic sequences of most IOCGs are typified by early sodic $\pm$ calcic alteration, followed by abundant Fe-oxides $\pm$ apatite $\pm$ biotite $\pm$ K-feldspar alteration, and then by the ore assemblage of Cu-Au $\pm$ Fe-oxides $\pm$ barite $\pm$ fluorite $\pm$ uraninite $\pm$ monazite $\pm$ bastnasite; some or all of these stages may be cyclic (e.g. Hitzman et al., 1992; Hitzman, 2000; Requia and Fontboté, 2000; Mark et al., 2006b). These alterations are typically also zoned in space, with sodic $\pm$ calcic alteration at depth, magnetite $\pm$ apatite $\pm$ biotite $\pm$ K-feldspar at intermediate levels, and hematite-sericite at shallower levels (Hitzman, 2000). The particular minerals expressed

in these alterations are strongly controlled by host rock composition (Hitzman, 2000). Additionally, at greater depths, IOCG mineralisation may transition to magnetite-apatite-dominated and Cu-Au-poor, Kiruna-style, iron oxide-apatite (IOA), mineralisation (Knipping et al., 2015).

True IOCG deposits are found across the globe and throughout geological time, from the Archean to the Cenozoic. They occur in a variety of tectonic settings, ranging from intracontinental orogenic collapse, to intracontinental anorogenic magmatism, and to proximal or distal collision-related extensional backarc basins (Hitzman, 2000; Groves et al., 2010; Hayward and Skirrow, 2010). Notable IOCG and IOA districts include the Gawler Craton, South Australia, Australia, which hosts the type-deposit and largest IOCG orebody, Olympic Dam; the Andean Coastal Cordillera in Chile and Peru; the Carajás District, Brazil; and the host district of the E1 Group – the Cloncurry District of the Mount Isa Inlier, Queensland, Australia. The E1 Group will be compared and contrasted with deposits in these major districts.

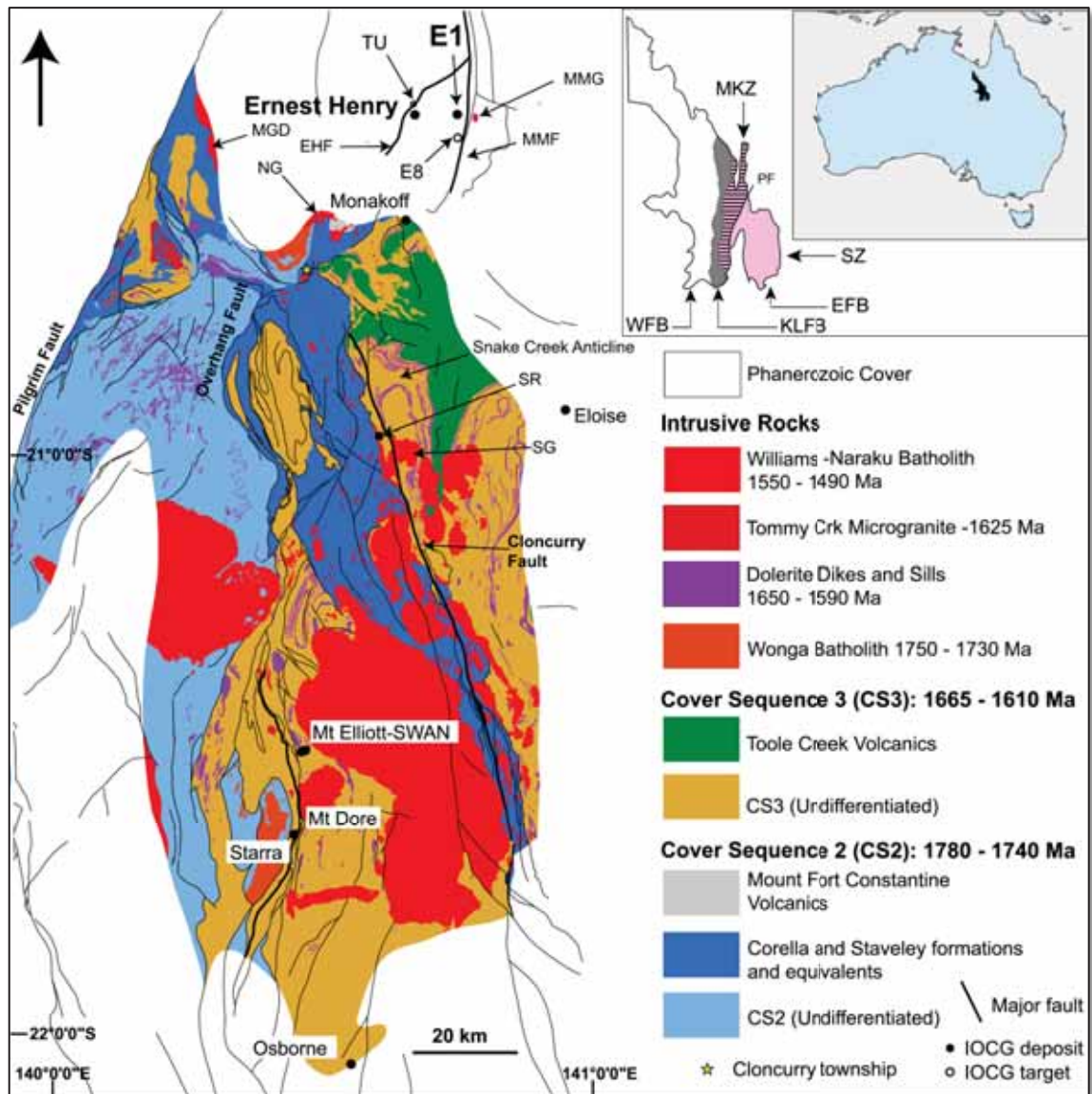


Figure 2.1: Exposed geology and structures of the Eastern Fold Belt east of the Pilgrim Fault (the Selwyn Zone). Geology polygons and structure polylines modified from the Geological Survey of Queensland (2011). Structures below cover were interpreted by the authors of the report from geophysical datasets. GDA 94 projection. EFB, Eastern Fold Belt; MKZ, Mary Kathleen Zone; SZ, Selwyn Zone; KLF3, Kalkadoon-Leichhardt Fold Belt; WFB, Western Fold Belt; MMG, Mount Margaret Granite; PF, Pilgrim Fault; MMF, Mount Margaret Fault; EHF, Ernest Henry Fault; MGD, Mavis Granodiorite; NG, Naraku Granite; SR, Suicide Ridge; SG, Saxby Granite; TU, Third Umpire target.

Regional Setting: Geological History and IOCG mineralisation of the Cloncurry District

The E1 Group of IOCG deposits is located 41 km northeast of Cloncurry in the Selwyn Zone of the Eastern Fold Belt of the Proterozoic Mount Isa Inlier of northwest Queensland (Fig. 2.1). The Mount Isa Inlier is conventionally subdivided into the Western Fold Belt, Kalkadoon-Leichhardt Belt, and Eastern Fold Belt tectonic domains (Blake, 1987). The Pilgrim Fault subdivides the Eastern Fold Belt into the Mary Kathleen Zone to the west, and Selwyn Zone to the east (Fig. 2.1). The Inlier is metalliferous, but deposit styles vary substantially between belts. The Western Fold Belt is dominated by Mount Isa-style Cu and Pb-Zn deposits, while the Eastern Fold Belt and Kalkadoon-Leichhardt Belt host varying styles of Cu-Au and BHT and SEDEX Pb-Zn $\pm$ Ag mineralisation, of which many of the Cu-Au deposits are grouped into the IOCG classification (Williams et al., 2005; Groves et al., 2010).

Cover sequence deposition and early intrusions

The sedimentary and volcanic country rocks of the Eastern Fold Belt were deposited between 1875 and 1610 Ma in an intracratonic rift setting (Blake, 1987 and references therein; O’dea et al., 1997). They overlie the ~1900 Ma basement rocks of the Barramundi Orogeny and are divided into three major unconformable cover sequences (Blake and Stewart, 1992). The rocks that comprise these cover sequences are summarised below. It should be noted that the rock type terms used to describe these rocks based on their interpreted protoliths, rather than on their metamorphosed forms.

Cover Sequence 1 includes the 1870–1840 Ma Leichhardt (felsic) Volcanics, as well as their source magmas, the Kalkadoon and Ewen granites, which were intruded between 1870 and 1840 Ma (Wyborn and Page, 1983). Following a significant hiatus, the Argylla Formation, Marraba (mafic) Volcanics, Mitakoodi Quartzite, Overhang Jaspilite, and Corella/Doherty Formation of Cover Sequence 2 were deposited between 1780 and 1740 Ma. The Argylla Formation is made up of rhyolite, dacite, andesite and lesser quartz arenite, feldspathic sandstone and shale (Passchier, 1992). The Marraba Volcanics comprise mainly basalt, sandstone and siltstone (Blake and Stewart, 1992). The Mitakoodi Quartzite contains quartz arenite, siltstone, basalt, shale and lesser limestone. The Corella Formation, Doherty Formation and Overhang Jaspilite are

considered to be temporally equivalent across the Eastern Fold Belt (Foster and Austin, 2008). These units are dominated by limestone and calcareous siltstone, but also contain quartz arenite, basalt and shale (Blake and Stewart, 1992). The Overhang Jaspilite also contains jaspilite beds. The presence of metamorphic scapolite and gypsum pseudomorphs in many outcrops has led to the conclusion that evaporite rocks originally formed part of these three formations (e.g. Reinhardt, 1991; Hammerli et al., 2014). The Corella Formation was deposited between 1750–1740 Ma (Foster and Austin, 2008). The maximum age (~1780 Ma) of Cover Sequence 2 rocks is based the depositional age of Argylla Formation (Foster and Austin, 2008). Northeast of Cloncurry, the Mount Fort Constantine Volcanics formed between 1750 and 1740 Ma (Page and Sun 1998, Foster and Austin, 2008). This volcanic/hypabyssal sequence is dominantly intermediate to felsic in composition, but includes minor mafic-intermediate flows (Blake et al., 1997); these volcanic rocks are not recognized south of Cloncurry. Whole-rock geochemical analysis of the Mount Fort Constantine Volcanics indicates that this suite is characterised by a mix of within-plate and syn-collisional-volcanic arc granitic Nb/Y signatures (Blake et al., 1997). Some debate still remains concerning the Staveley Formation, which has been placed into Cover Sequence 3 (see below) by some authors (Foster and Austin, 2008), but has some temporal overlap with the Corella and Doherty formations; it may be as old as ~1740–1720 Ma (Betts et al., 2011; Carson et al., 2011). It is also lithologically similar and contains calcareous to siliceous arenite, siltstone, calcareous sandstone, and minor marble and iron-rich beds. It is shown later in this study that the Corella Formation and Mount Fort Constantine Volcanics are the host rocks of the E1 Group.

After deposition of Cover Sequence 2, renewed extension took place and granites of the 1750–1740 Ma Wonga Batholith were intruded mostly in the western portion of the Eastern Fold Belt, west of the Pilgrim Fault (Wyborn et al., 1988). Following the Wonga event, the Cover Sequence 3 rocks were formed. They include the Llewellyn Creek Formation, Mount Norna Quartzite, Toole Creek (mafic) Volcanics, which were deposited between 1690 and 1650 Ma (Foster and Austin, 2008; Rubenach et al., 2008). The Llewellyn Creek Formation is composed mainly of shale and sandstone turbidite sequences. The Mount Norna Quartzite, despite its name, is made up mostly of pelite, feldspathic sandstone and basalt, with a basal quartz arenite bed. The Toole Creek Volcanics are dominated by basalt and black shale, and lesser chert, limestone and iron-

rich beds. The 1650 Ma minimum age is based on the age of the Toole Creek Volcanics (1658 ± 8 Ma; Page and Sun, 1998), while the maximum age of ~ 1690 Ma for Cover Sequence 3 rocks is based on the age of dolerite dykes intruding them (Rubenach et al., 2008). Around the cessation of deposition of Cover Sequence 3, the Ernest Henry Diorite suite crystallized at ~ 1650 Ma (Page and Sun, 1998); it is limited in extent to the region around the E1 Group and Ernest Henry.

Scott et al. (1998), Jackson et al. (2000), Betts and Giles (2006) and Neumann et al. (2009) present an alternative stratigraphic framework for the entire Mount Isa Inlier, and Betts and Giles (2006) consider the Western and Eastern fold belts to be broadly stratigraphically correlated in the form of superbasins. Their framework groups the formations of Cover Sequence 2 into the Leichhardt Superbasin, while those of Cover Sequence 3 are divided into the Calvert Superbasin (Llewellyn Creek Formation – Mount Norna Quartzite) and Isa Superbasin (Toole Creek Volcanics and Staveley Formation). Similar correlations have also been proposed by Foster and Austin (2008).

Isan Orogeny: deformation and metamorphism

Deformations in post-Barramundian rocks in the Mount Isa Inlier are dominated by the 1650–1500 Ma Isan Orogeny (Blake et al., 1990; Rubenach et al., 2008), which was probably driven early on by collision of Laurentia with the North Australian Craton (Betts and Giles, 2006), and later (after ~ 1550 Ma) by orogenic collapse (Duncan et al., 2014). The deformation and metamorphic history of this orogeny is complex, but most workers (e.g. Adshead-Bell, 1998; Rubenach and Lewthwaite, 2002; Giles et al., 2006; O’dea et al., 2006; Rubenach et al., 2008; Abu Sharib and Bell, 2011) agree that at least four major contractional events occurred. The D₁ event (1630–1600 Ma) formed poorly-preserved east-west trending, steep, folds (Rubenach et al., 2008). The dominant north-south-trending, steep, folds and fabric ubiquitous in the Eastern Fold Belt formed in D₂ (1600–1580) at amphibolite facies peak metamorphic conditions (Page and Sun, 1998; Giles and Nutman, 2002; Rubenach et al., 2008). This was followed by the D₃ event (~ 1550 Ma; Page and Sun, 1998; Rubenach et al., 2008; Duncan et al., 2011), which generated steep north-northwest-trending folds and crenulation of S₂ (Rubenach et al., 2008). Steep, northeast-trending folds associated with additional crenulation of S₂ fabric are a late D₄ event that lasted from around 1530 to 1500 Ma (Davis et al., 2001; Rubenach et al., 2008).

Late intrusions and sodic-calcic metasomatism

Following peak metamorphism in the Isan Orogeny, voluminous A-type granitoids of the Williams-Naraku Batholith (Williams-Naraku Batholith; 1550–1490 Ma) were intruded throughout the Eastern Fold Belt (Page and Sun, 1998). The Mount Margaret Granite, 2 km east of the E1 Group, is the nearest Williams-Naraku Batholith outcrop to the deposit and is dated at 1530 Ma (Page and Sun, 1998). No other outcrops of Williams-Naraku Batholith granites occur near Ernest Henry or E1; the next nearest other granite pluton, the ~1505 Ma Malakoff Granite (Page and Sun, 1998); crops out 20 km southwest.

During the 1600–1500 Ma time period, numerous episodes of regional sodic (albite $\pm$ scapolite) and sodic-calcic (albite $\pm$ actinolite $\pm$ scapolite $\pm$ diopside $\pm$ titanite) alteration also took place across the Eastern Fold Belt (Rubenach, 2013 and references therein). Sodic $\pm$ calcic alteration textures typically vary from fine-grained, pervasive alteration, to coarse-grained veining and brecciation. The breccias that are hosted mostly within the Corella Formation are referred to as Corella Breccias (Marshall, 2003), while others contain clasts of both the Corella Formation and much younger Cover Sequence 3 rocks and are named differently (e.g. Suicide Ridge Breccia; Gilded Rose Breccia) at individual localities (Oliver et al., 2004; Bertelli and Baker, 2010). Notable examples of extensive Na-Ca alteration include the Knobby Quarry albitite and breccia and the Suicide Ridge breccia. Some regional Na-Ca alteration zones overlap with some Fe-oxide-Cu-Au orebodies including Starra (Rotheram, 1997), Osborne (Fisher and Kendrick, 2008) Ernest Henry (Mark et al. 2006b), and the E1 Group (this study), but others are generally barren. The origins of these breccias are discussed in detail in Marshall (2003), Oliver et al. (2006), Bertelli and Baker (2010) and Marshall and Oliver (2008).

IOCG mineralisation

The Cloncurry District hosts abundant IOCG and Fe-oxide-rich Cu-Au ores; the largest of these is the world-class Ernest Henry IOCG deposit. Other significant deposits and prospects include Osborne, Starra, Eloise, Mount Elliott-SWAN, Monakoff and the E1 Group (Figs. 2.1–2.2). Total resources in the district may exceed 20 Mt Cu and 9.5 Moz Au (Duncan et al., 2011; Williams, 1998).

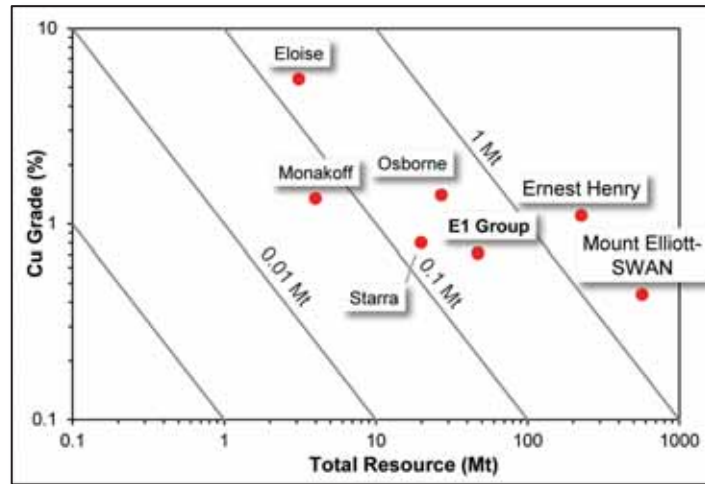


Figure 2.2: Grade-tonnage diagram of Cloncurry District IOCGs. The E1 Group is plotted based on its pre-mining resource (Table 1.1). See text for sources.

The classification of Cloncurry District IOCG deposits is somewhat controversial. As an example, Ernest Henry, Osborne and Mount Elliott are classified by Mark et al. (2006a) as IOCGs, while Starra is considered a Fe oxide-hosted Cu-Au deposit by the same workers. However, both Osborne and Mount Elliott have also been interpreted as skarns (Wang and Williams, 2001; Groves et al., 2010). The Eloise Cu-Au deposit has been suggested as a possible IOCG-related deposit by Baker et al. (2001). All of these deposits are treated as possible IOCGs in this study. Most of these deposits are characterised by a similar general paragenetic sequence of 1) early sodic-calcic alteration; 2) potassic-ferric/ferrous alteration; 3) Cu-Au mineralisation; differences in individual mineral assemblages are the result of variations in host rock composition and/or fluid compositions and conditions.

IOCGs in the Cloncurry District formed between 1600 and 1490 Ma (Duncan et al., 2011 and references therein). Temporally, the IOCG deposits can be grouped into those that formed before intrusion of the 1550–1490 Ma Williams-Naraku Batholith (early or pre-Williams-Naraku Batholith), and those that formed during intrusion (late or syn-Williams-Naraku Batholith). The pre-Williams-Naraku Batholith IOCG deposits are Osborne and Starra, while the Eloise, Mount Elliott-SWAN, Ernest Henry and Monakoff deposits are syn-Williams-Naraku Batholith. It is proposed later in this study, based on geochronological evidence, that the E1 Group is also part of the syn-Williams-Naraku Batholith IOCG deposits.

Pre-Williams-Naraku Batholith deposits

The Osborne (1595 ± 5 Ma, Re-Os; Gauthier et al., 2001) and Starra (1568 ± 7 Ma, Re-Os; Duncan et al., 2011) deposits are the oldest known IOCGs in the Cloncurry District, and are not temporally associated with any known magmatic events, with the exception of some peak-metamorphic anatectic pegmatites at Osborne (Fisher and Kendrick, 2008). The Osborne deposit is hosted in metasedimentary rocks of the Mount Norna Quartzite (and psammite) of Cover Sequence 3, and the Corella Formation (Cover Sequence 2) may be at depth (Fisher and Kendrick, 2008). The ore body is composed of banded magnetite, quartz and apatite ironstone, with minor pelitic layers. The ironstone is interpreted to be pre-metamorphic (Fisher and Kendrick, 2008; Oliver et al., 2008), and some of the ironstone domains are not mineralised (Fisher and Kendrick, 2008). The Starra deposit is interpreted to be hosted in the Staveley Formation (Duncan et al., 2011). The ores are typified by magnetite and hematite-rich breccias and replacement ironstones (Duncan et al., 2014).

Syn- Williams-Naraku Batholith deposits

The Eloise (1530 ± 3 Ma, Ar-Ar; Baker et al., 2001), Mount Elliott-SWAN (~ 1515 Ma, Re-Os; Duncan et al., 2011), Ernest Henry (~ 1525 Ma, Re-Os; Mark et al., 2004) and Monakoff (1508 ± 10 Ma, Ar-Ar; Pollard and Perkins, 1997) deposits all formed coevally with the 1550–1490 Ma Williams-Naraku Batholith.

The Eloise deposit is hosted in the Soldiers Cap Group (Cover Sequence 3) (Baker, 1998). Though formation names are not assigned by Baker (1998), his description of amphibolite, quartz-biotite (-muscovite) schist, and garnetiferous psammite host rocks is suggestive of the Toole Creek Volcanics and Mount Norna Quartzite formations. Eloise mineralisation is composed primarily of chalcopyrite and pyrrhotite, and transitions to lower-grade, massive, pyrite and magnetite in the southern portion of the deposit.

Mount Elliott occurs within metagreywackes and amphibolites of the Soldiers Cap Group, while SWAN is hosted within calcareous pelitic schists of the Staveley Formation (Duncan et al., 2014); the two orebodies are considered related systems. Ore mineralisation occurs mainly as open-space infill and breccias. Mount Elliott is characterised by an unusual Cu, Au, Ni, Co, Te, Se mineralisation suite associated with typical calcic skarn assemblages (Wang and Williams, 1998).

The Ernest Henry and Monakoff deposits are the most proximal known orebodies to the E1 Group; they are located 8 km west and 21 km south of the E1 Group, respectively (Fig. 2.1). Ernest Henry is the largest IOCG in the district by contained Cu, with 226 Mt of resource at grades of 1.1% Cu, 0.51 g/t Au, and 180 ppm Mo (Rusk et al., 2010). It is hosted within brecciated meta-andesite and of the Mount Fort Constantine Volcanics and lesser marble and metasiliciclastic rocks of the Corella Formation (Mark et al., 2006b). Ore mineralisation occurs as breccia infill predominately in the form of chalcopyrite, and is associated with magnetite, calcite, pyrite, biotite, K-feldspar, hematite garnet, barite, fluorite, quartz and minor molybdenite (Twyerould, 1997; Mark et al., 2000). Enriched amounts of uranium and rare earth elements (REE) are also present. Monakoff is hosted in the Toole Creek (mafic) Volcanics and quartz-mica schists and ironstones of the Mount Norna Quartzite. The ore body is characterised by massive to laminated magnetite-barite-carbonate-fluorite $\pm$ chalcopyrite.

The geological characteristics of these pre- and syn-Williams-Naraku Batholith IOCGs are compared and contrasted with the E1 Group later.

Concerning the origin of iron oxide in Cloncurry IOCGs

Iron oxide-Cu-Au terminology in the literature often includes the use of the terms “banded iron formation” and “ironstone,” which have been used by some workers (David and Large, 1994; Davidson, 1998; Oliver et al., 2008) to describe rocks in the Cloncurry District that contain abundant, stratiform or stratabound magnetite (-hematite); these terms can be genetically ambiguous. Such iron-rich rocks are typically layered, but can also be massive. Some of the ironstones are barren (e.g. those in the vicinity of the Pumpkin Gully Syncline; Hatton and Davidson, 2004), and some host potentially economic Cu-Au in the case of Starra, Osborne and Monakoff IOCG deposits and numerous smaller prospects (e.g. Hot Rocks; Davidson, 1998; Williams et al., 2005).

While the Cu-Au mineralisation in these systems is considered to be epigenetic, the origin of the laminated or massive magnetite and hematite is thought by some to be syngenetic prior to remobilization during peak metamorphism or intrusion of the Williams-Naraku Batholiths (Davidson and Large, 1994; Davidson, 1998; Hatton and Davidson, 2004; Oliver et al., 2008). This is in contrast to Ernest Henry, which is a clearly characterised by abundant hydrothermal, epigenetic, magnetite infill (Mark et

al., 2006b). Other workers (Williams, 1994; Rotherham, 1997; Duncan et al., 2011; Williams et al., 2015) argue that both the mineralisation and the magnetite in the ironstones are epigenetic. This study will show that the laminated, and partly-stratabound, magnetite of the E1 Group is epigenetic.

Sampling and Analytical Methods

Whole - rock geochemistry

One hundred and eleven host rock samples were collected from drill core along sections A–A' and B–B' (Fig. 2.4) for major, minor and trace element analyses. Samples were collected to encompass intensely- and weakly-altered host rock compositions with minimal vein interference, but the limited extent of diamond drilling has prevented access to unaltered host rocks; the average loss-on-ignition (LOI) values of most of the host rocks are >5 wt% (Table 2.1). Sample descriptions are shown in Appendix A.

The samples were analysed at Acme Labs in Vancouver, Canada. Major elements and 57 trace elements were analysed using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) for major element oxide abundances and via ICP-Mass Spectrometry to measure minor and trace elements. Total carbon and total sulfur were measured via a Leco analyser; Loss on Ignition (LOI) was also analysed. X-ray fluorescence analysis was also performed on 55 samples that contain greater than the 5% maximum detection limit for barium and fluorine in the AA-Litho Package. The elements and their detection limits, raw data, digestion, and analytical methods are presented in Appendix B.

Electron microprobe analysis

Polished thin sections and pucks were spot analysed via Wavelength-Dispersive Spectroscopy (WDS) on a JEOL JXA-8200 Superprobe at the James Cook University Advanced Analytical Centre (AAC). For WDS analyses, the microprobe was operated at 15 keV acceleration voltage, 19.7 nA current, 5 µm beam size, and 10.09 mm working distance. The following AAC standards were used: T-albite for Na₂O (all minerals) and SiO₂ and Al₂O₃ in tectosilicates; A2-almandine for FeO and SiO₂ and Al₂O₃ in phyllosilicates; T-spessartine for MnO; F-TAP for F in phyllosilicates and SrF₂ for F in apatite; A2-tugtupite for Cl in phyllosilicates and apatite; T-P₂O₅ for Ce₂O₃, La₂O₃ and P₂O₅ in apatite; T-BaSO₄ for BaO; T-TiO₂ for TiO; T-wollastonite for CaO in silicates and apatite and T-calcite for CaO in carbonates; T-olivine for MgO; T-

orthoclase for K₂O. To derive concentrations from raw counts, CITZAF® 3.50 software applying the Armstrong/Love-Scott Phi-Rho-Z correction (Armstrong, 1988) was used. Detection limits were <0.01 wt% for MgO, K₂O and Cl, <0.02 wt% for MnO, Na₂O and SiO₂, and <0.03 wt% for FeO and TiO₂; F in sheet silicates was < 0.05 wt%. Analytical errors for major oxides are generally <2%, but increase greatly to >40% near detection limits. In phyllosilicates, F and Cl errors are > 2% in all samples. No F diffusion correction was carried out for F-rich apatite or biotite, and as a result error in the F concentrations reported for apatite may be up to 0.5 wt%. Nonetheless, this does not effect identification of the apatite species reported below. Fluorine analysis in biotite does not have this problem.

MLA analysis

Mineralogical X-ray mapping of thin sections by Mineral Liberation Analysis (MLA) was conducted at the University of Tasmania Central Science Laboratory on a FEI Quanta 600 Mk1 ESEM utilizing the GXMAP method of Sylvester (2012). In the GXMAP mapping procedure, the SEM collects a backscattered electron (BSE) image of the mapping area, which is divided into frames of specified dimensions. The BSE image is then automatically particulated and segmented by the MLA software into individual mineral phases based on their BSE brightness, which is dependent on their mean atomic (Z) number. Relatively large, homogeneous minerals with sharp BSE boundaries are easily segmented due to high BSE contrast; they are analysed via a single X-ray spectrum over an area. Minerals and domains characterised by inclusions, patchy mineral boundaries, or low BSE contrasts (e.g. quartz and albite), are mapped in greater detail with X-ray spectra collected at points along predefined step intervals. Smaller step intervals correspond to finer resolution and longer mapping times. Each X-ray spectrum is automatically compared to spectra in a reference library, and the mineral spectrum with the closest match is selected. Prior to the mapping run, the sample is characterised in EDS to identify spectra that may not be in the MLA Software library.

In this study, a single representative area of 3.5 to 4.7 mm² was mapped on each of 11 polished thin sections chosen from cross section A–A' (see Fig. 2.20 for sample locations). Due to the fine grain size of the minerals (<10 µm), as well as the presence of inclusions in most minerals, a mapping resolution of 1.7 µm/pixel and stepping size of 2 pixels were required to accurately identify and map mineral species. Operating voltage was set to 15 kV. The modal mineralogy, in wt%, of each sample was

automatically calculated from the mapped area % by the MLA software and the average compositions and densities of the minerals in the MLA library. In order to correct for variations in composition of mica and carbonate minerals from those of the library standards, WDS analysis at JCU was used to quantify their composition. However, such variations result in wt% changes of less than 0.5. MLA maps are presented in Figure 2.9 and modal mineralogy tables are in Appendix C.

Monazite U-Pb Geochronology

Monazites in sample EMMD033-79.5m were ablated *in-situ* using a GeoLas 200 Eximer laser operating at 10 hz with a 24 µm spot size, and the isotopic ratios measured in a Varian 820 ICP-MS instrument. For dating the primary monazite standard used was Elk Mountain (1391–1404 Ma; Peterman et al., 2012), and the secondary standard was Manangoutry (555 Ma; Paquette and Tiepolo, 2007). Some trace elements—Si, P, Th—were also analysed, with NIST610 as the external standard.

E1 Group Deposit Geology

Stratigraphy

The mineralisation in the E1 Group deposits is hosted primarily in discontinuous layered metatuffs and metavolcanic breccias intercalated with marbles and minor psammities and partly albitised metasiltstone, and also in laminated- to thinly-bedded carbonaceous metasiltstone which grade upward into carbonaceous schist (Figs. 2.3–2.5). The host rocks are intercalated with thick (>100 m) sequences of mostly barren amygdaloidal, massive or porphyritic meta-andesite and meta-basaltic andesite. Prior to mineralisation, the metavolcanic-sedimentary sequence was intruded by diorite possibly related to the nearby ~1650 Ma Ernest Henry Diorite suite (Pollard and McNaughton, 1997; Mark et al., 2006b), followed by the formation of a polymictic discordant breccia, and the later intrusion of minor dolerite dykes. The paucity of drilling outside of the orebody has made distinguishing between the metatuffs, psammities and marbles difficult where texture-destructive alteration is prevalent. The descriptions below are based on the least-altered examples of these rock types. The E1 Group host rocks are correlated with the Corella Formation and Mount Fort Constantine volcanics in the Discussion section.

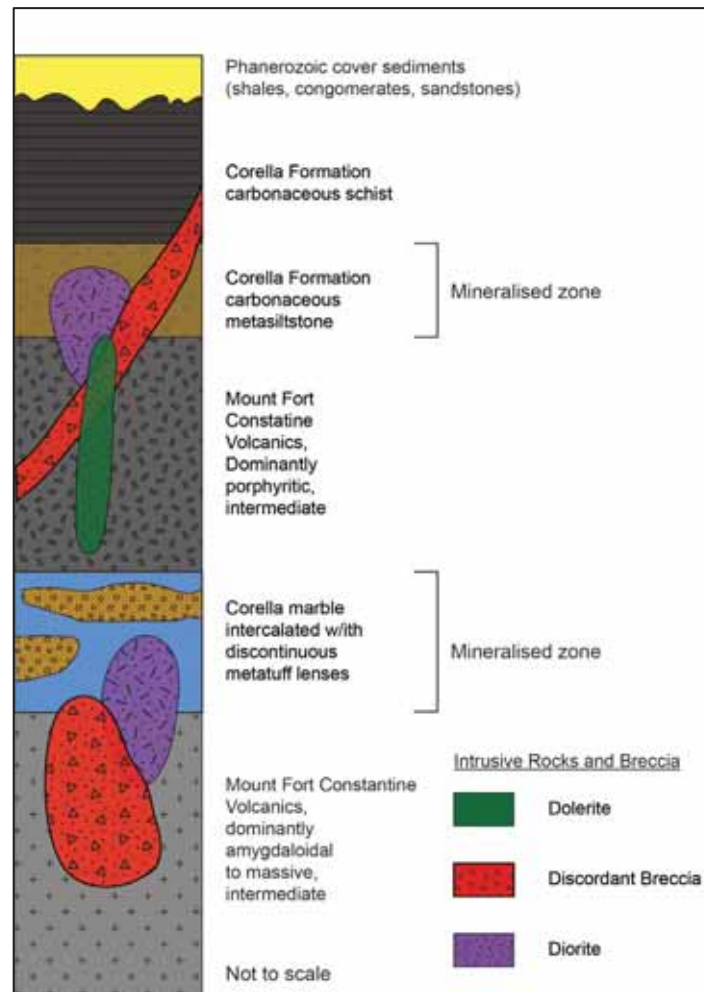


Figure 2.3: Simplified, idealized stratigraphic column of the E1 Group. Not to scale, but unit thicknesses are relative.

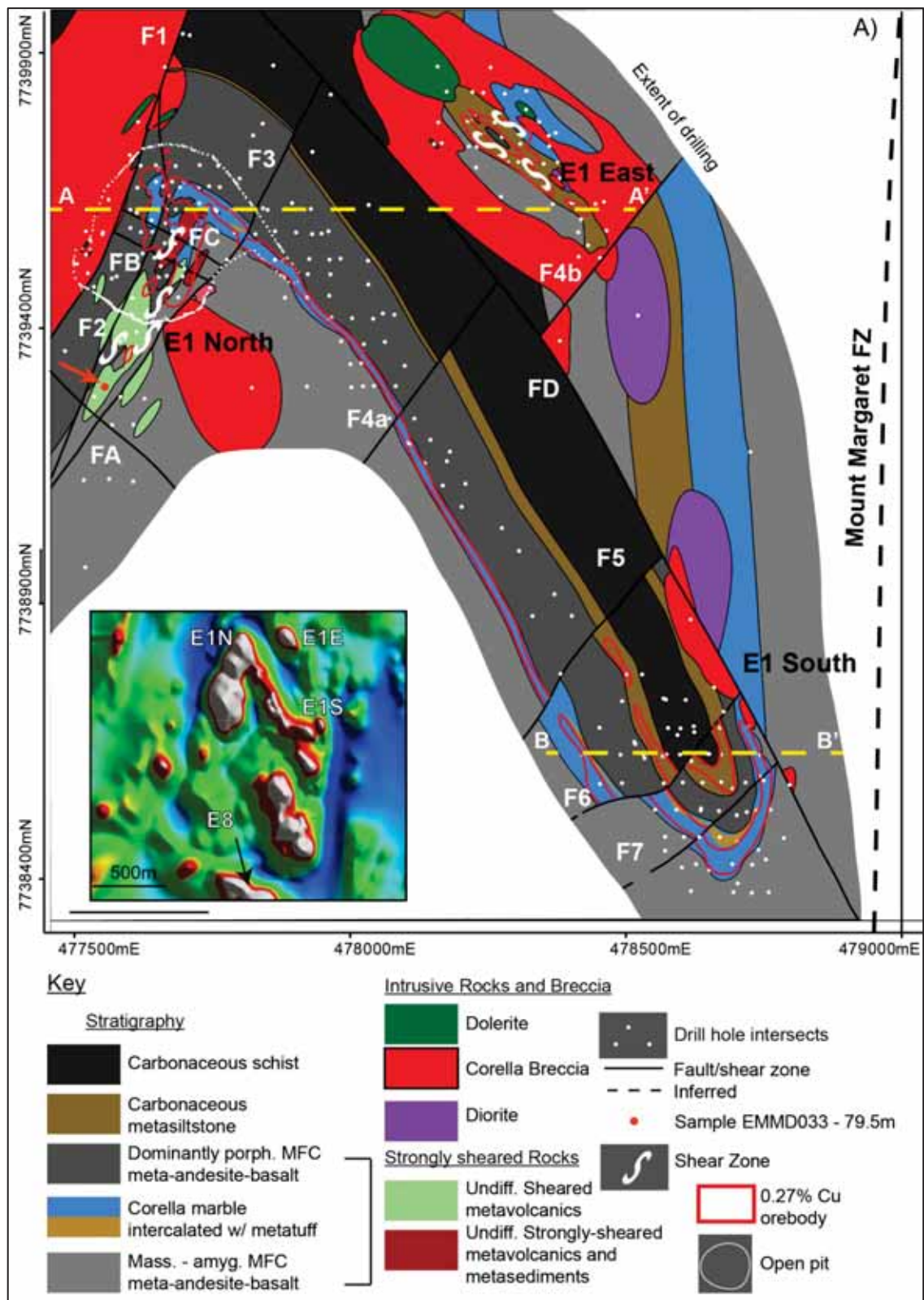


Figure 2.4: Plan geology of the E1 Group, 2075 m RL / 75 m ASL (~ 75 m below surface), interpreted from diamond drillhole logs and limited open pit mapping at E1 North (outline shown). Inset is aerial magnetic image from Chapter 3 (Fig. 3.9) showing location of the E8 target. Cross sections continued on the next page. GDA 94 projection. RL, relative level mine datum; ASL, above sea level.

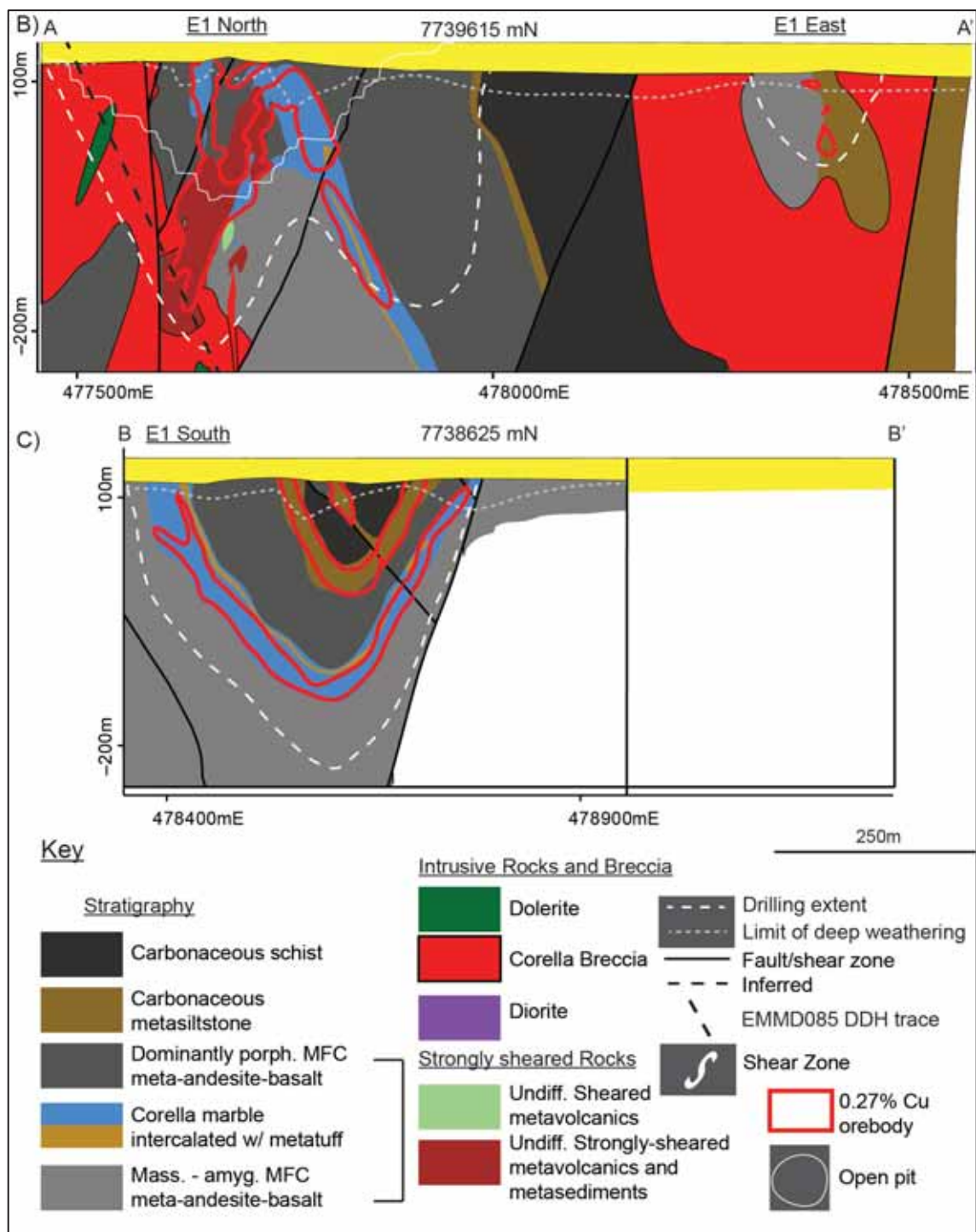


Figure 2.4 (cont.): E1 Group cross sections. B) E1 North and East along A–A', and C) E1 South along B–B'. Location of monazite sample EMMD033-75.9m indicated. Mineralisation outline traced from assay intersects >0.27% Cu. MFC = Mount Fort Constantine Volcanics. Mass. = massive, amyg. = amygdaloidal. Vertical axis is elevation above sea level.

Metasedimentary rocks

Two major metasedimentary horizons separated by a layer of porphyritic meta-andesite can be mapped throughout the E1 Group (Figs. 2.3–2.4). Cross bedding is sporadically observed in the deposit, but <10 m-scale folding has inhibited delineation of consistent younging directions, even within individual drillholes. Therefore, the stratigraphic column shown in Figure 2.3 is based solely on the relative positions of each unit. The lower metasedimentary rock horizon comprises primarily marble intercalated with metapsammite and metatuff, and the thickness ranges from 5 m in fold limbs to >50 m near hinges. The metapsammites (Fig. 2.5G) vary in grain size from fine (~250 μm) to coarse (~500 μm), and the marbles (Fig. 2.5F) from 50–250 μm , and both are laminated to thinly-layered. Much of the current layering is probably foliation, but some bedding is preserved (Fig. 2.5G). Some marbles are conglomeratic, with sporadic siliceous clasts 1–3 cm wide. The metapsammites are locally cross-laminated and composed primarily of quartz, albite (partially altered to K-feldspar), and muscovite. The marbles commonly contain amphibole and scapolite porphyroblasts in an albite-quartz-bearing calcareous to dolomitic groundmass. The porphyroblasts are commonly altered to albite, apatite, chlorite or quartz. The marbles typically contain 1–20 cm siliceous interbeds, as well as calcareous conglomerates. Quartz-albite rocks, characterised by a massive to laminated texture and comprise mainly very fine-grained (<20 μm) intergrown albite and quartz, are less common, and are mainly preserved at E1 East. Thin (<10 m), discontinuous lenses of marble within the metavolcanic rocks are common throughout the E1 Group.

The upper horizon is defined by a sequence of carbonaceous metasiltstone transitioning up-hole to carbonaceous schist (Fig. 2.5H, J). It is not intersected by drilling around E1 North but forms the core of E1 South Synform (see Structures below). The carbonaceous schist is characterised by graphite-muscovite-rich layers interlaminated with quartz-bearing, graphite-poor layers. Fine-grained (<10 μm) disseminated pyrite, and <5 mm pyrite blebs, are also present in some layers. The disseminated pyrite and pyrrhotite are probably recrystallized diagenetic sulfides. Layer-parallel, coarse-grained (up to 5 mm) quartz $\pm$ pyrite $\pm$ calcite veins are abundant and spatially associated with euhedral pyrite of similar coarseness. The metasiltstone is thinly-bedded and interbedded with calcareous and pelitic layers, some of which contain ~1 cm, lathy, amphibole porphyroblasts pseudomorphed by chlorite-magnetite-pyrite in a biotite-rich

groundmass (Fig. 2.7C). At E1 South the mineralised metasiltstone interval is ~20 m thick, while the metashale layer is about 50 m. The very high Fe₂O₃ content (mean >20 wt%; Table 2.1) in all metasedimentary rock types except carbonaceous schist is reflective of magnetite alteration.

Clastic volcanic rocks: Metatuffs and metavolcanic breccias

E1 Group metatuffs are characterised by thin (5–1 mm) laminae composed of alternating quartz and magnetite-biotite. The metavolcanic breccias are typified by aligned, angular, elongate clasts composed of quartz and plagioclase in a massive or laminated quartz-bearing matrix (Fig. 2.5D–E). The clasts have various degrees of magnetite and sericite alteration (Fig. 2.5D). Clast size and shape are highly variable, ranging from 1 mm to >100 mm, and from subrounded to angular. The matrix comprises varying proportions of quartz, magnetite, chlorite, sulfides, biotite, sericite and carbonate; most of these phases, except for quartz, may be secondary. Plagioclase phenocrysts or xenocrysts may be present in both clasts and matrix. The layered metatuff and metavolcanic breccia form a series of discontinuous lenses intercalated with coherent andesitic volcanic rocks, and the lenses may vary abruptly in thickness from 10–100 m. A discontinuous layer (<10 m) of metatuff is present within the lower marble horizon and is mappable from E1 South to E1 North (Fig. 2.4). The metatuffs may contain sporadic volcanic clasts grading into clast-dominated intermediate metavolcanic breccias, and this textural characteristic is useful for identification in heavily-altered intervals.

Table 2.1: Representative whole-rock geochemistry of E1 Group host rocks

Major oxides (wt%)	Meta- andesite	Metatuff	Metavolcanic breccia	Carbonaceous schist	Metasiltstone	Calcereous rocks	Psammite	Diorite	Discordant breccia
<i>n</i>	41	5	9	6	9	22	2	2	15
SiO ₂	50.9	45.5	33.6	57.3	38.4	19.4	41.1	51.2	49.9
Al ₂ O ₃	15.1	11.4	11.6	16.3	9.7	4.5	11.5	14.4	12.0
Fe ₂ O ₃	14.1	21.6	35.9	7.1	26.8	40.9	23.5	13.1	12.4
MgO	2.5	3.1	2.4	2.5	2.6	2.1	3.1	5.4	3.0
CaO	3.5	3.5	2.3	2.3	4.3	11.7	7.1	5.0	7.4
Na ₂ O	4.0	2.5	0.5	1.3	1.9	0.4	3.6	4.9	3.4
K ₂ O	2.4	2.2	2.9	4.5	1.8	1.1	0.6	0.9	2.4
TiO ₂	1.4	1.3	1.2	1.0	0.9	0.3	0.7	1.4	0.7
P ₂ O ₅	0.2	0.3	0.4	0.2	0.4	0.6	0.4	0.1	0.2
LOI	5.2	7.2	4.5	7.1	6.6	6.6	6.5	3.2	8.0
Total C	0.9	1.5	0.5	1.4	1.6	2.2	1.1	0.3	1.7
Total S	0.4	1.3	3.1	1.6	2.0	4.6	1.9	0.1	0.7
Element (ppm)									
F	0.2	0.3	1.0	0.2	0.3	2.5	1.7	0.1	0.2
Ba	2950.4	2777.2	23142.3	1242.3	22797.7	35243.5	6185.0	256.5	926.7
Sc	20.2	19.4	15.3	19.3	13.0	5.9	12.0	32.0	12.7
Cs	1.8	2.5	2.0	5.0	1.3	0.7	0.7	1.9	0.7
Ga	18.9	16.1	17.1	20.4	14.9	7.3	15.3	21.4	16.2
Hf	5.4	4.5	4.2	6.0	3.5	1.7	3.7	3.8	4.5
Nb	10.9	10.1	9.6	14.6	10.4	8.7	11.6	10.1	8.9
Rb	75.7	78.3	85.3	161.4	61.7	28.7	31.9	26.5	63.9
Sn	8.4	38.4	33.8	3.5	28.0	62.3	72.5	2.0	7.5
Sr	48.2	47.2	337.0	31.6	201.3	656.6	121.9	89.4	43.2
Ta	0.8	0.6	0.8	1.0	0.7	0.5	0.6	0.6	0.7
Th	12.0	10.1	11.7	17.1	9.5	5.7	11.4	5.7	11.5
U	8.0	28.1	51.8	5.4	42.9	125.2	60.5	2.0	10.9
V	206.9	218.8	262.1	166.5	164.2	115.5	115.5	265.5	127.0
W	11.7	20.4	50.8	15.9	38.9	72.8	8.3	8.9	11.7
Zr	198.3	166.8	155.8	220.4	129.8	63.5	132.2	134.2	169.0
Y	26.3	26.3	29.3	33.8	24.4	25.1	22.0	25.3	20.2

Table 2.1 (cont.): Representative whole-rock geochemistry of E1 Group host rocks

Element (ppm)	Meta-andesite	Metatuff	Metavolcanic breccia	Carbonaceous schist	Metasiltstone	Calcereous rocks	Psammite	Diorite	Discordant breccia
La	48.3	139.0	133.1	51.7	171.2	358.4	313.0	16.7	48.4
Ce	73.3	148.3	145.3	97.0	176.5	347.3	314.2	33.6	74.9
Pr	7.6	11.9	11.7	11.0	13.3	24.7	22.9	4.2	7.9
Nd	26.9	34.9	35.1	39.5	37.7	64.3	57.1	17.4	28.1
Sm	5.3	5.5	5.4	7.1	5.7	8.0	6.6	4.3	5.0
Eu	1.6	3.7	3.4	1.4	2.9	7.7	6.9	1.5	1.4
Gd	5.3	5.9	5.8	6.3	6.0	8.1	6.3	4.4	4.6
Tb	0.8	0.9	0.9	1.0	0.8	1.0	0.8	0.8	0.7
Dy	4.8	4.7	5.0	5.8	4.7	4.9	4.3	4.7	3.7
Ho	1.0	0.9	1.0	1.1	0.9	0.9	0.9	1.0	0.7
Er	2.9	2.7	3.2	3.4	2.5	2.5	2.4	2.8	2.1
Tm	0.4	0.4	0.5	0.5	0.4	0.4	0.4	0.4	0.3
Yb	2.8	2.6	3.1	3.1	2.3	2.2	2.2	2.8	1.9
Lu	0.4	0.4	0.5	0.5	0.3	0.3	0.3	0.4	0.3
Mo	6.9	26.6	64.5	3.8	30.0	143.0	172.1	0.5	12.6
Cu	312.6	4513.7	3398.2	156.6	4499.5	9247.7	5119.0	63.5	169.5
Pb	7.5	14.8	8.5	11.4	30.5	37.6	28.8	1.8	2.2
Zn	50.7	23.8	17.7	125.0	34.5	38.9	193.0	22.4	12.5
Ag	0.1	2.3	0.8	0.6	2.2	4.9	3.9	0.1	0.2
Ni	27.3	35.9	36.0	30.0	32.2	25.2	40.8	26.3	26.5
Co	30.0	145.0	211.0	10.0	115.7	255.0	167.0	21.1	51.0
Mn	1079.3	2969.6	1886.8	838.7	6580.9	3815.7	1639.0	704.5	1102.2
A	12.9	72.4	146.4	24.9	101.9	198.3	109.1	2.2	20.1
B	0.0	0.1	0.1	0.0	0.1	0.3	0.1	0.0	0.0
Sb	0.4	1.2	1.8	1.4	1.6	4.5	2.2	0.2	0.3
Bi	0.6	4.9	6.8	1.0	4.7	16.3	9.4	0.0	0.7
Cr	20.9	16.5	14.1	12.6	18.1	8.7	43.9	50.4	27.5
Tl	0.1	0.3	0.3	0.3	0.2	0.3	0.2	0.0	0.1
Be	0.4	0.7	0.6	0.5	0.6	0.6	1.1	0.4	0.5
Li	12.6	16.6	20.8	10.6	13.5	12.4	26.6	12.6	15.2

Values are averages of all samples for a given rock type

Coherent volcanic rocks: Basalt meta-andesite and meta-andesite

Basaltic meta-andesite and meta-andesite (Fig. 2.5A–C) are the dominant coherent volcanic rocks at the E1 Group, and exhibit massive, porphyritic, glomerophytic, amygdaloidal, and/or autobreccia textures. Their unaltered groundmass is typically dark gray, while chlorite-altered equivalents are green-gray, and they comprise albite (over 60%), 5–30% chlorite or biotite (after amphibole?), 5–10% primary magnetite and <5% quartz. Phenocrysts, where present, are dominantly plagioclase, although amphibole is also rarely present, and range in size from 0.5–2 mm. Both the phenocrysts and groundmass are variably altered by sericite, chlorite and carbonate. Vesicles, where present, are typically filled with quartz, carbonate, magnetite, pyrite and/or chalcopyrite, and these minerals may also make the amygdule boundary irregular. The amygdules may exhibit weak elongation but are generally not as well-aligned as metatuff clasts. These rocks also make up most of the single diamond hole that was drilled into the E8 target (Fig. 2.4A), and are intercalated with some metavolcanic breccias.

The results of the whole-rock geochemical analyses of the metavolcanic rock samples are shown in Table 2.1 and Figure 2.6. The meta-andesite rocks, on average, contain >50 wt% SiO₂ and >6 wt% Na₂O + K₂O (Table 2.1). Most of the metavolcanic rock samples are characterised by various degrees of alteration as revealed by petrography and high LOI values (up to 13.5 wt%). Therefore, these major oxide discrimination diagrams (Fig. 2.6A) are highly scattered and are no longer reliable. Additionally, mobility of La prohibits the use of the La-Y-Nb discriminant diagram for volcanic series (i.e. calc-alkaline). The high field strength elements (HFSE), on the other hand, are typically immobile and can still indicate the original rock type (Pearce, 1996). This appears to be the case for the E1 rocks, as the ratios of Zr/Ti and Nb/Y overlap substantially between relatively less-altered (LOI <6.9 wt%, or less than the 75th percentile) and altered samples (LOI >6.9 wt%); no trends are obvious (Fig. 2.6C). The E1 Group coherent metavolcanic rocks mostly cluster in the andesite-basaltic andesite region and uppermost basalt region, and overlap with meta-andesites of the Mount Fort Constantine Volcanics (Fig. 2.6B). They are distinct from the Toole Creek Volcanics samples, which plot in the middle of the basalt region. The E1 Group samples mostly plot in the volcanic arc–syn-collisional region on the Nb-Y diagram (Fig. 2.6D), though two plot in the within-plate area (Pearce et al., 1984).

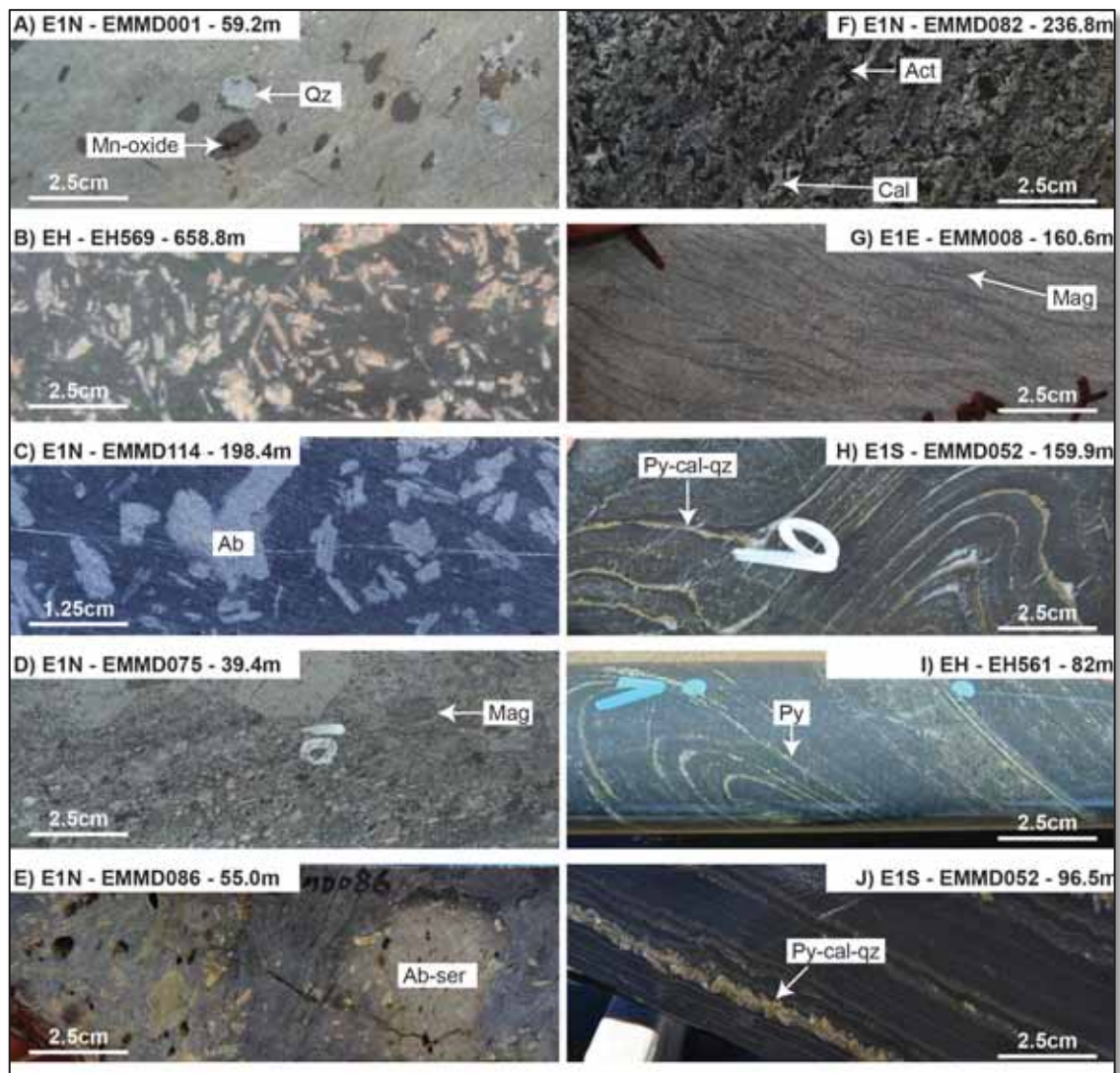


Figure 2.5: E1 Group host rocks and some Ernest Henry equivalents. A) Amygdaloidal metabasaltic-andesite. Amygdales infilled by quartz and Ca-Mn-carbonate. B) Plag-phyric meta-andesite of the Mount Fort Constantine Volcanics, Ernest Henry locality. Note red hue caused by light albite(-hematite) alteration. C) Same lithology as in (B), but from E1 North locality. D) Sericite-magnetite-biotite-altered (andesitic?) metavolcanic breccia. The clasts and matrix are mainly composed of albite and sericite. Small (<5mm) albite xenocrysts present. Dark clasts are magnetite-altered. E) Sericite-altered plag-phyric meta-andesite breccia. F) Magnetite-biotite-pyrite- and chlorite-altered porphyroblastic quartz-albite-bearing marble. Porphyroblasts altered to chlorite and apatite, probably after actinolite. G) Flaser cross-laminated feldspathic metapsammite. Cross-laminae defined by magnetite. H) Carbonaceous metasiltstone. Note pyrite-rich layers (see text for interpretation). White minerals are quartz and minor carbonate. I) Equivalent lithology at Ernest Henry locality. J) Carbonaceous schist, transitioning up-hole from the metasiltstone (not shown). Figure continued on the next page.

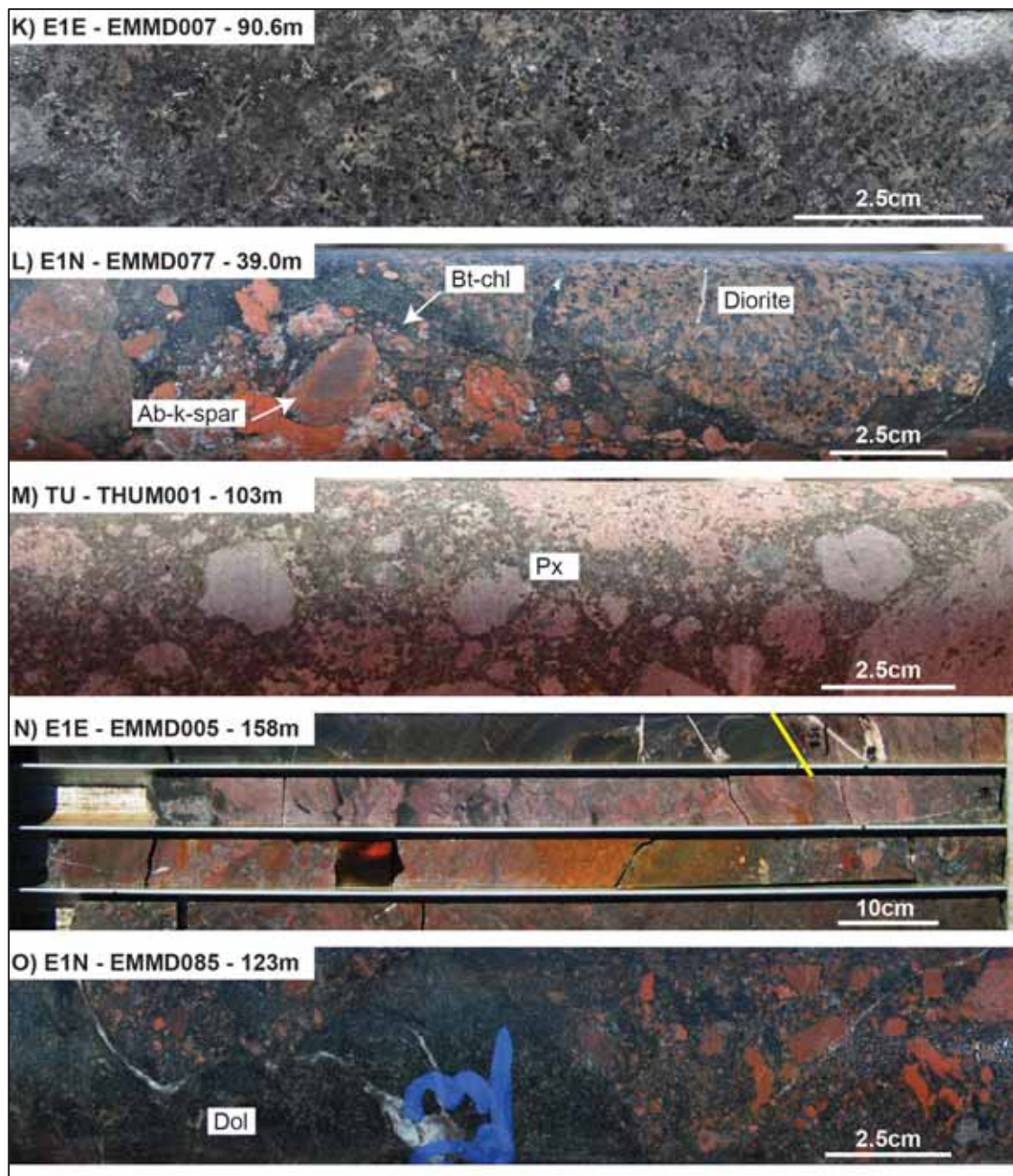


Figure 2.5 (Cont.): K) K-feldspar-albite-hematite $\pm$ epidote (not shown)-altered diorite. L) Strongly feldspathised discordant breccia with heavy, late chlorite and carbonate overprint of biotite-rich matrix. Note the prominent diorite clast. M) Discordant breccia from the Third Umpire target near Ernest Henry. This specimen is not significantly overprinted by later chlorite-carbonate alteration and the original amphibole-pyroxene-rich matrix is well-preserved. Note the poorly-defined boundary of some of the clasts, indicating some degree of chemical replacement, or 'chemical milling'. N) Abrupt, discordant contact between metasedimentary rocks (dark banded rock) and discordant breccia (red rock). O) Xenoliths of discordant breccia hosted in late, altered dolerite (Dol).

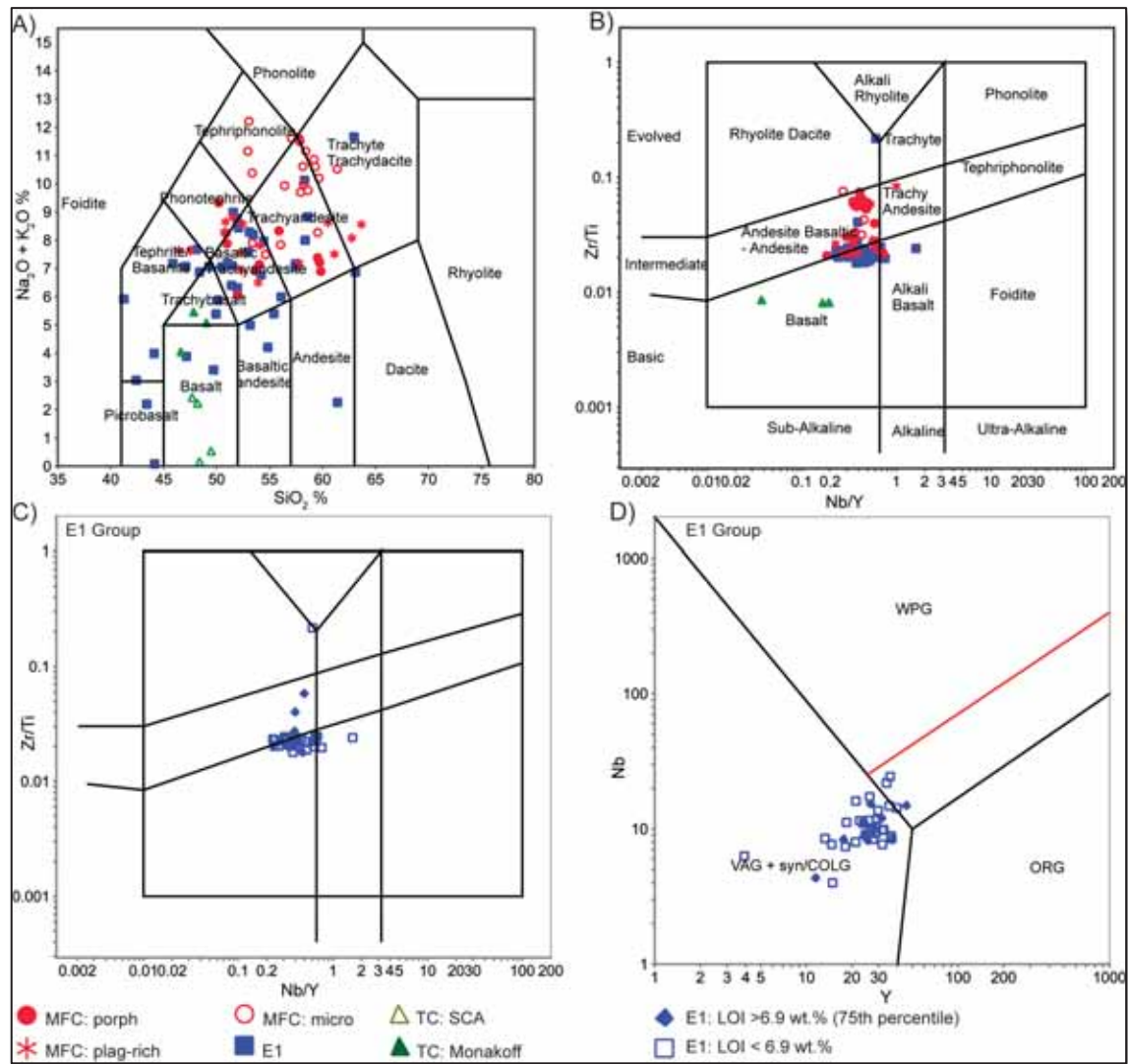


Figure 2.6: Whole-rock geochemistry of metavolcanic rocks from the E1 Group, along with reported values from Mount Fort Constantine Volcanics around the Ernest Henry locality (Blake et al., 1997), and reported values of the Toole Creek Volcanics from localities around the Snake Creek Anticline and Monakoff (Williams et al., 2015). A) SiO₂ vs Na₂O + K₂O TAS. B) Immobible HFSE trace element ratios: Nb/Y vs Zr/Ti, after Pearce (1996). Note the increased overlap between E1 and Ernest Henry samples in the latter diagram. C) Nb/Y vs Zr/Ti of E1 Group samples only, showing overlap of altered (high LOI) and less-altered (low LOI) samples. D) Y vs Nb tectonic discrimination diagram (after Pearce, 1984). MFC, Mount Fort Constantine Volcanics; porph, porphyritic; micro, microcline; TC, Toole Creek Volcanics; SCA, Snake Creek Anticline; WPG, within-plate granite; ORG, orogenic granite; VAG, volcanic arc granite; COLG, collisional zone granite.

Intrusive rocks

The metavolcanic and metasedimentary were intruded by diorite (Fig. 2.5K) interpreted to be part of the 1650 Ma Ernest Henry Diorite suite located ~5 km to the west of the E1 Group (Pollard and McNaughton, 1997; Mark et al., 2006b). The diorite is composed mostly of altered amphibole and plagioclase. Metadolerite dykes (Fig. 2.5O) intrude at

E1 North and East, and comprise pumpellyite and plagioclase, mostly altered to biotite, chlorite, sericite and minor titanite. The absolute timing of the metadolerite is unclear.

Discordant breccia

A polymictic discordant breccia cuts across all rock types at the E1 Group except for the metadolerite. The clasts include laminated metasedimentary rocks of the Corella Formation, metavolcanic rocks, and diorite (Figs. 2.5L–N). Clast size is highly variable and ranges from 1 mm to 10 m and unlike the metavolcanic breccia, the clasts are generally subrounded to rounded and unfoliated. Boundaries between clasts and matrix can be abrupt or gradational (Figs. 2.5L–M). The breccia is dominantly clast-supported, but locally may be matrix-supported. The breccia has sharp contact with host rocks at some locations (Fig. 2.5N), whereas at a few locations there are mosaic transition zones between larger breccia bodies and the host rocks. Typically at a contact the amount of host rock clasts is more than clasts of other rock types. Most clasts are variably altered by carbonate-albite-quartz-K-feldspar-hematite. Both K-feldspar and hematite dusting can impart a red hue to the breccia, leading to the terms “Red Rock Breccia,” or simply “Red Rock,” used to denote these breccias in exploration reports. The breccia matrix is dominantly composed of highly variable amounts of chlorite, carbonate, quartz, albite, biotite, and specular hematite. Because of extensive overprinting, it is not clear if the breccia at the E1 Group originally contained amphibole or pyroxene, or if the original matrix is in fact hematite-dusted albite and quartz. Regardless of the original matrix composition, it is obvious that the discordant E1 Group breccias have been strongly hydrothermally altered and the clasts have suffered significant chemical corrosion. Xenoliths, <1 m in diameter, of the breccia are present within the metadolerite (Fig. 2.5O), indicating that the breccia formed before metadolerite. The discordant breccias at the E1 Group can be difficult to distinguish from metavolcanic breccias that have been heavily altered by quartz, albite-hematite and K-feldspar; the latter, however, are always foliated and contain very little biotite and chlorite. Geochemically, the discordant breccias are characterised by similar major-element signatures to the country volcanic rocks, but have higher LOI (~8 wt%) and CaO (~7 wt%) values reflective of their higher carbonate alteration (Table 2.1).

Structures

The structural layout of the E1 Group was determined through a combination of drill core logging and mapping of the E1 North open pit. The structural framework is characterised by a series of north-northwest-plunging, similar, and open folds: the E1 North Antiform, and the corresponding E1 South Synform. The two folds share a limb referred to as E1 Central. The E1 North orebody is hosted in the hinge of the E1 North antiform, which plunges $\sim 65^\circ$ northwest; E1 South is in the hinge of the E1 South synform, which plunges shallower at $\sim 35^\circ$ northwest. The E1 East orebody is separated from E1 North and South by a major northwest–southeast trending fault (Fault D; Fig 2.4) which dips steeply southwest. The E1 East orebody is hosted within a single fold limb dipping steeply east (Fig. 2.4). Asymmetric folds observed in drill core are parasitic to the deposit-scale folds, and the dominant foliation is axial planar to these folds throughout the system. The preservation of the aforementioned cross bedding and porphyroblast-rich layers suggests bedding is mostly preserved in the deposit, but it is sometimes obscured by this foliation. Locally, the dominant foliation is crenulated and sheared by at least one generation of later foliation. Some marbles contain sporadic siliceous porphyroclasts. The folds are cut by several northeast-trending faults (Fig. 2.4). Fault 1 dips 85° southeast, and Faults 2 and 3 dip $\sim 70^\circ$ northwest. These faults bound intense shear zones trending northeast. The shear zones are coincident with zones of mineralisation and magnetite-apatite alteration and overprint the folds. Faults B and C are probably conjugate structures (Chapter 3) to Faults 1–3 and trend northwest. Faults 4–7 offset mineralisation. The Mount Margaret Fault Zone lies east of the deposit.

The discordant breccia bodies cut across the folds, and are displaced by later faults such as Fault D in E1 South and Fault 4b in E1 East. Detailed characterisations of these structures and foliations, along with the detailed structural history of the E1 Group, are presented in Chapter 3.

Alteration, Mineralisation and Ore Textures

Lithological controls and alteration textures

E1 Group ores and alterations are strongly lithologically-controlled and partially stratabound. Most Cu-Au-Fe-Ba-F-P-U-REE mineralisation is restricted to laminated marble, metasilstone and psammite and layered, matrix-supported, metatuffs and metavolcanic breccias, particularly at E1 East and E1 South. In E1 North, some strongly

sheared coherent metavolcanic rocks and clast-supported metavolcanic breccias are also mineralised; however, the coherent metavolcanic rocks are generally barren. Ore grades are generally the highest in thinly-layered or laminated protoliths with relatively few clasts. At E1 North some of this layering is interpreted to represent foliation (e.g. Fig. 2.7F), though away from the core of the orebody, and at E1 South, primary bedding is preserved.

E1 Group ores and alterations are typified by replacements; veins are less common. The euhedral, granular, and fine (<100 μ m)- to medium (~250 μ m)-grained magnetite $\pm$ carbonate (-Fe-Mg-Mn) $\pm$ barite $\pm$ fluorite $\pm$ biotite $\pm$ chlorite $\pm$ chalcopyrite $\pm$ apatite alteration dominant in the ore zones (Figs. 2.7D; 2.8B; 2.9A–E) is layer-controlled in layered rocks (Fig. 2.7A–C), and matrix-controlled in metavolcanic breccias (Fig. 2.7H). The layer-controlled alteration in the metasedimentary rocks is typically defined by carbonate or quartz-albite(-hematite)-rich layers (lighter color) alternating with carbonate-magnetite-biotite-sulfide-rich layers with darker color (Fig. 2.7A–B). Less-commonly, euhedral magnetite, pyrite and arsenopyrite alteration can form sporadic crystals greater than 3 mm in diameter, and tend to form in layers. In the metasedimentary-volcaniclastic rocks, replacement becomes texturally-destructive as alteration intensity increases, eventually forming massive, coarse-grained (>500 μ m) granular magnetite and sulfide alteration which obliterates original layering (Fig. 2.7B, L). In the metavolcanic breccias most sulfides occur in the matrix, while the clasts are magnetite-rich; in some instances, the rims of the clasts are depleted in magnetite and are sericite-rich (Fig. 2.7H). Alteration in metasiltstones is generally finer-grained (~100–250 μ m) and strongly layer-controlled.

In weakly-altered coherent metavolcanic rocks, magnetite-sericite-biotite $\pm$ carbonate alteration is typically disseminated; plagioclase phenocrysts may be preferentially albitised. Magnetite alteration is focused at plagioclase and biotite grain boundaries in more strongly-altered rocks (Fig. 2.8C). Chlorite alteration is ubiquitous and ranges from localized patches to pervasive replacement of the groundmass. In heavily-deformed metavolcanic rocks at E1 North, alteration follows biotite-muscovite shear fabric (Fig. 2.8A). Magnetite-sulfide-rich replacement in coherent volcanic rocks is generally only intense within <5 m from their contacts with metasedimentary rocks and metavolcanic breccias that are also intensely altered; the exception to this is when the coherent metavolcanic rocks are proximal (< ~10 m) to the E1 North Shear Zone. Some

coherent metavolcanic rocks are pervasively albite (-hematite)-altered; such rocks are generally devoid of magnetite and sulfides. The more intensely-albitised rocks are generally massive, but relict porphyritic and amygdaloidal textures may be preserved. These alteration styles are also observed at the E8 target, where magnetite-apatite-pyrite-quartz-chlorite-carbonate $\pm$ chalcopyrite alteration is focused mainly in sporadic intercalations of clastic metavolcanic breccia; the coherent volcanics are less altered by disseminations of these same minerals.

Significant mineralisation also occurs as carbonate $\pm$ quartz $\pm$ barite $\pm$ fluorite dominated veins and localised breccias (Fig. 2.7J–K); these minerals comprise multiple paragenetic stages (see Paragenetic Sequence below). The veins vary in size from <0.5 mm up to 3 m wide. Vein intensity is the greatest in coherent metavolcanic rocks, likely due to their more brittle rheology. Veins in these rocks, however, tend to be mostly Cu-Au-barren, and instead contain only minor sulfide in the form of pyrite. The halos of the veins typically contain pyrite, magnetite, carbonate, chlorite and/or sericite. Petrography reveals that layer-parallel to layer-subparallel microveins may also be present (Fig. 2.8B).

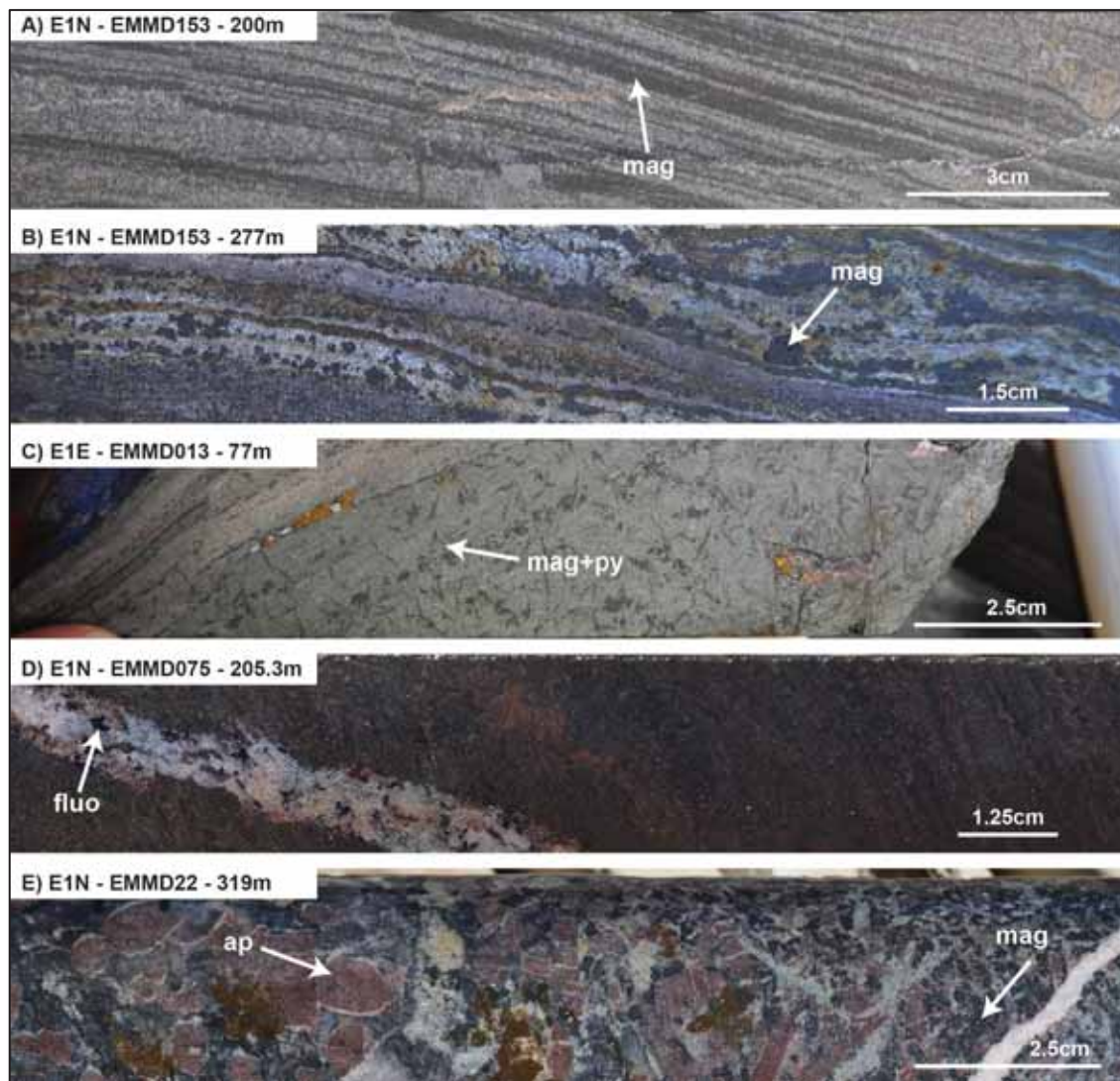


Figure 2.7: E1 Group ore textures. A) Fine-grained layer-controlled magnetite alteration of marble. B) Coarse-grained layer-controlled alteration of marble and psammitic layers. It is not certain if the layering is primary or tectonic. C) Fine-grained magnetite-pyrite $\pm$ chalcopyrite alteration of lathy porphyroblasts in calcareous? metasediment. The original mineral is not preserved but presumably was an amphibole. Groundmass is mostly biotite and chlorite. D) Carbonate-fluorite-barite $\pm$ chalcopyrite vein associated with laminated rock completely altered by the same assemblage, plus earlier magnetite. Whole-rock geochemistry indicates that barite content of the laminated domain is over 20 wt%. E) Large, Stage 2a apatite crystals interstitial with magnetite and pyrite. Carbonate and chalcopyrite are Stage 2c and 3 overprints. The calcite vein in the lower-right is Stage 3. The intensity of the apatite-magnetite is typically somewhat gradational, suggesting an alteration texture. Figure continued on the next page.

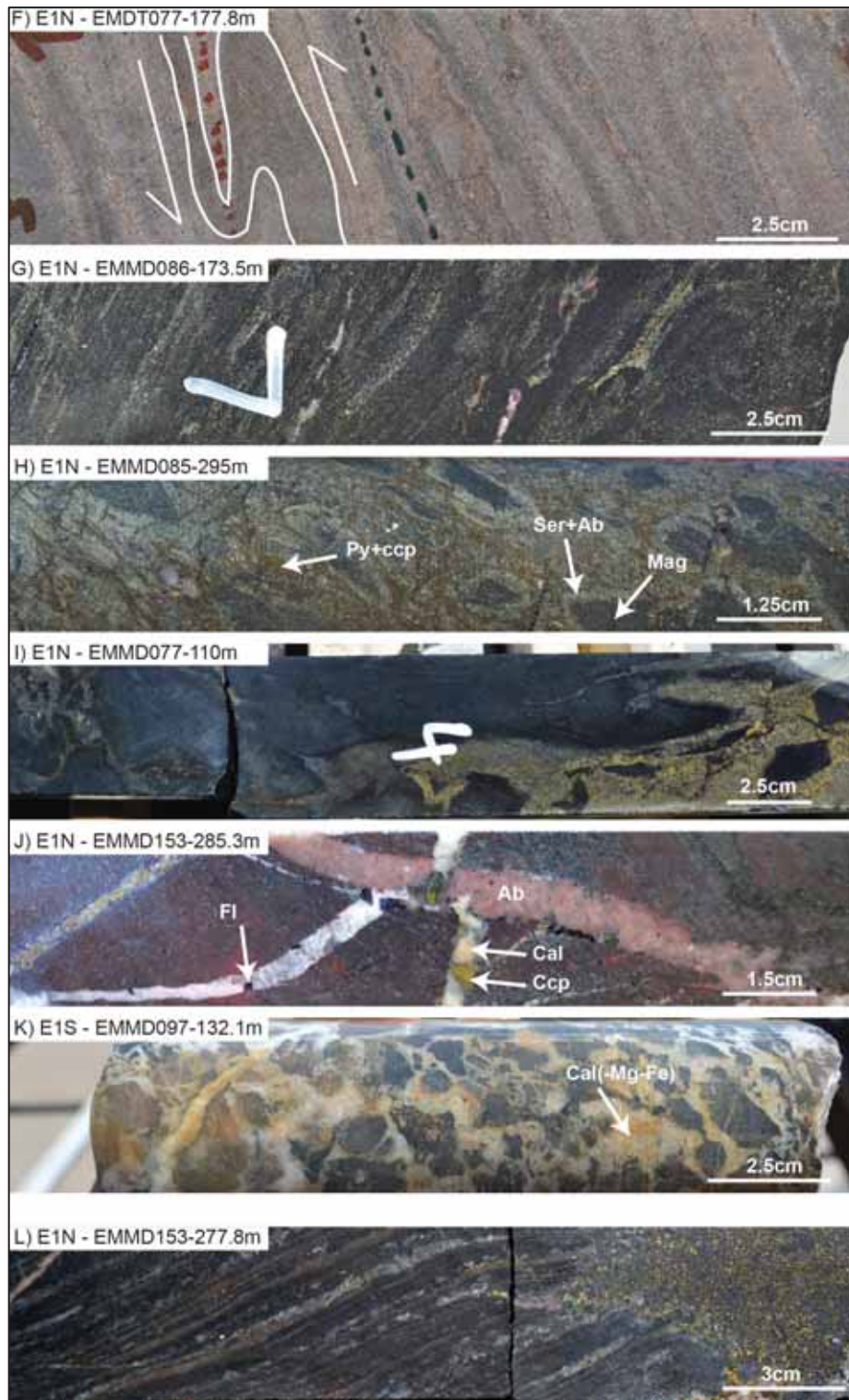


Figure 2.7 (Cont.): F) Sheared metasedimentary? rock with close folds. Strongly altered to magnetite, barite, fluorite and chalcopyrite. G) Strongly-sheared, magnetite-sulfide-altered metavolcanic or metasedimentary rocks. H) Foliated metavolcanic breccia. In less-altered equivalents the clasts and matrix are mostly sericite and albite. Here the clasts are magnetite-altered while the matrix is pyrite-chalcopyrite-rich. The light-colored haloes of the clasts are sericite-rich. I) Anastomosing pyrite alteration in massive metavolcanic rocks immediately outside of the laminated orebody. J) Less-common vein equivalents of alteration. Stage 2b albite vein overprinted by Stage 2c carbonate (yellow-white) and Stage 3 carbonate-fluorite. The chalcopyrite associated with Stage 2c is probably an overprint related to Stage 3. K) Amygdaloidal meta-basaltic andesite brecciated in-situ by Stage 2c carbonate. L) Coarse magnetite-chalcopyrite-pyrite alteration overprinting magnetite-rich laminae.

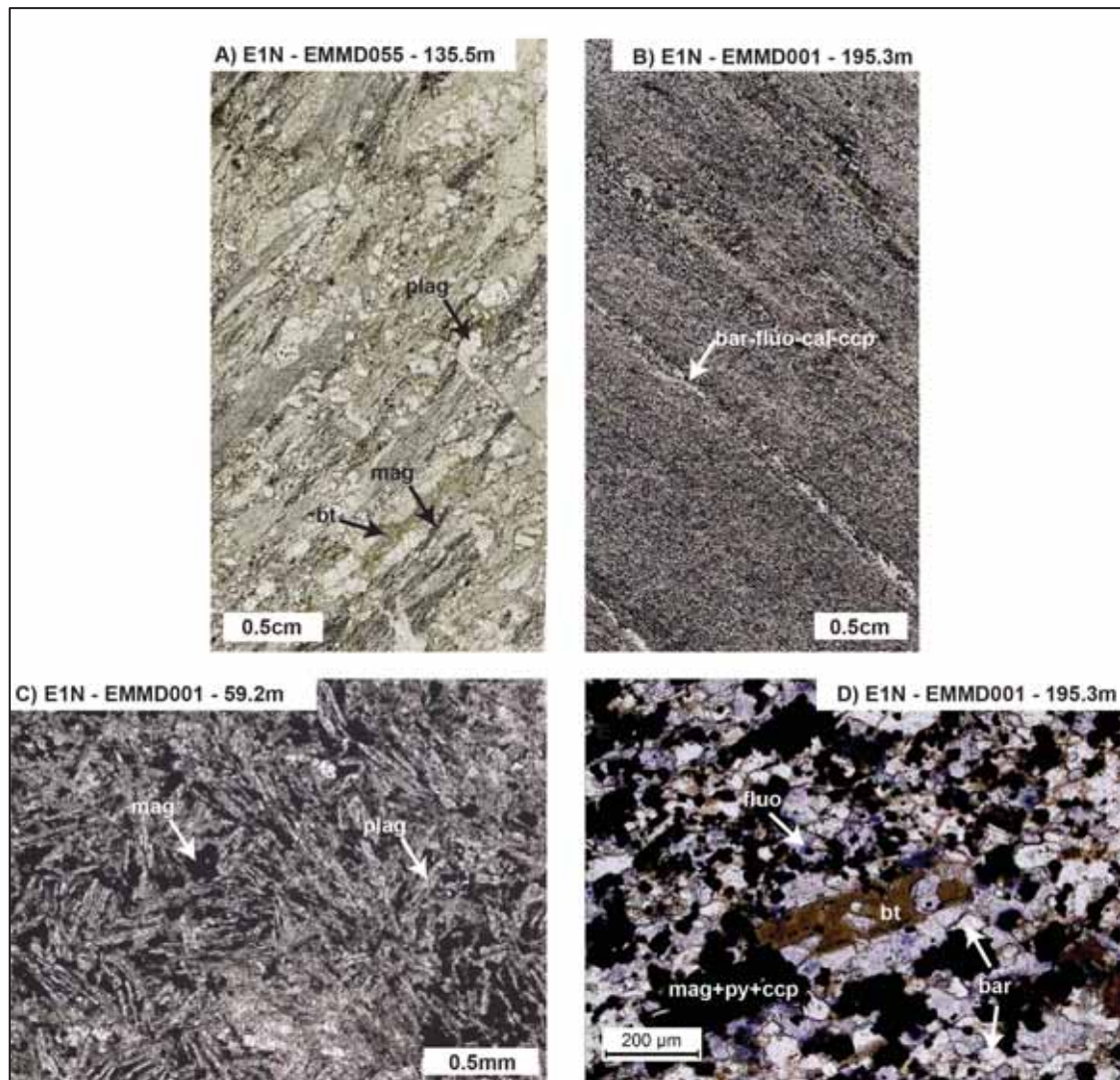


Figure 2.8: Ore microtextures. A) Scan of thin section of strongly-sheared porphyritic meta-andesite. Pepper texture is characterised by magnetite alteration of mica shear fabric. B) Scan of thin section of laminated metasediment entirely replaced by magnetite, barite, fluorite, chalcopyrite, pyrite and minor albite, biotite, and apatite. Note the layer-parallel microvein (labelled). C) Plagioclase-rich meta-andesite with moderate magnetite alteration, focused mainly along plagioclase crystal boundaries. D) Plain light photomicrograph of thin section from (B), showing abundant fluorite, barite, and magnetite alteration.

Ore and alteration mineralogy

The mineralogy of ore samples is characterised by variably abundant magnetite, barite, fluorite, chalcopyrite, carbonate (calcite to ankerite), and chlorite, lesser biotite, muscovite, and quartz, and minor albite (Fig. 2.9; App. C). EDS analysis suggests trace monazite, bastnäsite, coffinite, uraninite, and cassiterite are also present in both metasedimentary and metavolcanic rocks, while rutile and ilmenite are present mostly in altered metavolcanic rocks.

Alteration in metasedimentary rocks

MLA mapping indicates that the abundance of barite and fluorite in metasedimentary rock-hosted ores, and the composition of carbonate minerals associated with them, vary considerably. Most of the samples analysed that contain high chalcopyrite, barite and fluorite also contain ankeritic carbonate, while a less-mineralised marble is dominated by dolomite and calcite. For example, sample EMMD075-205.3m (Fig. 2.9A), collected from the west limb of the E1 North Antiform, hosts 12 wt% fluorite, 25 wt% barite, 8 wt% chalcopyrite and about 14 wt% Ca-Mg-Fe-Mn-ankerite ($\text{Ca}_{0.46}\text{Mg}_{0.23}\text{Fe}_{0.17}\text{Mn}_{0.10}$; Table 2.5). In contrast, sample EMMD055-14 (155.35m; Fig. 2.9B), taken less than 100 m west of the previous sample and also on the west side of the antiform, does not contain abundant barite but has 15 wt% fluorite, 11 wt% chalcopyrite and only 4 wt% Fe-Mn-ankerite (based on EDS; not shown). Sample EMMD153-7 (76.55m; Fig. 2.9C), collected on the east limb of the E1 North Antiform, is similar to sample EMMD055-155.35m; it lacks barite but contains abundant magnetite (30 wt%) and Mn-ankerite (27 wt% $\text{Fe}_{0.64}\text{Mn}_{0.22}\text{Ca}_{0.03}\text{Mg}_{0.01}$; Table 2.5), as well as high fluorite (8 wt%). Sample EMMD085-310.5m (Fig. 2.9E), collected from the west limb of the E1 North Antiform, contains significant barite (16 wt%), fluorite (9 wt%), magnetite (19 wt%) and chalcopyrite (8 wt%), but hosts far less carbonate (9 wt%) than the other samples; EDS suggests the carbonate is mostly pure calcite. In contrast to these mineralised samples is sample EMMD153-13 (311.7m; Fig. 2.9D), which contains no chalcopyrite and is dominated by dolomitic carbonate (22 wt%; $\text{Ca}_{0.49}\text{Mg}_{0.33}\text{Fe}_{0.17}\text{Mn}_{0.01}$; S13, Table 2.5) and calcite. However, both magnetite and pyrite are significant at about 17 wt% each. Quartz, calcite, chlorite, biotite, albite and apatite are minor phases. In addition to the carbonate and siliciclastic rocks, one sample (EMMD167-105m; Fig. 2.9K) of carbonaceous schist, collected, between E1 North and E1 East, was mapped in MLA. It comprises mainly muscovite (51 wt%) and quartz (40 wt%), with minor biotite (4 wt%), ankerite (3 wt%) and chlorite (2 wt%).

In addition to the major and minor phases described above, MLA analysis detected trace amounts of La-Ce- and U-bearing phases in some altered metasedimentary rocks. The phases were identified based on their EDS spectra. As an example, sample EMMD153-76.55m (Fig. 2.9C) contains monazite (0.3 wt%), bastnäsite -La (0.08 wt%), and a U-oxide phase (brannerite or uraninite). Sample EMMD055-155.35m contains a Ca-Ce-La fluorocarbonate phase, possibly rontgenite ($\text{Ca}_2(\text{Ce}, \text{La})_3(\text{CO}_3)_5\text{F}_3$), though it is very

fine-grained (aggregates of $<10\mu\text{m}$ crystals) and may be a composite spectrum resulting from the replacement of a carbonate mineral by bastnäsité. The same sample also hosts a trace (0.1 wt%) U-silicate phase interpreted to be coffinite.

Alteration in metavolcanic rocks

The metavolcanic rock samples EMMD001-59.9m, EMMD146-215m and EMMD167-180m (Fig. 2.9F, H–I) are composed mostly of near endmember albite (31 wt% and 56 wt%, respectively), though WDS indicates that EMMD146-215m contains a few wt% Ca-plagioclase (Fig. 2.12C). Sample EMMD001-59.9m also contains 18 wt% sericite/muscovite, while the latter contains 15 wt% chlorite. The former two samples have moderate (8–10 wt%) magnetite, along with quartz and calcite, while ankerite is the dominant carbonate species in EMMD167-180m. The high albite content of these metavolcanic rocks, coupled with significant magnetite, calcite, chlorite and sericite, suggest that most of the minerals are metasomatic. Sample EMMD182-94.5m (Fig. 2.9G) is from porphyritic meta-andesite on the east limb of the E1 North Antiform. The groundmass of this sample comprises mostly biotite and sericite, while the phenocrysts are composed of albite. The sericite appears to cluster with dolomite alteration, and the sample is cut by an albite vein. MLA mapping of a (meta)-dolerite sample (EMMD085-112m; Fig. 2.9J) reveals it is composed mostly of muscovite, actinolite and biotite, with accessory titanite and ankerite. The latter two phases are probably alteration phases, though the paragenetic timing of the titanite is not clear in this sample.

Interpretations

The presence of ankeritic carbonate in both metavolcanic and metasedimentary rocks suggests that much of the carbonate minerals in mineralised metasedimentary rocks are alteration phases, rather than primary marble carbonate. Given the abundance of dolomitic carbonate and calcite in sample EMMD153-311.7m, it is speculated that the Fe-Mn-rich alteration carbonate is replacing existing primary carbonate. Additional, geochemical, evidence for carbonate replacement is presented in the Ore Chemistry section.

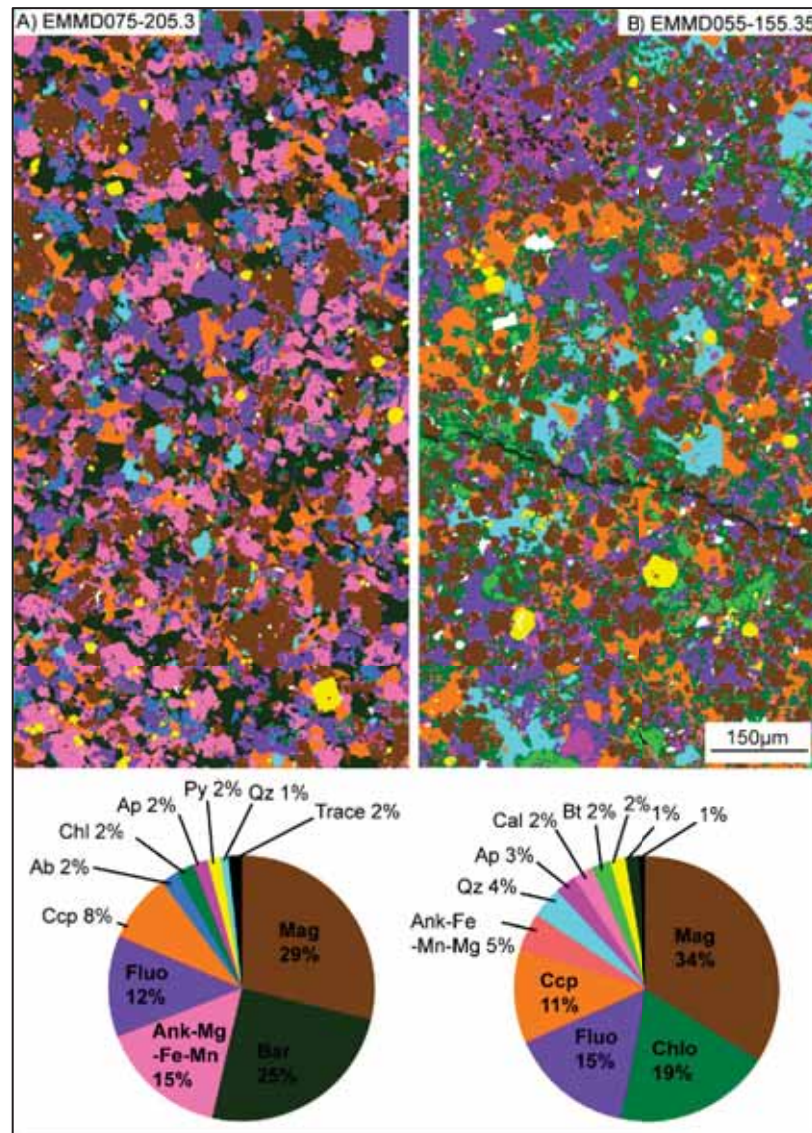


Figure 2.9: Ore textures observed in Mineral Liberation Analysis (MLA) maps of two distinct ore samples. All abundances are wt%. A) Barite-rich ore from the deeper, barite-rich zone of the E1 North orebody (see Fig. 2.20). B) Barite-poor ore from upper portion of E1 North orebody. Continued on next three pages.

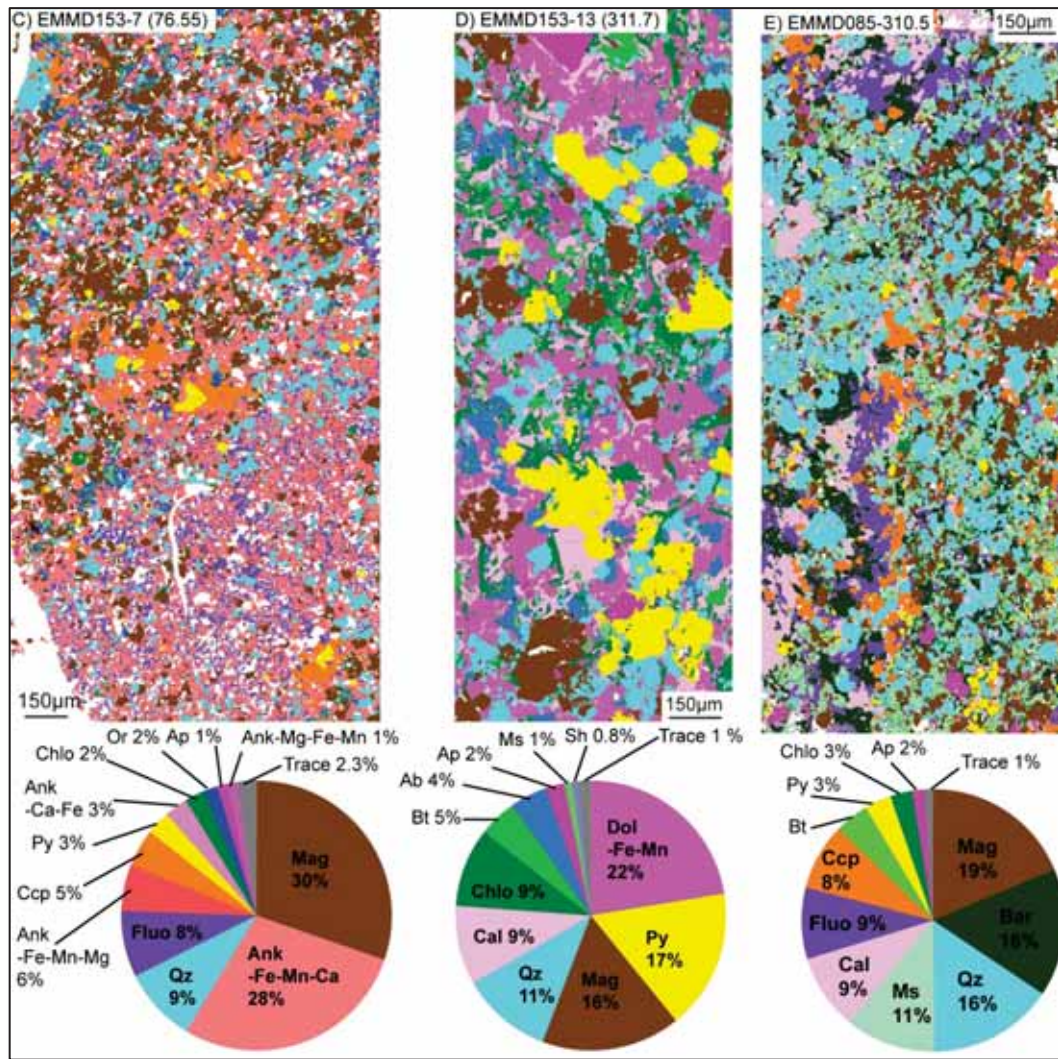


Figure 2.9 (cont): C) Marble? sample from Mn-F-rich zone in upper E1 North orebody (see Fig. 2.20). D) Less-altered marble downhole from the sample in C. E) Barite-fluorite-quartz-rich ore from deeper part of E1 North orebody.

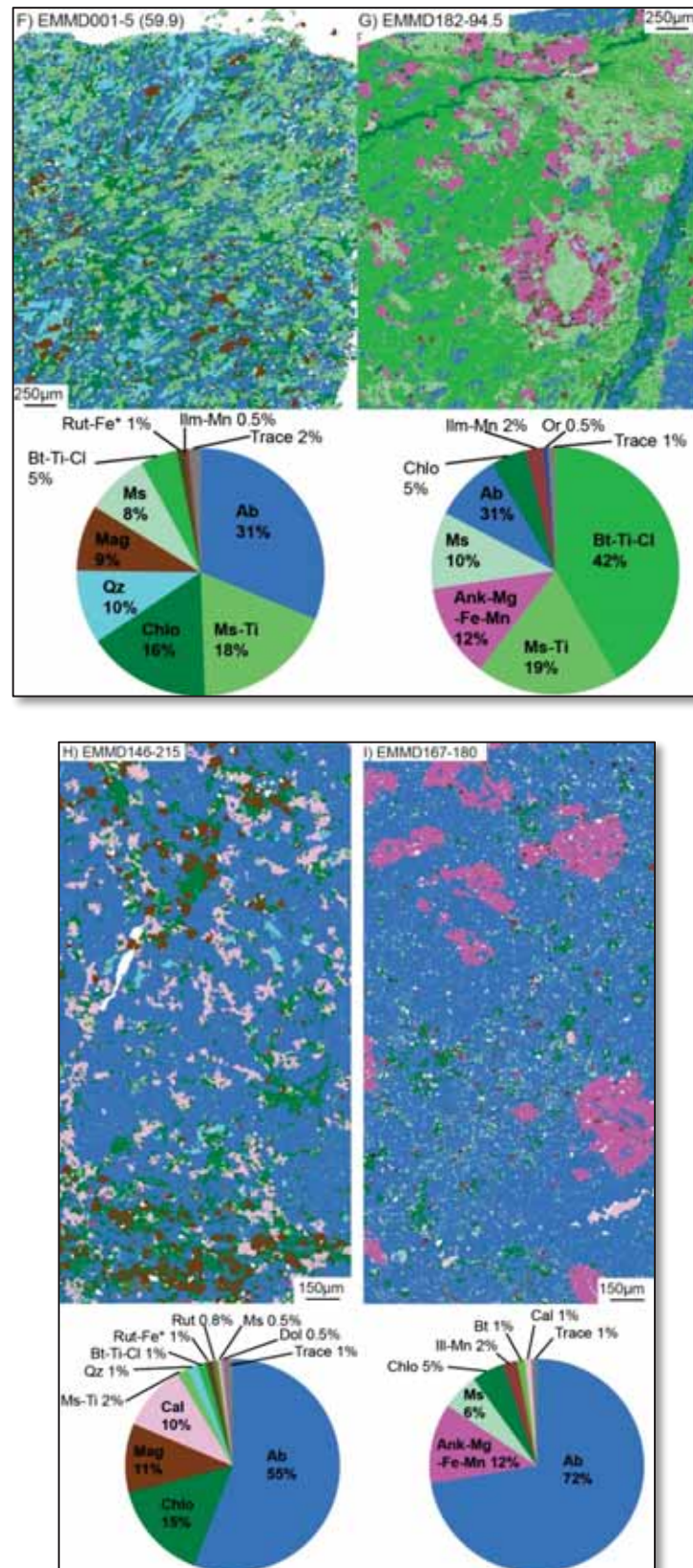


Figure 2.9 (cont.): F) Muscovite-magnetite-altered meta-andesite from the west limb of E1 North. G) Biotite-albite-ankerite-altered porphyritic meta-andesite from the east limb E1 North. H) Calcite-chlorite-magnetite-altered meta-andesite from the east limb of E1 North. I) Ankerite-altered meta-andesite between E1 North and E1 East.

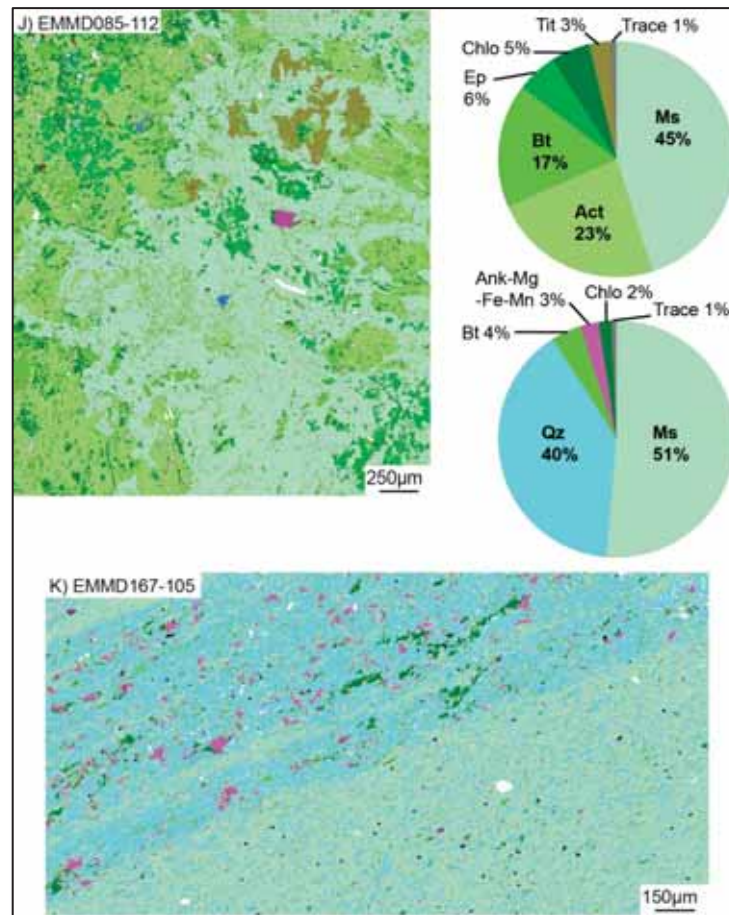


Figure 2.9 (cont.): J) (Meta)-dolerite. K) Carbonaceous muscovite schist between E1 North and E1 East; note that the carbon was likely too fine-grained to be mapped by this method.

Paragenetic Sequence

Alteration at the E1 Group is complex, and is grouped into three major paragenetic stages, with the second, pre-ore, stage comprising three substages (Figs. 2.10–2.11). The stages are: 1) early sodic-(-calcic), 2a) precursor ferric/ferrous-potassic-silicic, 2b) intermediate sodic (-Ti), 2c) early carbonate (-Fe-Mg) flooding and mineralisation, and 3) main Cu-Au-carbonate (-Fe-Mn)- barite-fluorite-U-REE mineralisation. This sequence was also observed at the nearby E8 target.

Stage 1: Early Na-(Ca) alteration:

All of the host rocks within the mine lease (at least 2 km from the orebody) are variably altered by albite (Figs. 2.11A–B, I; 2.9G–I) and, to a lesser extent, quartz, actinolite, and titanite; the latter two minerals are rare and are only locally abundant in metadolerite (Fig. 2.9J), diorite and discordant breccia. Red hematite dusting overprints the albite as a late substage (Fig. 2.11A–B and I). Stage 1 alteration is most abundant in the discordant breccia, with the assemblage replacing both the infill and the clasts (Fig.

2.11B). Quartz infill and alteration are locally abundant in the breccia (Fig. 2.11B). In some instances, the assemblage also strongly alters metasedimentary (Fig. 2.11A) and metavolcanic country rocks less than 5 m from contacts with the hydrothermal breccia. In less-altered porphyritic metavolcanic rocks, the albitisation is focused in plagioclase phenocrysts. Disseminated albite is common in marble. Microprobe analysis of plagioclase in the discordant breccia, marble and meta-andesite indicates that it is essentially pure albite (<5 wt% anorthite; Table 2.2, Fig. 2.12C). The plagioclase analyses of meta-andesite shown in Figure 2.12C are from the groundmass of samples which, visually, appear only lightly albite altered. Such pure albite content, however, suggests pervasive albitisation. Semi-quantitative EDS analyses of other plagioclase-rich metavolcanic rocks also indicate nearly pure albite. Albitisation may therefore be more widespread than drill core observations indicate. Rarely, clasts of the metavolcanic breccia within the discordant breccia are altered by magnetite with hematite rims. This magnetite is probably part of Stage 1.

Table 2.2: Representative microprobe analyses of feldspar

Sample (EMMD)	001_5	001_5	153_7	153_1	146_215	146_215	008_1	008_1	007_3	001_1
Point	S1	S5	S1	S8	S2	S4	S1	S9	S2	S2
Oxide (wt%)										
SiO ₂	68.47	70.86	64.48	70.25	68.12	68.38	67.79	65.36	67.79	67.79
TiO ₂	0.05	0.01	BD	0.03	0.06	BD	BD	BD	0.01	BD
Al ₂ O ₃	18.34	18.78	17.24	18.42	18.95	18.62	19.36	17.36	19.72	18.87
FeO ¹	0.60	0.17	0.87	0.21	0.41	0.05	0.06	0.26	0.45	0.06
MnO	BD	BD	0.09	0.01	0.02	BD	BD	BD	BD	BD
MgO	BD	0.02	BD	BD	BD	BD	BD	BD	BD	0.01
CaO	0.06	0.04	BD	0.05	1.01	0.49	0.74	BD	0.04	0.02
Na ₂ O	12.05	11.78	0.09	12.01	11.53	11.97	10.86	0.20	10.86	12.39
K ₂ O	0.04	0.02	17.13	0.05	0.08	0.09	0.12	16.51	0.03	0.07
Total	99.62	101.7	99.9	101	100.2	99.61	98.93	99.69	98.9	99.21
Cations on the basis of 8 O										
Si	3.01	3.04	3.01	3.04	2.99	3.01	2.99	3.03	2.99	2.99
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.95	0.95	0.95	0.94	0.98	0.97	1.01	0.95	1.03	0.98
Fe ²⁺	0.02	0.01	0.03	0.01	0.01	0.00	0.00	0.01	0.02	0.00
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.00	0.00	0.00	0.00	0.05	0.02	0.03	0.00	0.00	0.00
Na	1.03	0.98	0.01	1.01	0.98	1.02	0.93	0.02	0.93	1.06
K	0.00	0.00	1.02	0.00	0.00	0.00	0.01	0.98	0.00	0.00
Total	5.02	4.98	5.03	5	5.01	5.02	4.97	4.99	4.96	5.05
Ca+Na+K+other-1	0.06	0.01	0.07	0.02	0.05	0.05	0.03	0.01	0.05	0.07
4-(Si+Al)	0.03	0.01	0.04	0.02	0.03	0.03	0.00	0.02	0.01	0.02
Al-(2Ca+K+Na)	-0.08	-0.04	-0.08	-0.08	-0.10	-0.11	0.00	-0.05	0.09	-0.08
Or	0.21	0.12	95.74	0.25	0.44	0.46	0.70	97.23	0.19	0.37
Ab	97.42	98.92	0.74	98.75	93.52	97.12	95.46	1.76	97.88	99.28
An	2.37	0.95	3.53	1	6.04	2.42	3.83	1.01	1.92	0.36

General formula: (K, Na, Ca) (Al, Si)₄O₈¹All Fe reported as Fe²⁺

BD = below detection

	Stage 1 Early Na-Ca	Stage 2a Fe-K-P	Stage 2b Na-Ti	Stage 2c CO ₃ flood	Stage 3 Late Min.	
Albite	██████████		-----			
Amphibole	██████████					
K-feldspar		██████████				
K(-Ba)-feldspar		-----				
Quartz	██████████	██████████		-----		
Ba-silicate		-----				
Biotite		██████████		-----	Fe-Mn-rich	
Carbonate				██████████ Mg-Fe-rich		
Apatite		██████████				
Barite					██████████	
Chlorite				██████████	██████████	
Epidote					-----	
Fluorite			?		██████████	
Arsenopyrite		-----	-----			
Chalcopyrite				? ██████████	██████████	
Bi-Au-sulfosalt*				██████████		
Electrum*						
Pyrite				██████████		
Pyrrhotite		-----	-----	-----		
Hematite	██████████		?			
Magnetite		██████████	-----	██████████		
Bastnäsite					██████████	
Monazite					██████████	
U-silicate (tr)					██████████	
Uraninite (tr)					██████████	
Ilmenite		? - - - -	-----			
Rutile		-----	-----			
Sericite	-----				██████████	
Titanite	██████████			?	-----	
Sphalerite				----- ?	-----	
Equivalent Ernest Henry Stage (Mark et al., 2006)	Na-Ca Cycle 1 Stage 1 Albite, amphib., titanite	Stage 2 K-Fe Biotite, magnetite, K-feldspar	Na-Ca Cycle 2 Stage 2 Albite	Stage 3 Mineralization		
Equivalent Monakoff Stage (Williams et al., 2014)	Stage 1 Ca Garnet, biotite	Stage 2 K-Fe Magnetite, biotite, pyrrhotite		Stage 3 Main ore Fluorite, barite, calcite (-Mn), chalcopyrite, galena., sphalerite., U-REE		Stage 4 Late ore Alloclasite, Au-pyrite, Arsenopyrite

Figure 2.10: E1 Group paragenetic sequence, with equivalent Ernest Henry (Mark et al., 2006b) and Monakoff (Williams et al., 2015) stages shown. Bar thickness corresponds to relative abundance. Dashed line indicates uncertain timing. *Indicates phases identified in Williams et al. (2015).

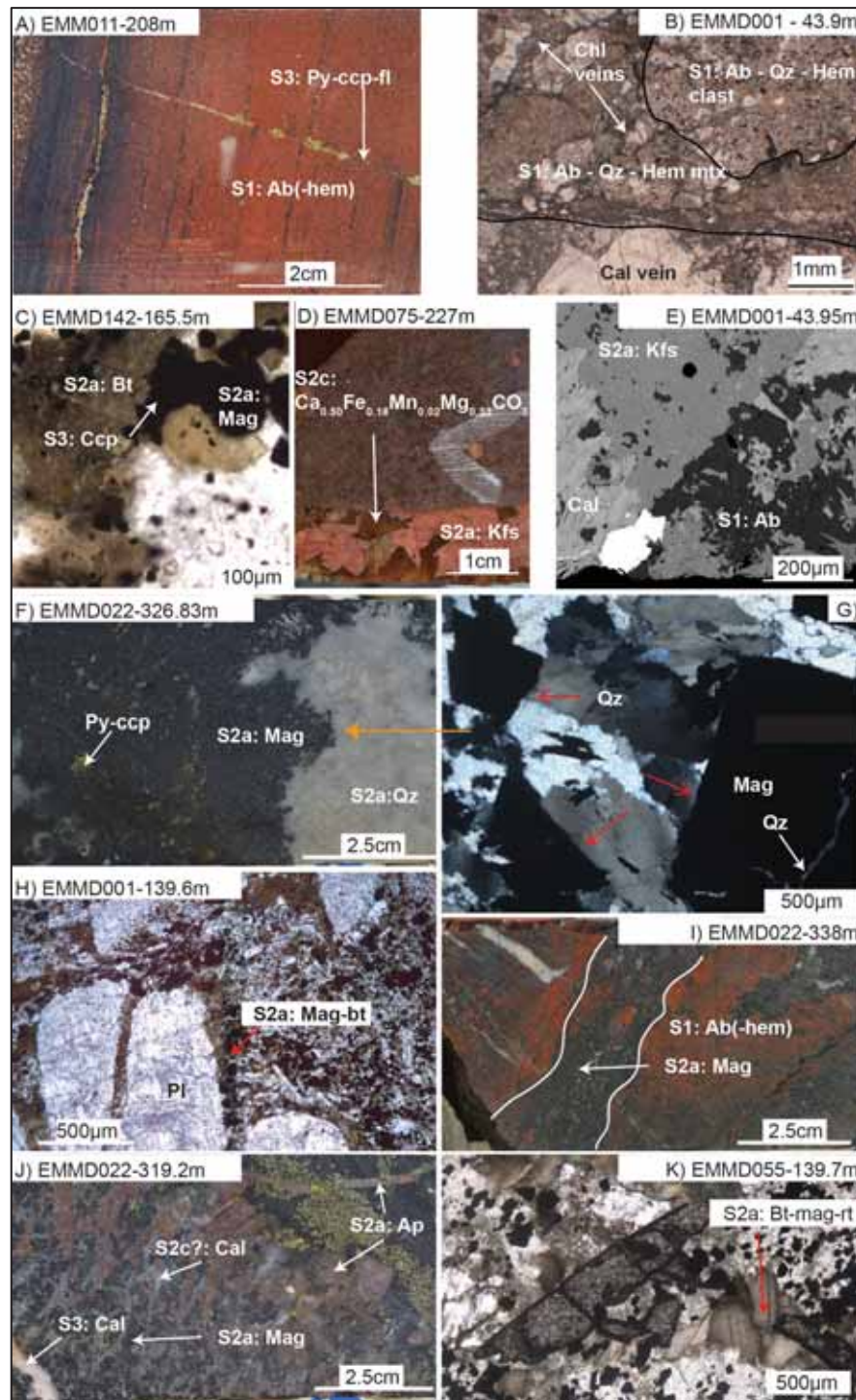


Figure 2.11: E1 Group paragenesis cross cutting and overprinting relationships. A) Metaspammitite with Stage 1 albite alteration. B) Photomicrograph of discordant breccia with Stage 1 albite-quartz-hematite – altered clast and matrix; cut by later calcite; plain light C) Stage 2a biotite and magnetite replaced by Stage 3 chalcopyrite. D) Stage 2a K-feldspar vein partly refilled and altered by Fe-rich Stage 2c carbonate. E) Backscattered Electron (BSE) image of Stage 2a K-feldspar replacing Stage 1 albite in discordant breccia. F) Stage 2a euhedral magnetite intergrown with Stage 2a quartz. Minor sulfide and carbonate overprints. G) Photomicrograph from the same sample, showing partial recrystallization of the quartz intergrown with magnetite; Cross Nicols. H) Photomicrograph of Stage 2a biotite and magnetite veinlets cutting albitised plagioclase phenocrysts in porphyritic meta-andesite; plain light. Note the extensive magnetite alteration (opaque minerals). I) Stage 2a magnetite patch overprinting Stage 1 albite. J) Coarse-crystalline Stage 2a apatite-magnetite alteration, with interstitial carbonate possibly related to Stage 2c?. They are cut by Stage 3 calcite. Sulfides are probably Stage 2c. K) Photomicrograph of Stage 2a biotite and magnetite associated with rutile; Cross Nicols. Continued on the next four pages.

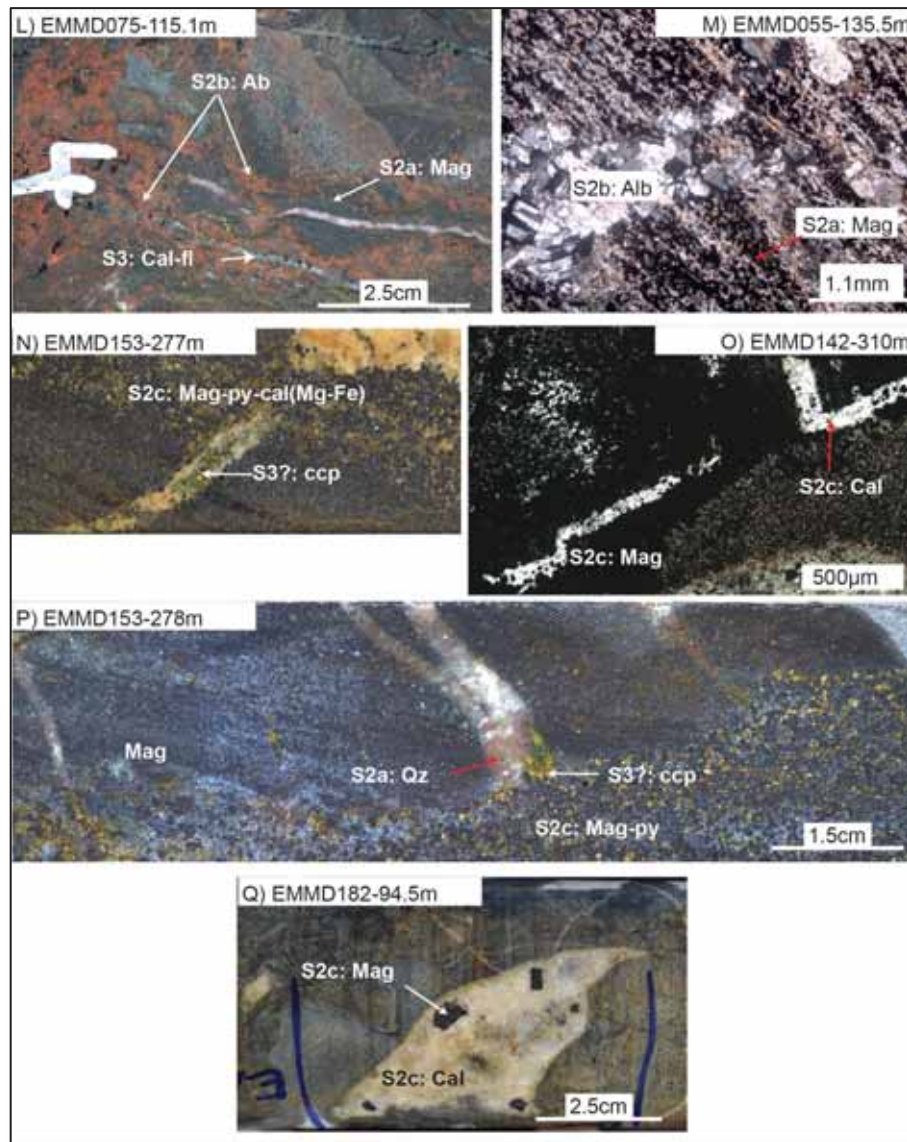


Figure 2.11 (cont.): L) Stage 2b albite veinlets overprinting Stage 2a magnetite; both are cut by Stage 3 carbonate-fluorite veins. M) Photomicrograph of Stage 2b albite cutting Stage 2a magnetite-altered meta-andesite. N) Coarse-crystalline, Stage 2c, magnetite-pyrite-carbonate alteration. O) Stage 2c carbonate vein in discordant breccia, with obvious magnetite-pyrite alteration halo. P) Coarse-crystalline, Stage 2c, magnetite-pyrite-carbonate alteration overprinting a Stage 2a quartz vein and finer-grained Stage 2a magnetite. Q) Stage 2c carbonate-magnetite infill in meta-andesite.

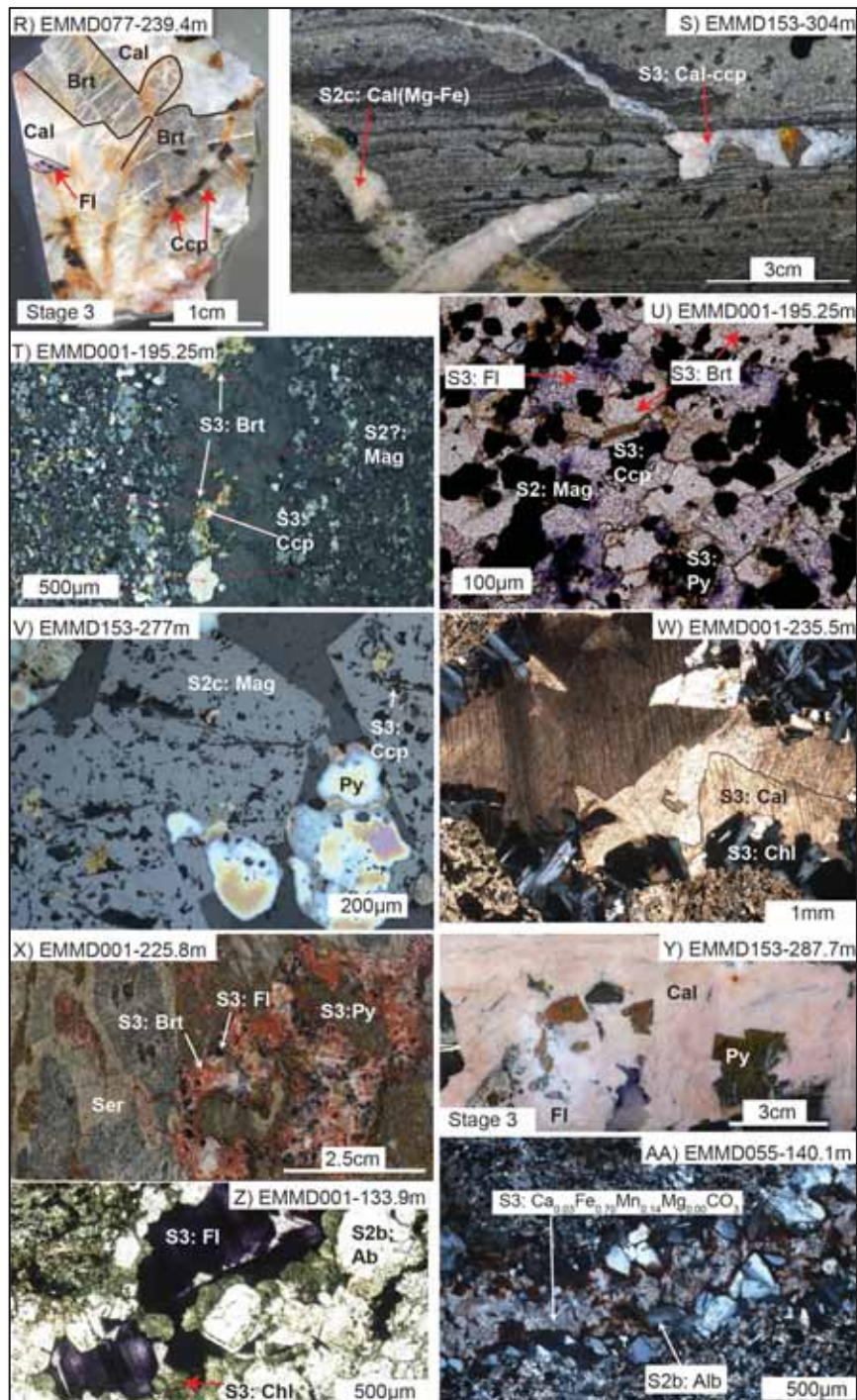


Figure 2.11 (cont): R) Stage 3 barite-calcite-chalcopyrite-fluorite vein. Note the hematite staining in late fractures. S) Stage 3 calcite and chalcopyrite cutting yellowish Stage 2c calcite vein. T) Photomicrograph of Stage 3 barite intergrown with chalcopyrite and pyrite in a ~500 μm -wide vein; reflected light. U) Photomicrograph of fine-grained Stage 3 fluorite, barite and chalcopyrite alteration; plain light. V) Photomicrograph of the sample shown in (N) showing Stage 3 chalcopyrite veinlets cutting coarse crystalline Stage 2c magnetite. W) Photomicrograph of Stage 3 chlorite and calcite infill; Cross Nicols. X) Stage 3 barite-fluorite-carbonate infill in an altered metavolcanic breccia. The clasts of the breccia contain some quartz and albite but are altered to magnetite and sericite, while the clast rims have been more strongly sericite altered and depleted in magnetite. The breccia matrix is composed of sericite and pyrite, with minor chalcopyrite. Y) Stage 3 pink calcite(-Fe-Mn) vein with pyrite, chalcopyrite and fluorite. Note the calcite veinlets fracturing the sulfides, suggesting reworking of the carbonate. Z) Photomicrograph of Stage 3 fluorite-chlorite infill in a re-opened Stage 2b albite vein; plain light. AA) Photomicrograph of Stage 3 Fe-Mn-calcite filling in a re-opened Stage 2b albite vein. Cross Nicols.

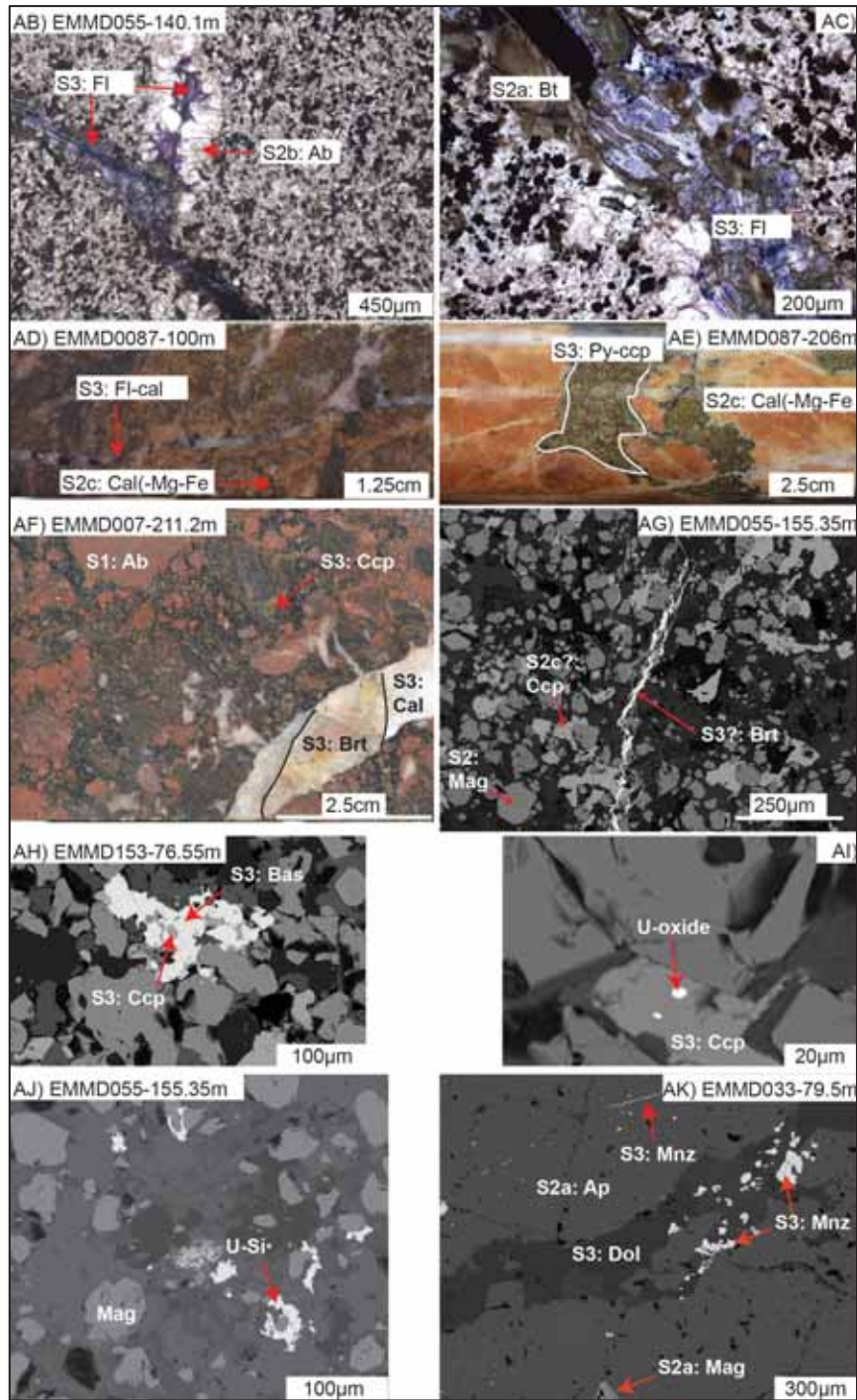


Figure 2.11 (cont.): AB) Photomicrograph of same sample showing Stage 3 fluorite filling in another Stage 2b albite vein; plain light. AC) Photomicrograph of same sample showing Stage 3 fluorite replacing Stage 2a biotite along cleavage planes; plain light. AD) Stage 3 calcite-fluorite vein cutting yellow-brown-weathered Stage 2c carbonate(-Fe-rich?). AE) Stage 3 pyrite and chalcopyrite overprinting a large (>1m) Stage 2c sideritic carbonate vein. AF) Stage 3 calcite-barite vein cutting across Stage 1 and 2-altered Discordant breccia. Note the disseminated sulfide alteration probably related to the veining. AG) BSE image of MLA-mapped sample EMMD055-155.35m, showing a barite veinlet cutting across chalcopyrite-magnetite alteration. AH) BSE image of bastnäsite intergrown with chalcopyrite. AI) BSE image from same sample showing U-oxide (uraninite?) inclusion in chalcopyrite. AJ) BSE image of a U-silicate (coffinite?) phase growing around magnetite alteration. AK) BSE image of the sample used for monazite U-Pb dating, showing Stage 3 dolomitic calcite-monazite veinlet cutting across Stage 2a apatite. Note the tiny monazite inclusions and veinlets in the apatite.

Stage 2a: Pre-mineralisation Fe-K-P-Si alteration

The precursor ore stage is subdivided into three stages. Stage 2a, the ferric/ferrous-potassic alteration stage, is characterised by magnetite (Fig. 2.11F–M), biotite (Fig. 2.11C, H, and K), apatite (Fig. 2.11J), K(-Ba)-feldspar (Fig. 2.11D–E), quartz (Fig. 2.11F–G), and pyrite (Fig. 2.11J) alteration. Rutile and ilmenite may also be present in minor amounts (Fig. 2.11K). K(-Ba)-feldspar and specularite are most common in the discordant breccia and metasedimentary rocks (Fig. 2.11E), while biotite, magnetite and some hematite mainly alter the intermediate-mafic metavolcanic rocks and marble. The discordant breccia is virtually devoid of magnetite. Some of the biotite and magnetite may be igneous in origin, but the two minerals occur in veins that cut across these rocks, indicating that much of the biotite and magnetite currently visible are hydrothermal (Fig. 2.11H). Microprobe analysis indicates that Stage 2a biotite composition varies significantly between the fluorannite and fluorophlogopite solution series, but is generally fluorine-rich (up to 4% F) and contains up to 2% Cl (Table 2.3). The molar ratios of TiO_2 , FeO^* ($\text{FeO} + \text{MnO}$), and MgO are displayed in Figure 2.12A. This type of ternary plot was demonstrated by Nachit et al. (2005) to discriminate between magmatic biotite (domain A; Fig. 2.12A), biotite re-equilibrated with hydrothermal fluids (neoformed; domain B), and hydrothermal biotite (domain C). The latter has lower TiO_2 (<1.5–2.0 mol%). All of the E1 Group biotite analysed plots outside of the magmatic domain. Most crystals plot in the neoformed domain; one analysis from a biotite veinlet and two replacement biotite crystals plot in the hydrothermal domain. Microprobe analyses with totals <95 % were omitted from the plot, as they are probably partly chloritized.

Biotite and K(-Ba)-feldspar alteration overprint both clasts and infill of discordant breccia (Fig. 2.11B, E). The replacement of albite by K(-Ba)-feldspar and magnetite is also common in albitised metapsammites. Coarse-grained (up to 5mm), euhedral arsenopyrite is ubiquitous, but variable, in the carbonaceous metasiltstone at E1 South and E1 East. The metasiltstone also hosts widespread magnetite alteration, and arsenopyrite and magnetite may occur in the same samples. Arsenopyrite is cut by Stage 2c or 3 chalcopyrite veinlets and is interpreted to represent a spatial variation of Stage 2a sulfide species due to the more reducing nature of the carbonaceous host rocks. The quartz is locally polycrystalline and characterised by microdeformation textures in the form of undulating grain boundaries (Fig. 2.11G). In some places it appears to overprint

magnetite (Fig. 2.11G), and this is interpreted to represent partial remobilization during later stages. For example, in hand specimen, the quartz and magnetite in sample EMMD022-326.83m appear to be intergrown (Fig. 2.11F). However, in thin section recrystallized grain boundaries are visible in the quartz, and quartz veinlets cut across a few magnetite crystals (Fig. 2.11G). The remobilization may be partly due to deformation.

Table 2.3: Representative microprobe analyses of biotite

Sample (EMMD)	008-1	153-13	153-13	182-94-5	182-94-5	182-249-6	001-14	008-15	055-15
Point	S5	S18	S19	S6	S10	S1	S3	S3	S2
Oxide (wt%)									
SiO ₂	40.29	25.29	36.00	35.10	36.67	36.64	37.79	38.01	36.80
TiO ₂	2.08	0.03	1.73	1.36	1.77	0.87	0.63	1.69	1.01
Al ₂ O ₃	13.32	22.66	16.94	15.87	17.24	14.17	14.25	15.46	14.28
FeO ¹	11.59	29.86	15.79	26.77	20.89	15.28	10.31	15.84	12.46
MnO	0.04	0.24	0.04	0.08	0.04	0.04	0.19	0.13	0.15
MgO	18.41	10.88	10.08	6.83	9.23	13.46	17.91	13.21	15.38
CaO	BD	0.05	0.03	0.04	BD	0.01	0.07	BD	0.03
Na ₂ O	0.05	0.12	0.10	0.06	0.07	0.09	0.26	0.05	0.28
K ₂ O	9.99	0.01	7.27	9.42	9.76	7.74	8.46	9.70	7.82
F	0.91	BD	1.34	0.49	0.98	3.03	4.02	0.95	3.65
Cl	0.51	0.13	0.13	2.08	0.17	0.97	0.02	0.52	0.08
Total	97.20	89.27	89.45	98.11	96.83	92.30	93.90	95.57	91.93

Cations on the basis of 24 total O

C-H ₂ O ²	3.55	3.57	3.08	3.03	3.42	2.07	1.99	3.37	2.04
O-F-Cl	0.50	0.03	0.59	0.68	0.45	1.49	1.70	0.52	1.55
T-Si	5.88	4.21	5.76	5.55	5.60	5.86	5.82	5.76	5.82
T-Al	2.12	3.79	2.24	2.45	2.40	2.14	2.18	2.24	2.18
T-Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sum T	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
M-Al	0.17	0.65	0.95	0.51	0.70	0.53	0.40	0.52	0.48
M-Ti	0.23	0.00	0.21	0.16	0.20	0.10	0.07	0.19	0.12
M-Fe ²⁺	1.41	4.15	2.11	3.54	2.67	2.04	1.33	2.01	1.65
M-Mn	0.01	0.03	0.01	0.01	0.01	0.00	0.02	0.02	0.02
M-Mg	4.00	2.70	2.40	1.61	2.10	3.21	4.11	2.98	3.62
Sum M	5.81	7.54	5.68	5.84	5.68	5.89	5.94	5.72	5.89
I-Ca	0.00	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00
I-Na	0.02	0.04	0.03	0.02	0.02	0.03	0.08	0.02	0.09
I-K	1.86	0.00	1.48	1.90	1.90	1.58	1.66	1.88	1.58
Sum I	1.87	0.05	1.52	1.93	1.92	1.61	1.75	1.89	1.67
A-F	0.42	0.00	0.68	0.25	0.47	1.53	1.96	0.45	1.83
A-Cl	0.13	0.04	0.03	0.56	0.04	0.26	0.00	0.13	0.02
A-OH	3.45	3.96	3.29	3.20	3.48	2.20	2.04	3.41	2.15
Sum A	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Fe/(Fe+Mg)	0.26	0.61	0.47	0.69	0.56	0.39	0.24	0.40	0.31

Endmembers (%)

Phlogopite	74	39	53	31	44	61	76	60	69
Annite	26	61	47	69	56	39	24	40	31

General formula: I₂ M₄ T₈ O₂₀ A₄¹All Fe reported as Fe²⁺²Calculated H₂O

EDS analysis shows trace amounts of barium-rich (>30 wt% Ba) silicate – possibly celsian ($\text{BaAl}_2\text{Si}_2\text{O}_8$) or cymrite ($\text{BaAl}_2\text{Si}_2(\text{O}, \text{OH})_8 \cdot \text{H}_2\text{O}$) – associated with Stage 2a K-feldspar. The same samples are devoid of barite. WDS analysis of apatite indicates that it is end-member fluorapatite with minor Ce (up to 0.87 wt%), La (up to 0.4 wt%), and Cl (up to 0.48 wt%). The apatite data are shown in Table 2.4.

Table 2.4: Microprobe analyses of apatite

Sample Point	EMMD022-319m						EMMD033-79.5m					
	S1 dark ¹	S1 light ¹	S2 dark	S2 light	S3 dark	S3 light	S2 dark	S2 light	S3 dark	S3 light		
CaO	55.96	54.97	56.32	54.22	56.04	54.72	56.36	55.62	55.20	56.57		
Na ₂ O	BD	0.14	BD	0.079	0.05	0.08	BD	0.11	0.07	BD		
MnO	0.04	0.013	0.04	0.03	0.04	0.05	0.04	0.04	0.04	0.03		
La ₂ O ₃	0.06	0.45	0.03	0.51	BD	BD	0.01	0.18	0.18	0.02		
Ce ₂ O ₃	0.01	0.73	0.04	0.76	0.02	0.87	0.01	0.40	0.29	0.03		
P ₂ O ₅	40.13	40.60	41.11	40.31	41.63	40.28	41.48	41.18	40.97	41.60		
Al ₂ O ₃	BD	BD	BD	0.00 ³	BD	BD	0.01	BD	0.01	BD		
Cl	0.03	0.12	0.01	0.12	0.04	0.08	0.38	0.48	0.49	0.38		
F ²	4.43	4.52	4.69	4.69	4.45	4.27	4.12	3.6	3.38	3.54		
Total	98.79	99.61	100.26	98.72	100.38	98.53	100.59	99.99	99.08	100.60		
Total+OH-F-Cl	100.67	101.54	102.23	100.72	102.26	100.3	102.41	101.62	100.61	102.17		

Cations on the basis of 25 O, OH, Cl, F											
Ca	9.86	9.63	9.74	9.57	9.67	9.69	9.74	9.72	9.73	9.80	
Na	0.00	0.05	0.00	0.03	0.02	0.03	0.00	0.04	0.02	0.00	
Mn	0.01	0.00	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.00	
La	0.00	0.03	0.00	0.03	0.00	0.00	0.00	0.01	0.01	0.00	
Ce	0.00	0.04	0.00	0.05	0.00	0.05	0.00	0.02	0.02	0.00	
P	5.59	5.62	5.62	5.62	5.67	5.63	5.66	5.69	5.71	5.69	
Al	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Cl	0.01	0.03	0.00	0.03	0.01	0.02	0.10	0.13	0.14	0.10	
F	2.30	2.34	2.39	2.44	2.26	2.23	2.10	1.86	1.76	1.81	
OH	-1.31	-1.37	-1.40	-1.47	-1.27	-1.25	-1.20	-0.99	-0.89	-0.91	
Total	16.46	16.37	16.37	16.30	16.36	16.41	16.40	16.48	16.49	16.50	

General formula: $(\text{Ca}, \text{Na}, \text{Mn}, \text{La}, \text{Ce Al})_{10}(\text{PO}_4)_6(\text{Cl}, \text{F}, \text{OH})_2$

¹light' and 'dark' indicate relative BSE brightness

²signal not manually adjusted for peak movement; see text for explanation

³measured value <0.01

Calculated in GabbroSoft (2011) spreadsheet

Stage 2b: Intermediate Na(-Ti)

Stage 2a disseminated to laminated magnetite alteration overprints Stage 1 albite (Fig. 2.11I–J). On the other hand, red albite (-hematite)-rutile veinlets and small (<1m) breccia pods cut across magnetite-biotite alteration (Fig. 2.11L). These veins are designated to be Stage 2b. Some of these veins were not completely filled, and have been subsequently infilled with Stage 3 fluorite and carbonate. Breccias filled in by

Stage 2b albite are characterised by albitised clasts; some clasts also contain extensive magnetite alteration. It is notable that the dominant Ti-bearing phases in this sodic stage are rutile and ilmenite, rather than titanite as in Stage 1.

Stage 2c: Early carbonate (-Mg-Fe) flooding and mineralisation

Following Stage 2b is a major phase of dolomitic-sideritic-calcite (-Mg-Fe; Table 2.5, Fig. 2.11D) $\pm$ magnetite (2.11N–Q) $\pm$ quartz $\pm$ pyrite (2.11N, P) $\pm$ chalcopyrite (2.11N) alteration. The Stage 2c assemblage comprises most of the carbonate veins in the deposit. Stage 2c minerals also make up massive, coarse-grained ($>250\ \mu\text{m}$), domains that overprint finer-grained magnetite (Fig. 2.11N). In some instances, it may not be possible to differentiate early (Stage 2a) and later (Stage 2c) magnetite-pyrite alteration. Stage 2c is, however, interpreted to be later than Stages 2a on the basis that: 1) Fe-Mg-rich carbonate always overprints or fills open spaces in Stage 2a K-feldspar (Fig. 2.11D) and quartz veins (Fig. 2.11P), 2) coarse ($>5\text{mm}$) magnetite and sulfide alteration appear to overprint finer-grained magnetite (Fig. 2.11P), and 3) carbonate overprints Stage 2a magnetite-apatite (Fig. 2.11J). Albite is never observed to cut carbonate, therefore Stage 2c is later than 2b. Additionally, Coleman (2015) found some examples of magnetite-calcite veinlets cutting across coarse-grained pyrite; these are probably of Stage 2c. It is not common, though; typically pyrite, chalcopyrite and carbonate overprint magnetite. For this reason, it is suggested that most magnetite formed in Stage 2a. Filling in of voids in Stage 2a and 2b veins by Stage 2c suggests that the latter formed relatively soon after Stage 2a; this in contrast to Stage 3 minerals, which usually (but not always) occupy new veins. For the reason, the stages between Stage 1 and Stage 3 are grouped into Stage 2.

Stage 2c veins may contain Fe-Mg-carbonate (Fig. 2.11D), magnetite, pyrite, and chalcopyrite. The chalcopyrite appears to be texturally associated with magnetite and pyrite at hand specimen scale (e.g. Fig 2.11N), but in thin section it overprints these minerals (Fig. 2.11V). For this reason, it is likely that most of the chalcopyrite is later than Stage 2c. Stage 2c carbonate veins are often recognizable by the distinct yellow-brown weathering coloration of the carbonate due to the Fe in them. Smaller veins ($100\ \mu\text{m}$ – $1\ \text{cm}$) are typically parallel to laminations. Magnetite alteration halos may form around the smaller veins ($<1\ \text{cm}$; Fig. 2.11O).

Stage 3: Main Cu-Au mineralisation

The last phase of the hydrothermal event, Stage 3, produced most of the Cu-Au mineralisation. The Stage 3 assemblage is dominated by carbonate (calcite (-Fe-Mn) to siderite to ankerite(-Mn); Table 2.5, Fig 2.11S, AA–AB; Fig. 2.12B)-barite (Fig. 2.11R, T–U, X, AF)-fluorite (Fig. 2.11R, U, X–Z, AF)-chalcopyrite (Fig. 2.11R–AI)-pyrite (Fig. 2.11AE). Stage 3 veins are common, but are relatively less abundant than Stage 2c veins. Some Stage 3 veins also contain chlorite (Fig. 2.11W, Z), and most rocks are variably altered by Stage 3 chlorite and sericite. Indeed, most mafic minerals (biotite, amphibole) are at least partly chlorite-altered. Monazite (Fig. 2.11AK) and bastnäsite (Fig. 2.11AH) occur in minor amount in some Stage 3 veins. The other U-REE phases seen in EDS (Figs. 2.11AI–AJ) are only constrained as post-Stage 2a. EDS analysis by Williams et al. (2015) indicates that Au at the E1 Group is hosted in both electrum and Bi-sulfosalts. However, these phases were not seen in this study; despite analysis of dozens of samples on the EDS, visible Au was not encountered. Copper and gold are strongly correlated ($r = 0.74$; not shown), which suggests that most gold may be incorporated into the chalcopyrite, either as micro-inclusions or as substitutions. Minor sphalerite is present at E1 South, and is associated with Stage 3 fluorite veins. Like the arsenopyrite in Stage 2a, the Stage 3 sphalerite is probably localized at E1 South by the reducing carbonaceous metasiltstone.

Table 2.5: Representative microprobe analyses of carbonate

Sample (EMMD)	052_6		153_14			055_11		153_13		075_205	075_227	153_7
Point	S1	S2	S2	S4	S5	S1	S2	S13	S15	S1	S3	S7
FeO ¹	0.90	1.04	21.60	18.65	21.10	50.57	1.25	12.25	1.09	12.14	10.27	46.10
MnO	2.19	1.15	1.56	1.77	3.00	9.81	0.12	0.97	0.85	7.23	0.78	15.27
MgO	0.30	0.59	6.70	8.50	5.23	0.08	0.08	13.36	0.45	9.26	14.67	0.24
CaO	55.22	54.18	25.63	26.23	25.91	1.75	55.41	27.54	55.82	25.93	27.02	1.53
Total	58.60	56.95	55.48	55.15	55.23	62.21	56.86	54.12	58.22	54.56	52.74	63.14
Fe ²⁺	0.01	0.02	0.30	0.26	0.29	0.70	0.02	0.17	0.02	0.17	0.14	0.64
Mn	0.03	0.02	0.02	0.03	0.04	0.14	0.00	0.01	0.01	0.10	0.01	0.22
Mg	0.01	0.02	0.17	0.21	0.13	0.00	0.00	0.33	0.01	0.23	0.36	0.01
Ca	0.99	0.97	0.46	0.47	0.46	0.03	0.99	0.49	1.00	0.46	0.48	0.03
Total	1.04	1.01	0.95	0.96	0.93	0.88	1.01	1.01	1.03	0.96	1.00	0.89
Ca/(Ca+Mg+Fe+Mn)	95.11	95.53	48.32	48.57	49.80	3.57	97.91	48.78	96.29	48.02	48.20	3.07
Fe/(Ca+Mg+Fe+Mn)	1.20	1.43	31.80	26.95	31.65	80.41	1.73	16.94	1.47	17.55	14.29	72.08
Mn/(Ca+Mg+Fe+Mn)	2.98	1.60	2.32	2.59	4.56	15.79	0.17	1.36	1.16	10.58	1.10	24.18
Mg/(Ca+Mg+Fe+Mn)	0.71	1.44	17.56	21.89	13.99	0.23	0.19	32.92	1.09	23.85	36.41	0.68

General formula: (Ca, Fe, Mn, Mg) CO₃¹All Fe reported as Fe²⁺

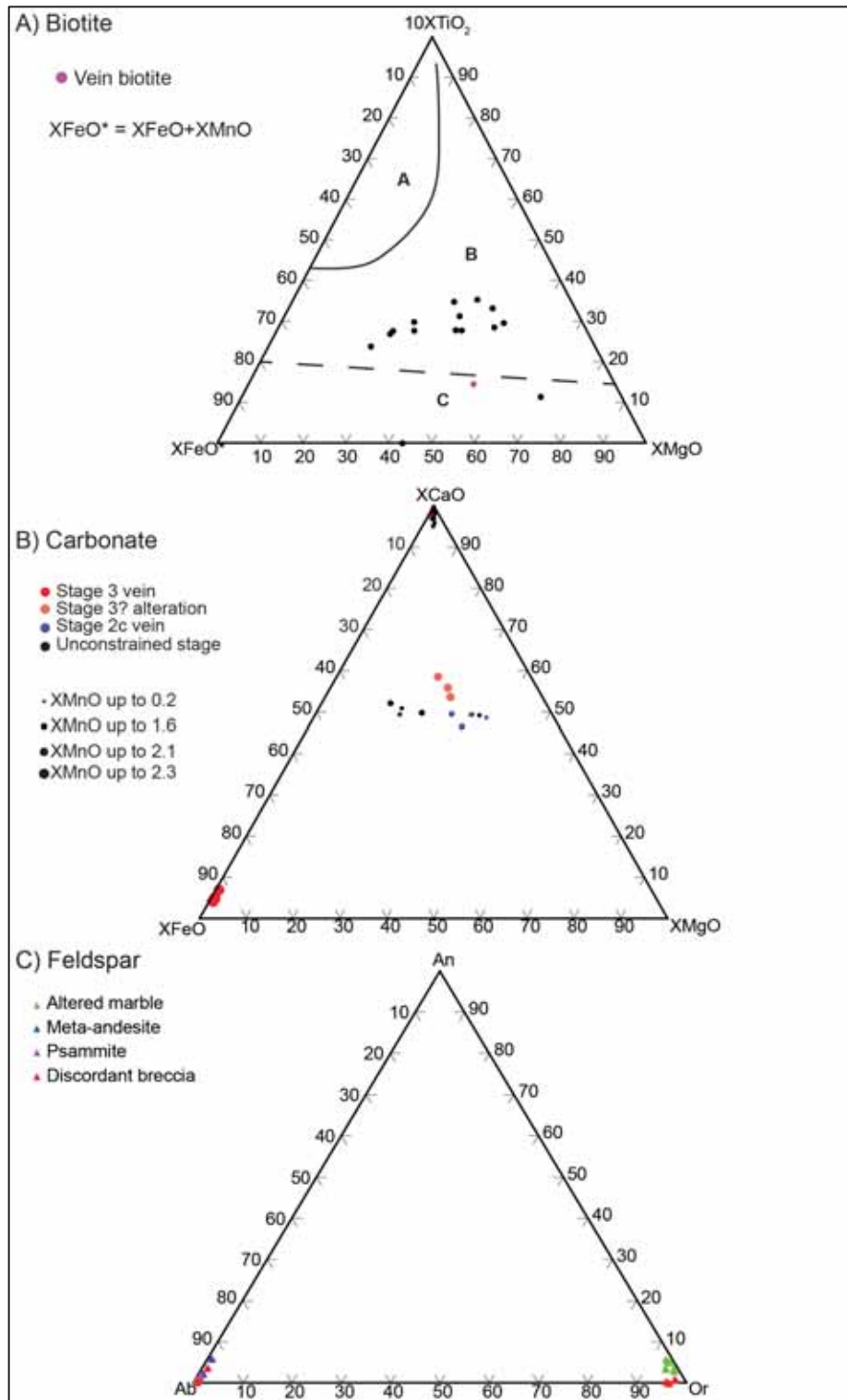


Figure 2.12: A) Ternary plot of E1 Group biotite WDS analyses, based on Nachit et al (2005). Domain A is magmatic biotite. Domain B is neoformed or hydrothermally-requillibrated biotite. Domain C is purely new hydrothermal biotite. B) Ternary plot of carbonate WDS analyses, coloured by constrained paragenetic Stage. C) Ternary plot of feldspar WDS analyses.

Stage 3 can typically be distinguished from Stage 2c by the elevated manganese content of some Stage 3 vein carbonate (Fig. 2.12B), which typically imparts a pink hue (weathering to black pyrolusite) to the mineral, and is distinct from the yellow-brown carbonate of Stage 2c. In one sample, EMMD055-155.35m, MLA mapping (Fig. 2.9B) revealed a barite veinlet cutting across chalcopyrite. In other instances, the two minerals appear to be cogenetic (Figs. 2.11T–U). It is possible that chalcopyrite in that sample is related to Stage 2c, or that there may be an additional late barite stage. However, such a stage appears to be relatively minor. Furthermore, most chalcopyrite-bearing veins cut across Stage 2c ankeritic-dolomitic carbonate (Fig. 2.11AD–AE). Some Stage 3 fluorite replaces biotite (Fig. 2.11AC), possibly because it is generally F-rich. Fluorite is also rarely observed as late infill in Stage 3 carbonate veins, suggesting multiple sub-stages of fluorite input during this stage. Stage 3 also introduced minor epidote veins and replacement at E1 East, but they only occur in altered metadolerite. Minor barren calcite veins cut across Stage 3 assemblages, and are considered the last substage of the system. These late calcite veins may be of similar timing to the late, barren, barite veinlets.

Geochronology

Sampling

A sample from DDH EMMD033 at 79.5m contains hydrothermal monazite appropriate for *in-situ* dating. The sample was collected from a zone of abundant magnetite-apatite alteration southwest of the E1 North orebody (location in Fig. 2.4; alteration in Fig. 2.19). Samples within the orebody also contain monazite associated with chalcopyrite, but crystals in these samples were either too small ($< 40 \mu\text{m}$), or contain sulfide inclusions. The sample is composed of an assemblage of coarse, euhedral magnetite intergrown with apatite and minor quartz (Fig. 2.11AK), which is overprinted by an assemblage of pyrite, chalcopyrite, carbonate, chlorite and monazite. The protolith is obscured by these hydrothermal assemblages, but is adjacent to less altered, sheared, massive to amygdaloidal metavolcanic rocks. Apatite crystals in this sample are up to 1 cm in length (e.g. Fig. 2.7E), though crystals up to 3 cm are present in other drill holes. The boundary of the apatite-magnetite-rich domain is gradational and the magnetite-apatite assemblage is interpreted to be mostly replacement rather than infill. Monazite is present in carbonate $\pm$ chalcopyrite veins and also as veinlets and disseminations overprinting apatite (Fig. 2.11AK). Bastnäsite is also hosted within some carbonate

veins in this sample. The magnetite and apatite together are part of paragenetic Stage 2a, and the carbonate, monazite, chalcopyrite and bastnäsité are part of Stage 3 (Fig. 2.10, 2.11AK). Backscatter electron (BSE) imaging revealed that most monazite crystals are homogenous, though some contain uranium- and thorium-bearing minerals as detected by EDS; these inclusions could be huttonite or uraninite, and were excluded from analysis. Monazite grain size varies from 40–100 μm . The monazites are characterised by low Th and U concentrations, as indicated by their count rates; such low counts are typical for hydrothermal monazite (e.g. Davis et al., 1994; Davidson et al., 2007). The monazites do not contain significant amounts of ^{204}Pb .

Results

Thirty-four monazite crystals were analysed and half were discarded due to interference from sub-surface inclusions of sulfides, U-silicates, U-oxides and Th-silicates; the inclusions were visible as distinct U or Th spikes in the ICP-MS signal count. The U-Pb concordia plot of the remaining 17 spots is shown in Figure 2.13A. Of these 17 spots, four were highly discordant (Fig. 2.13A) and were therefore removed. Another three points yielded anomalously young (1350–1250 Ma) ages, and were excluded from the U-Pb concordia plot in Figure 2.13B, which shows the remaining 10 points. The significance of the younger ages is discussed later. The upper intercept age of the monazite is 1433 ± 28 Ma (MSWD = 0.87, probability of fit (PF) = 0.54; Fig. 2.13B). The 10 concordant spot analyses have a weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1456 ± 44 Ma (MSWD = 0.90, PF = 0.53; Fig. 2.13C).

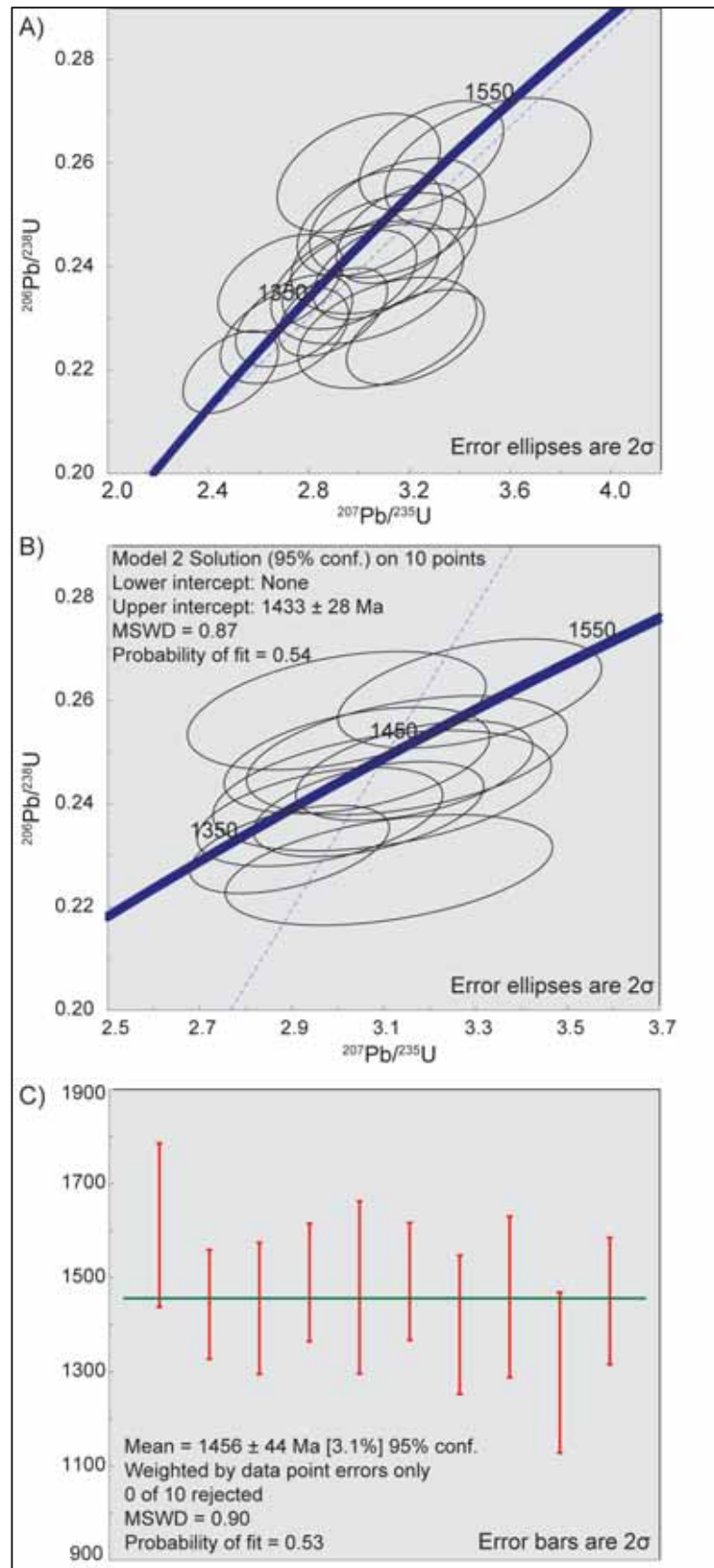


Figure 2.13: A) U-Pb Concordia of all 17 monazite analyses. B) U-Pb Concordia of the 10 best monazite analyses, with discordant or anomalously-young ages removed. C) Weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age of the points in (B). Concordia generated in Isoplot for Excel.

Ore Chemistry

The whole-rock geochemical data for all samples are presented in Appendix B. To conduct statistical analyses, geochemical values below the detection limit (DL) were assigned to be $0.5 \times \text{DL}$. The average LOI of the whole-rock samples is 6.1 wt%, suggesting significant alteration even in metavolcanic rocks that contain few veins. Thus, meaningful comparisons between unaltered and altered host rocks are not possible. Instead, comparisons are made based on differences between economic and sub-economic samples. The cut-off ore grade at the E1 Group is 0.27 wt% Cu. It is relatively low because it is only 8 km away from an existing concentrator of the same company. Out of 111 whole-rock samples collected, 24 are of ore grade.

Most unmineralised metavolcanic rock samples show significant enrichment (10x or 100x), relative to primitive mantle, in all elements except for Sr and Tl (Fig. 2.15A). The ore-grade samples, mainly volcanic breccias and metatuffs, are characterised by strong (100x to 1000x) enrichment in Pb, Ba, U and La, and are not depleted in Sr. The metavolcanic and metasedimentary rocks show similar trends compared to average crust (Fig. 2.15B–C), but the former are relatively more depleted in Sr and Sm (Fig. 2.15B–C). The unmineralised carbonaceous schists are less enriched in Ba, U, La, Ce, Nd and P compared to mineralised metasedimentary rocks, but are higher in Th, K, Hf, Zr and Tl (Fig. 2.15B).

The ore-grade E1 Group samples have high concentrations of Fe (mean 43 wt%), Ba (up to 22 wt%), F (up to 15 wt%), and are also locally enriched in U (up to 450 ppm), REE (up to ~1500 ppm total), P (up to 7500 ppm P_2O_5), Mn (locally over 2100 ppm; Fig. 2.20), As (locally up to 520 ppm), Co (up to ~500 ppm), Mo (400 ppm), and Sn (150 ppm), but are depleted in Si, Na, K, Mn (locally; Fig. 2.14) and Zr (Fig. 2.14). Silver concentrations in ore-grade samples ($n = 24$) average 6ppm, while sub-grade samples ($n = 87$) average 0.27 ppm; both are orders of magnitude higher than mean crustal concentrations (0.055 ppm; Wedepohl, 1995).

Lead and zinc levels are generally very low in the E1 Group. Lead concentrations average 6 ppm and 49 ppm in sub-economic and ore-grade samples, respectively. Zinc abundance in Cu-ores, at 50 ppm, is only 8 ppm higher than in sub-grade samples, except in the carbonaceous lithologies in E1 South where Zn concentrations are locally >300 ppm. The overall low concentrations of Pb and Zn are consistent with the presence

of minor to trace amounts of galena and sphalerite. Arsenic is also more enriched in these protoliths, with As concentrations up to 500 ppm, consistent with the occurrence of arsenopyrite in these host rocks in E1 South; it is 50–150 ppm in other areas of the E1 Group of deposits. Compared with the average crust, Ba, U, La, Ce, Nd, and P in E1 Group ores are 10 to 100 more concentrated (Fig. 2.15B–C). In contrast, Rb, Sr, Th, K, Hf, Zr, and Tl are nearly 100 times more depleted in the ores (Fig. 2.15B–C). The E1 Group ores contain 500–2000 ppm total REE (Fig. 2.14). The ores are enriched in LREE relative to sub-grade samples, whereas the HREE contents are similar (Fig. 2.15D–E). The ores in all rock types have a positive Eu anomaly whereas the sub-grade samples do not (Fig. 2.15D–E). The most abundant elements among the REEs are La and Ce.

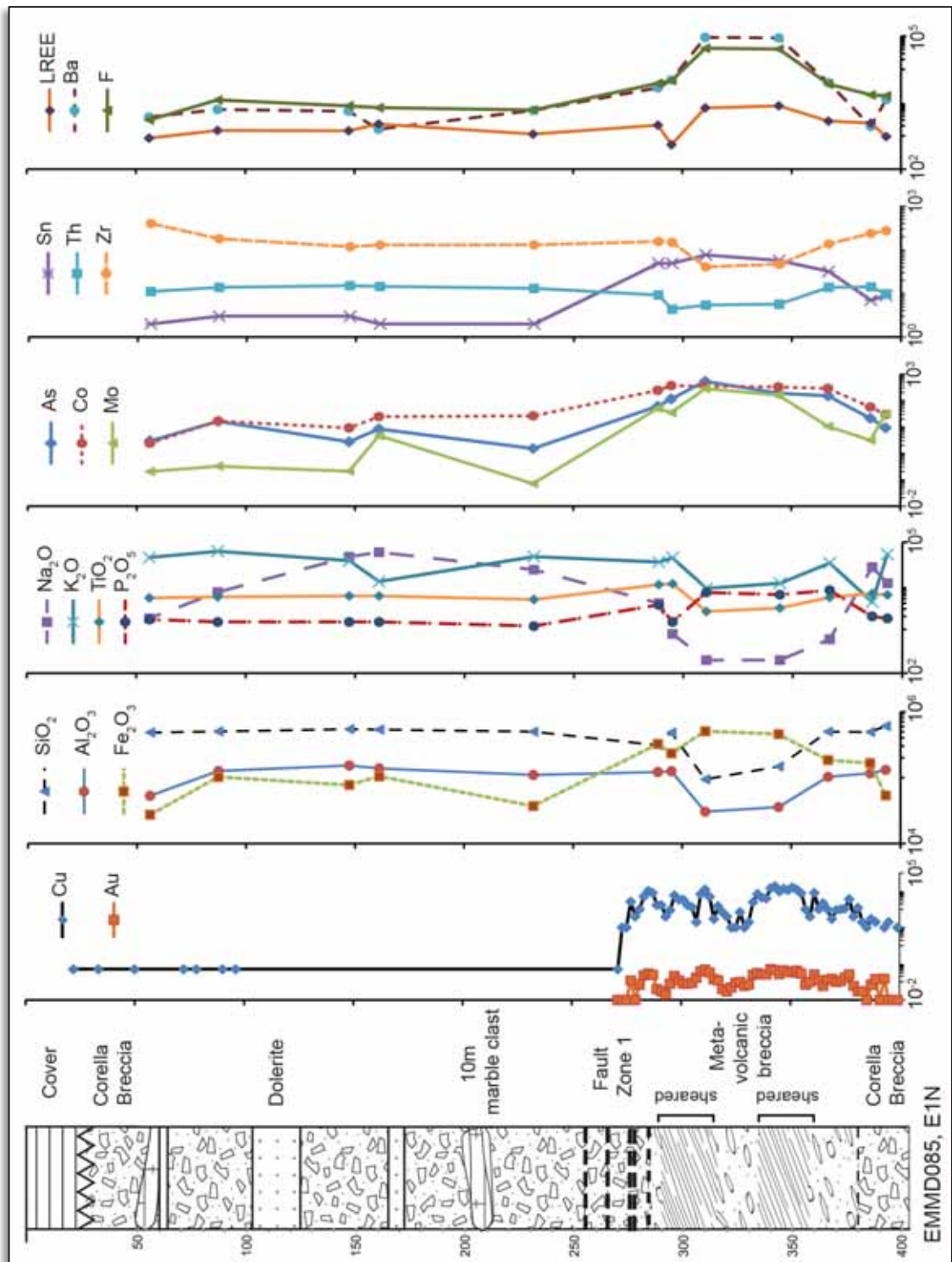


Figure 2.14: Downhole rock type log and whole-rock geochemistry of EMMD085 (trace shown in Fig. 2.4B). Depth in meters. Cu-Au values from mine assay. All values in ppm. Note the abrupt increase in Cu-Au grade in the sheared/layered intervals from 290–315 m and from 335–355 m.

Microprobe analysis of fluorapatite (Table 2.4) from outside of the Cu-Au orebody indicates that it can carry at least up to 0.9 wt% Ce and 0.5 wt% La, and is the main host of these elements.

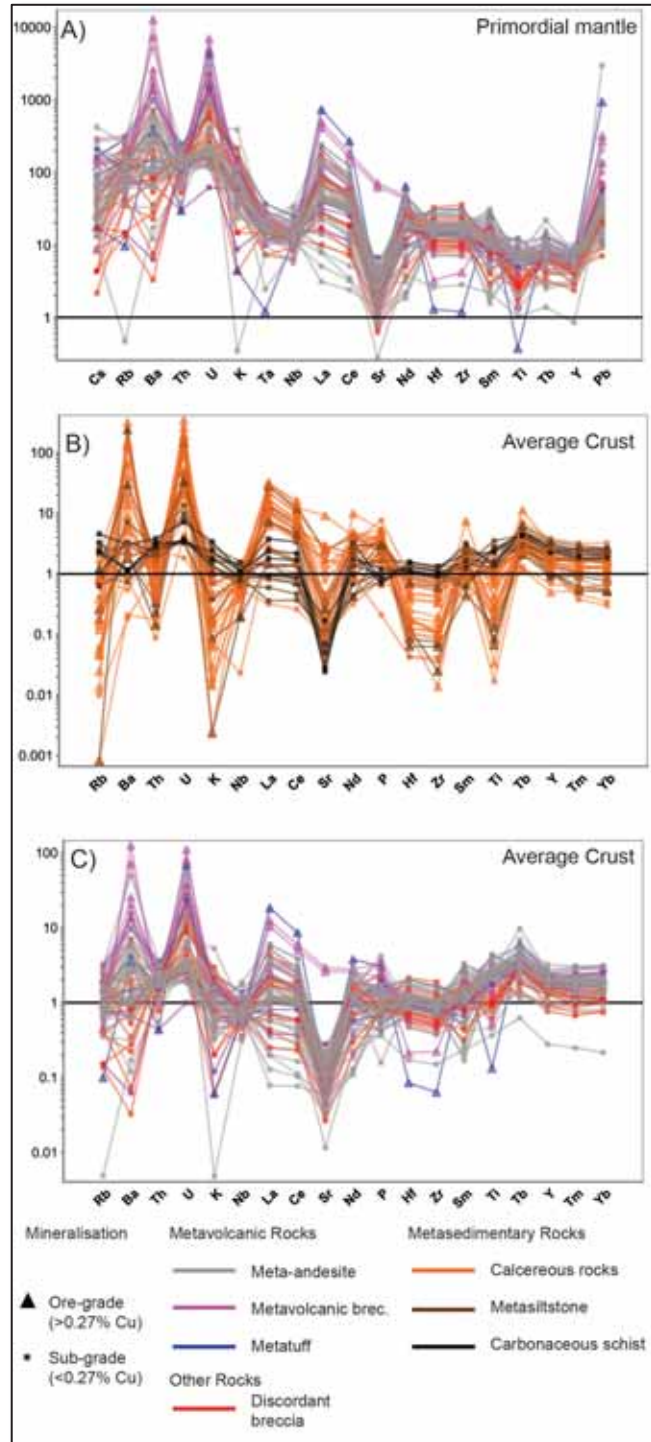


Figure 2.15: Ore (>0.27 wt% Cu) and sub-grade (<0.27 wt% Cu) whole-rock chemistry. A) Primordial mantle-normalized plots for metaigneous rocks (after McDonough et al., 1992). B) Average crust-normalized plots for metasedimentary rocks after Weaver and Tarney (1984). C) Average crust-normalized plots for metaigneous rocks and discordant breccia. Continued on the next page.

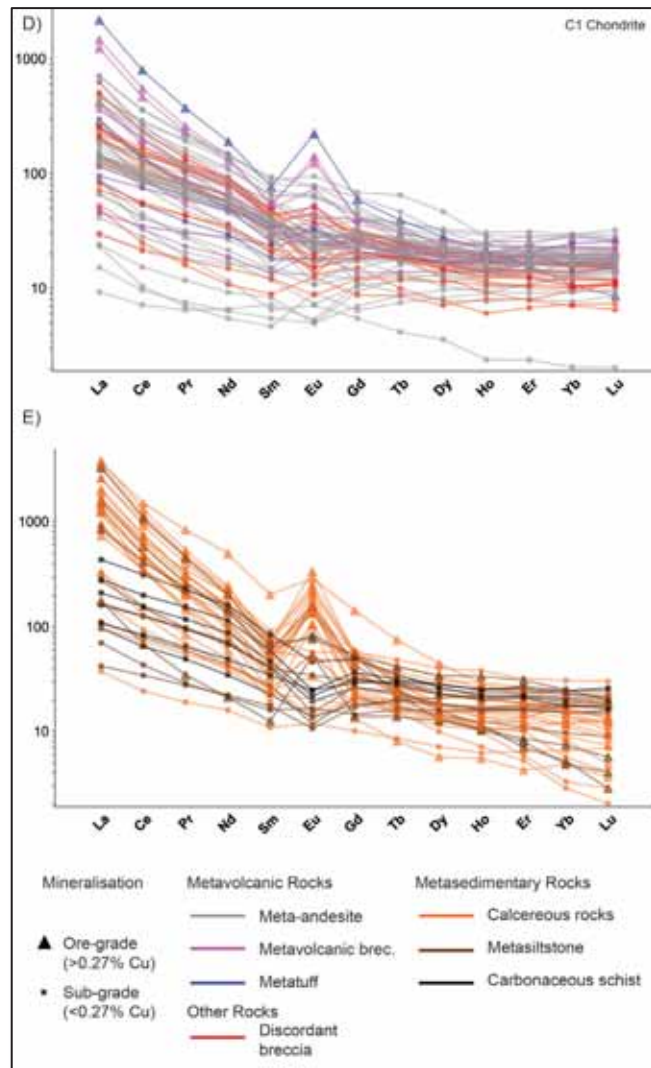


Figure 2.15 (cont.): C1 Chondrite-normalized REE plot) for (D) metaigneous rocks and discordant breccia and (E) metasedimentary rocks (after McDonough and Sun, 1995).

Barium and fluorine levels at the E1 Group reach up to 22 wt% Ba and 8 wt% F in the orebody (App. B). Barium is hosted mostly in barite. As previously described, however, EDS analysis reveals that some Stage 3 K-feldspar can contain a few wt% Ba. Energy-dispersive spectroscopic analysis indicates that some K-Al-silicates or hydroxyl silicates replacing K-feldspar, possibly celsian or cymrite, also contain up to ~10 wt% Ba.

However, the Ba-rich silicates are rare and do not constitute a significant source of Ba in ores. Fluorine in the orebody is contained mainly in fluorite, but most hydrothermal biotite and apatite in the system is also F-rich (Tables 2.3–2.4). As previously mentioned, it should be noted that the fluorine content of fluorapatite compositions shown in Table 2.4 are probably up to 0.5 wt% higher than reality. Regardless, the apatite is near-endmember fluorapatite. The high Fe associated with ores occurs mainly in magnetite (Fig. 2.9). Samples with >1 wt% Ba and F also typically contain ore-grade

Cu, but some Cu-ores are not Ba-F-rich. All Cu-rich samples contain high Fe, but not all Fe-rich samples are ore-grade, with some of the most intensely magnetite-altered rocks containing sub-grade mineralisation. Uranium levels in ores range from 50–250 ppm. Uranium is hosted in U-silicate (coffinite?) and U-oxide (uraninite?), as revealed by EDS analyses.

Correlations

Correlations between Fe_2O_3 and other major oxides are shown in Figure 2.16, and correlations between Cu and Ba, F, U, La, Pb, and Zn are displayed in Figure 2.17. In order to prevent potential spurious correlations, particularly between major oxides, the data shown here were transformed in ioGAS® software using the centered log-ratio (CLR) method described in Aitchison (1986). For transformation, values below detection limits were replaced with half the detection limit. The axes of the transformed correlation plots in Figures 2.16 and 2.17 are unit-less; higher CLR values correspond to higher concentrations.

Relatively high ferric oxide abundances ($> \sim 30\%$ Fe_2O_3) can be visually linked to samples with high magnetite alteration. Biotite alteration generally contributes less than $\sim 5\%$ Fe to total Fe_2O_3 content. Therefore, Fe_2O_3 can serve as a reasonable indicator for Stage 2 magnetite alteration. Although untransformed Fe_2O_3 and SiO_2 are strongly negatively correlated ($r = -0.85$), the transformed data in Fig 2.16A indicate that this is a spurious correlation, and that iron and silicon are in fact only weakly correlated ($r = -0.38$). Iron is only weakly positively correlated with phosphorus ($r = 0.32$; Fig. 2.16E). It is weakly negatively correlated with Na ($r = -0.37$; Fig. 2.16B) and Ti ($r = -0.35$; Fig. 2.16F). Potassium and iron have a slightly higher negative correlation ($r = -0.51$; Fig. 2.16C).

Copper is strongly positively correlated ($r = 0.74$) with Au. Both elements are strongly correlated with Ag ($r = 0.78$ and 0.79 , respectively). Copper is weakly positively correlated with Ba ($r = 0.43$; Fig. 2.17A), and slightly more correlated with F ($r = 0.54$; Fig. 2.17B), La ($r = 0.58$; Fig. 2.17D), As ($r = 0.60$), Co ($r = 0.61$), Mo ($r = 0.65$), and S ($r = 0.62$; not shown); it is more strongly correlated with U ($r = 0.69$; Fig. 2.16C), Pb ($r = 0.65$; Fig. 2.17E), Bi ($r = 0.71$), and Ag ($r = 0.78$; not shown). Gold r values for most elements are comparable (± 0.1) to those for Cu, but Au has a stronger correlation with As ($r = 0.72$) and Co ($r = 0.79$). Copper and Zn are not correlated ($r = -0.11$; Fig.

2.17F). Barium and fluorine are correlated with U ($r = 0.52$ and 0.61 , respectively), while fluorine is only weakly correlated with La ($r = 0.4$; not shown). Calcium and carbon are negatively correlated with iron, barium, fluorine and copper in marble and metasilstone samples (Fig. 2.18).

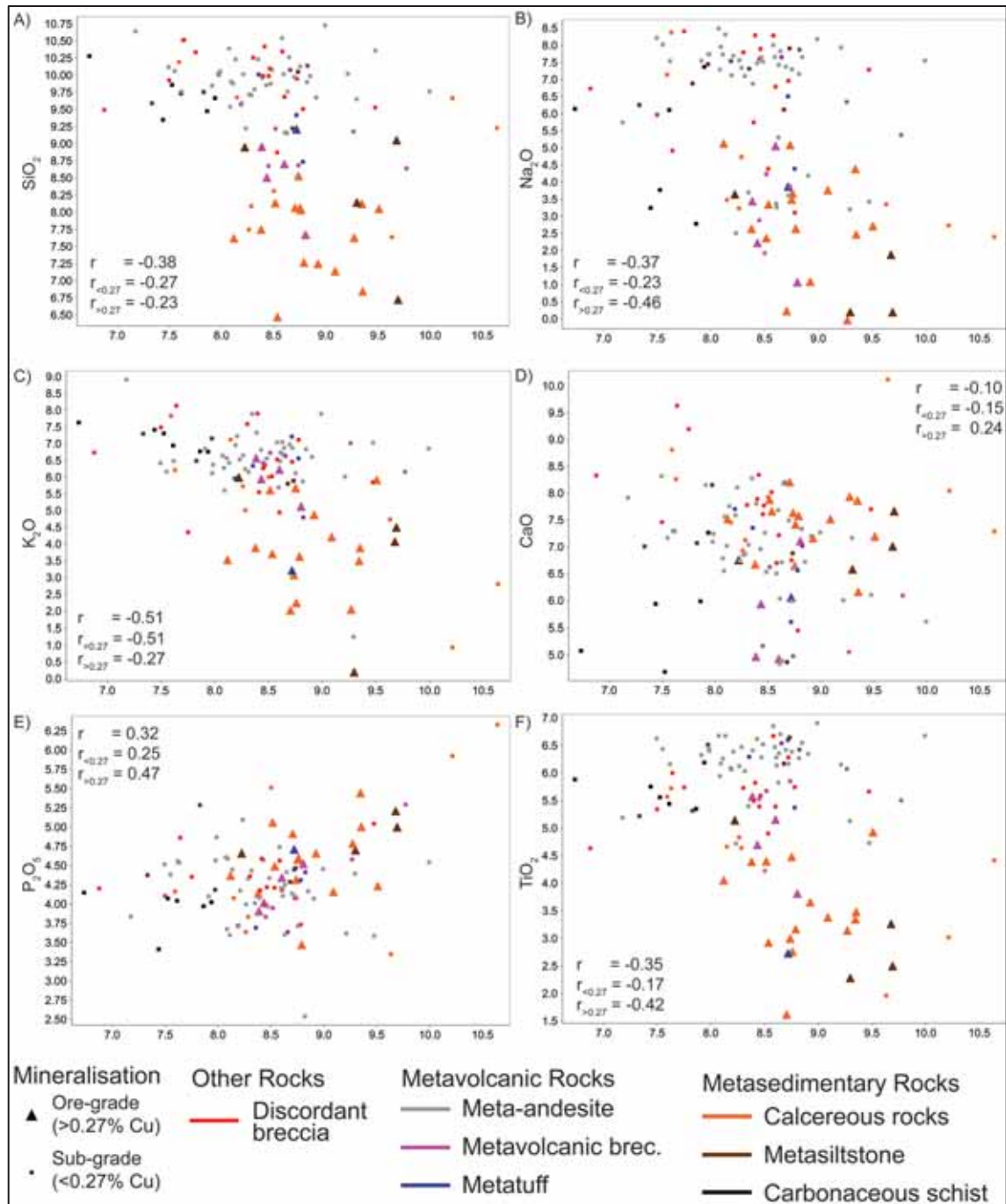


Figure 2.16: Correlations of Fe_2O_3 with other major oxides. All data were CLR-transformed in ioGAS®. The axes are unitless.

Summary and Interpretations

E1 Group Cu-Au ores are highly enriched in Fe, Ba, F, and less enriched in P, Ag, U, REE, As, Co, Mo, and Sn; Mn is locally enriched. This wide range of elements is suggestive of a complex hydrothermal system with multiple fluid and/or metal and halogen sources. The ores are depleted in the rock-forming elements Si, Na and K. Compared to average crustal values, Rb, Sr, Th, K, Hf, Zr, and Tl are highly (100x) depleted in the orebody. Such depleted concentrations may be the result of the marble protolith, which probably has lower concentrations of these elements than average crust. Iron, barium and fluorine are hosted mostly in magnetite, barite and fluorite, respectively.

The positive Fe-P correlation is consistent with Fe and P input during Stage 2a magnetite-apatite alteration. Correlations between Fe and K – the other major input in Stage 2a – are probably weak because although Stage 2a biotite and magnetite are typically both abundant in the same samples, Stage 2a K-feldspar and magnetite are not. Furthermore, magnetite and apatite are only both abundant in the magnetite-apatite zone southwest of the orebody. The positive correlation between Au and As suggests that some of the Au may be hosted in As-bearing pyrite (arsenopyrite is rare at E1 North). The weak correlations between Cu-Au and Ba and F are probably because zones of enriched barite and fluorite are restricted to the cores of the E1 Group orebodies, and do not extend spatially as far as Cu and Au. Such restriction may be the result of the comparatively poor solubility of these minerals with respect to Cu-sulfides and uraninite. Lanthanum is weakly correlated because it is enriched in the orebody as well as in the Cu-Au-barren magnetite-apatite zone. MLA mapping indicates that barite, fluorite, monazite and bastnäsite occur together in the orebody; the weak correlations between Ba, F, U and La, however, are probably the result of elevated REE in the apatite-rich zone beyond the orebody, where Ba and F are much less abundant. The negative correlations between C, CaO and Ba, F, and Fe₂O₃ in metasedimentary rocks suggests that much of the magnetite-sulfide-barite-fluorite alteration is replacing primary carbonate (Fig. 2.18A). This is also apparent in thin section, where magnetite is shown to replace calcite (Fig. 2.18B).

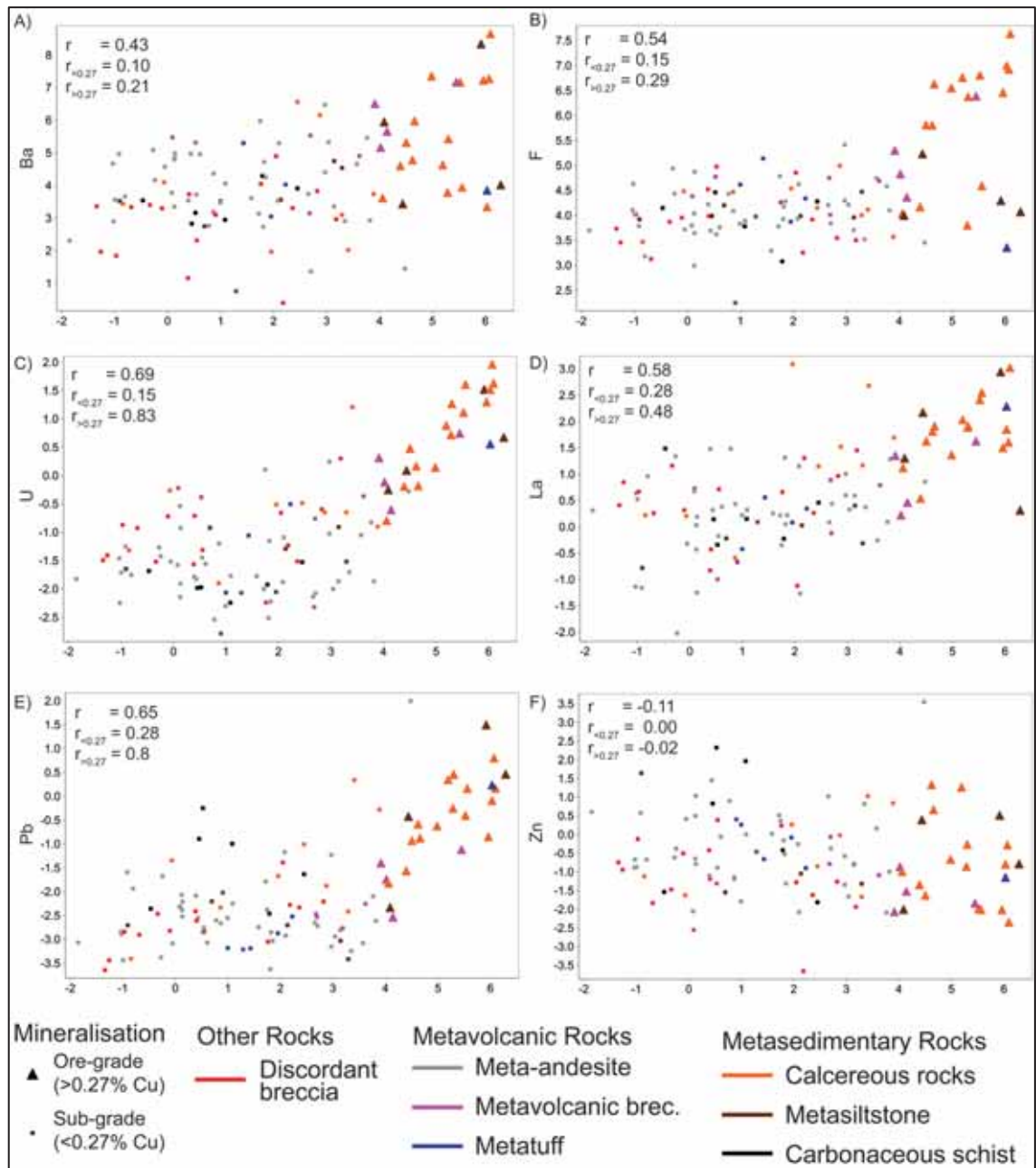


Figure 2.17: Correlations of Cu with selected elements. All data were CLR-transformed in ioGAS®. The axes are unitless.

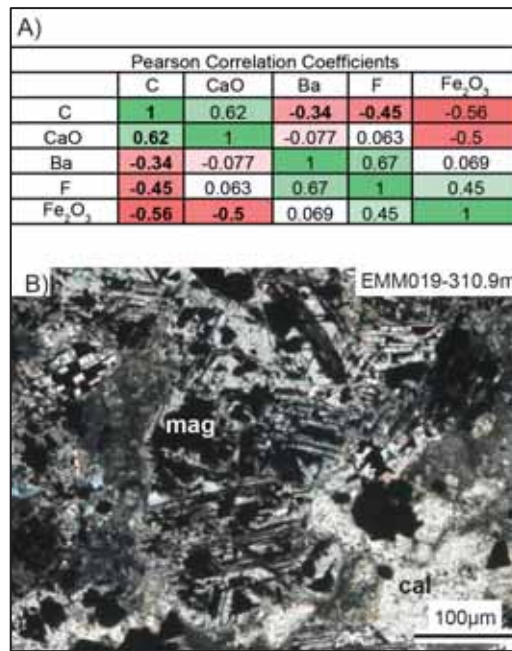


Figure 2.18: Alteration in calcareous protoliths. A) Pearson Correlation Coefficients of carbonate rock type-indicators (Ca, CaO) and alteration indicators (Ba, F, Fe₂O₃). All data CLR-transformed prior to correlation as described in the text. Note that the alteration indicators are negatively correlated with the carbonate indicators. B) Cross-Nicols photomicrograph of magnetite replacing primary calcite along cleavage and twin planes.

Zonation Patterns

The construction of the zonation map and cross sections (Figs. 2.19–2.20)

The distribution of various types of alterations in E1 North is shown in a plan map at 75m below the surface in Figure 2.19 and along cross section A–A' (Fig. 2.20; position of A–A' shown in Fig. 2.19), based on drillcore logging, petrography and MLA analysis. Also shown is the 0.27% Cu orebody contour, based on exploration drill hole ($n = 678$) and blast hole assays ($n = 2300$). The Ba, F and Mn element contours presented in Figures 2.19 and 2.20 are based only on the whole-rock data ($n = 111$), as these elements were not assayed previously. The lateral extent of magnetite ± biotite, apatite, and pyrite in Figure 2.19 are based on a combination of mine Fe-P-S assays, and open pit and drill core observations. There are insufficient core log and geochemical data to project the K-feldspar-biotite and Mn-rich zones shown in the Figure 2.20 cross sections onto the plan map.

The lack of outcrop in the study area has prohibited detailed regional geochemical surveys, and consequently there are insufficient data to determine regionally significant geochemical anomaly thresholds for the Ba-F-Mn contours (Figs. 2.19–2.20). However, Ba, F, and Mn data approximate a log-normal distribution (Fig. 2.21), statistically

enabling the use of the median + 2MAD (median absolute deviation) method (Riemann et al., 2005) for determining anomalous cutoffs (F: 1804 ppm; Ba: 1746 ppm; Mn: 950 ppm). Therefore, these anomalous thresholds are only valid in the vicinity of the E1 Group deposit. Regardless, some insight may be gained by observing the contours of the thresholds.

Zones of high Fe (> ~20% Fe) correspond to strong magnetite alteration zones in the open pit. Most of the magnetite is related to Stage 2a, and less is from Stage 2c. Apatite is the only P-rich mineral in significant quantities, and thus P abundance is an indicator of the apatite alteration zones shown in Figure 2.19. Southwest of the E1 North orebody, pyrite is the only sulfur-bearing mineral observed in major amounts; the pyrite zone in Figure 2.19 is defined by approximately >4% sulfur, which includes pyrite from multiple stages.

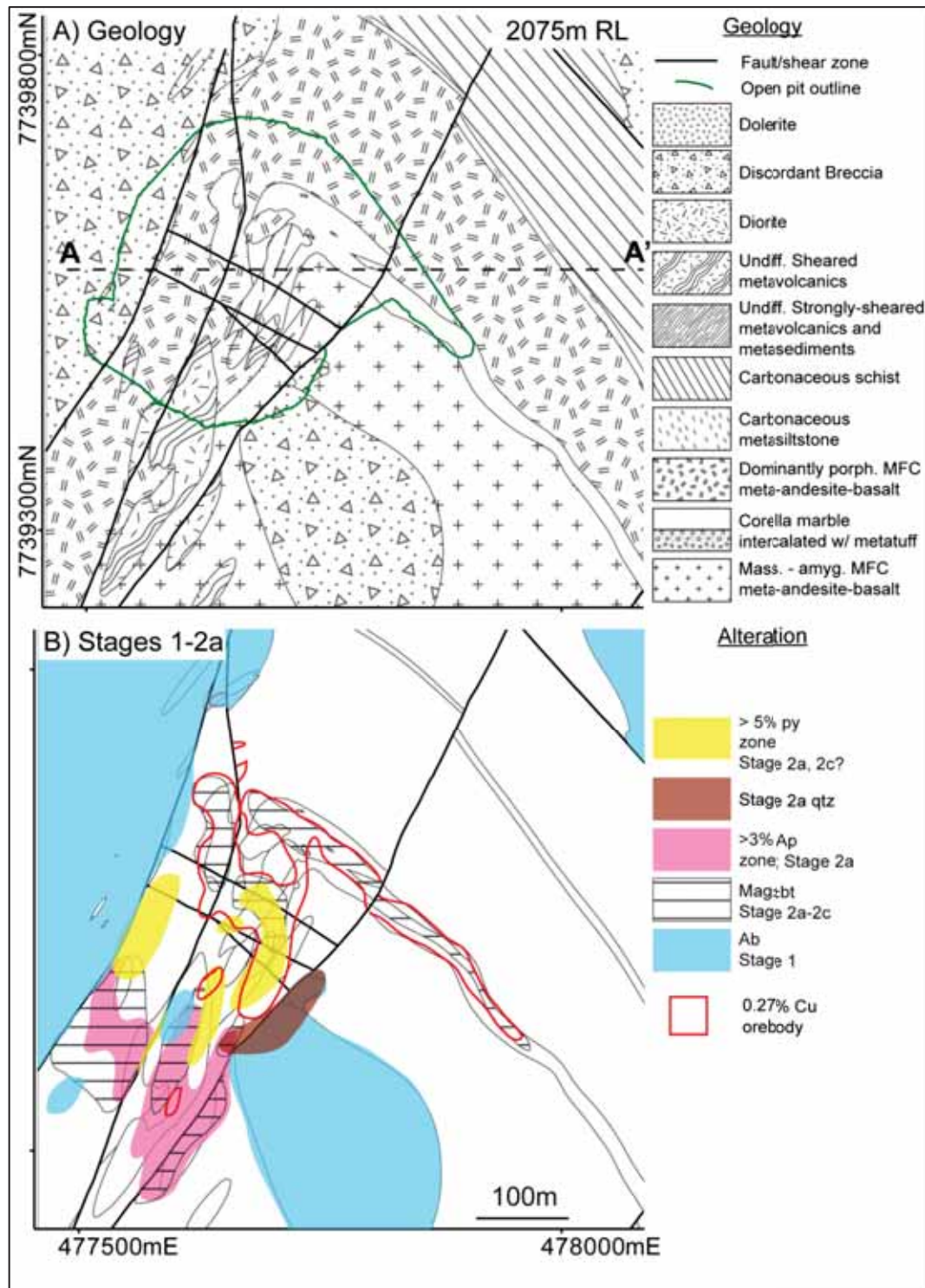


Figure 2.19: E1 North zonations interpreted at 2075m RL / 75m ASL. A) Stages 1–2c alteration. Strong Stage 1 alteration is mainly only preserved in the discordant Breccias. In other lithologies it is obliterated by later stages. B) Stages 2c alteration. Continued on the next page. GDA 94 projection. RL, relative level mine datum; ASL, above sea level.

Variation within the orebody

Barite and fluorite alteration are most abundant in the lower portion of the E1 North orebody, on the west limb of the E1 North Antiform, where their abundances exceed 5

wt%. The barite-fluorite alteration is broadly coincident with the major northeast-southwest trending shears and associated faults (Faults 2 and 3). At E1 South, Ba concentrations above 4 wt% are focused near the hinge of the E1 South synform. Outside of the orebody, anomalous levels of barium are present at least 150 m from the E1 North orebody (see next section). Barium concentrations reach up to 7 wt% in the E1 South lower metatuff lens, but are only up to 0.08 wt% in the upper carbonaceous metasiltstone and metashale lens of the E1 South orebody (Fig. 2.20C) and portions of the E1 East orebody. Fluorine follows a similar enrichment distribution, but is mainly restricted to the west limb of the synform. Whole-rock geochemistry demonstrates a zone of Mn-enrichment (over 2100 ppm) at the hinge of the E1 North Antiform and continuing into its east limb. This zone of enrichment overlaps somewhat with, but is distinct from, the zone of Ba-F enrichment (Fig. 2.20). The manganese is hosted mainly in calcite, and may reflect the distribution of calcareous rocks.

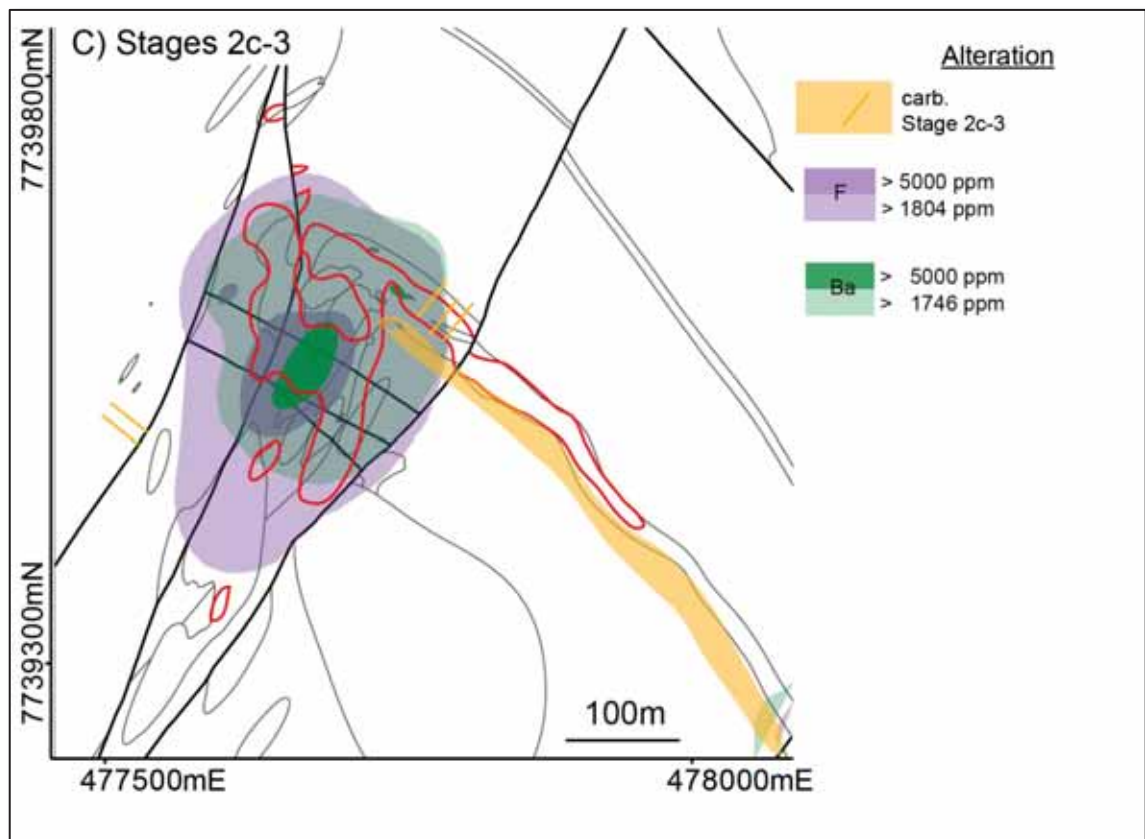


Figure 2.19 (cont.): Stage 3 alteration. See part A–B for legend.

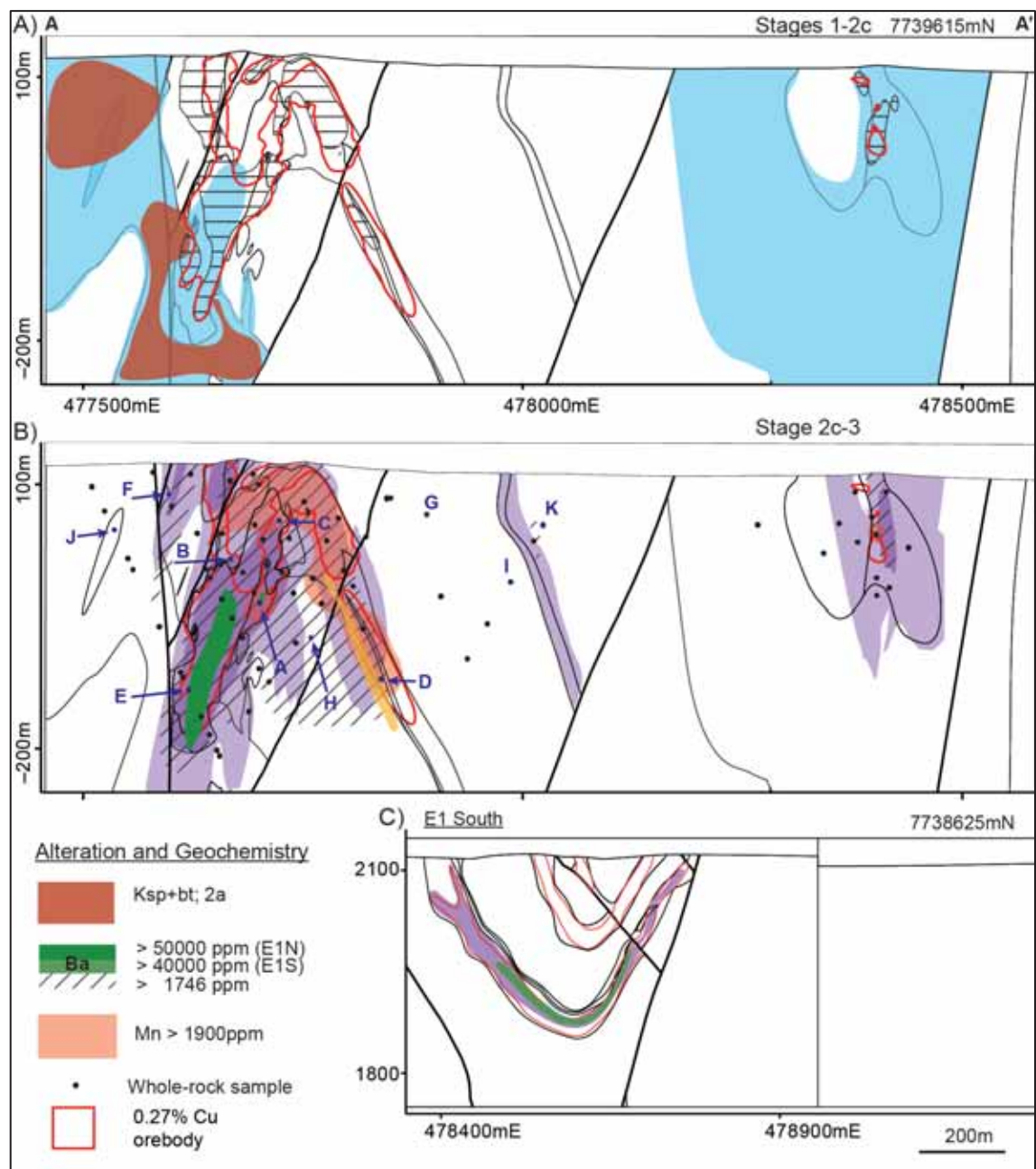


Figure 2.20: Cross sections of E1 North zonation along A–A' (see Figs. 2.4; 2.19). A) Pre-Stage 2c. B) Stages 2c–3. Whole-rock geochemical samples taken along this section indicated by black circles. Blue circles indicate MLA samples, which are labelled based on their corresponding map letter in Figure 2.9. See Figure 2.4 for rock type cross section.

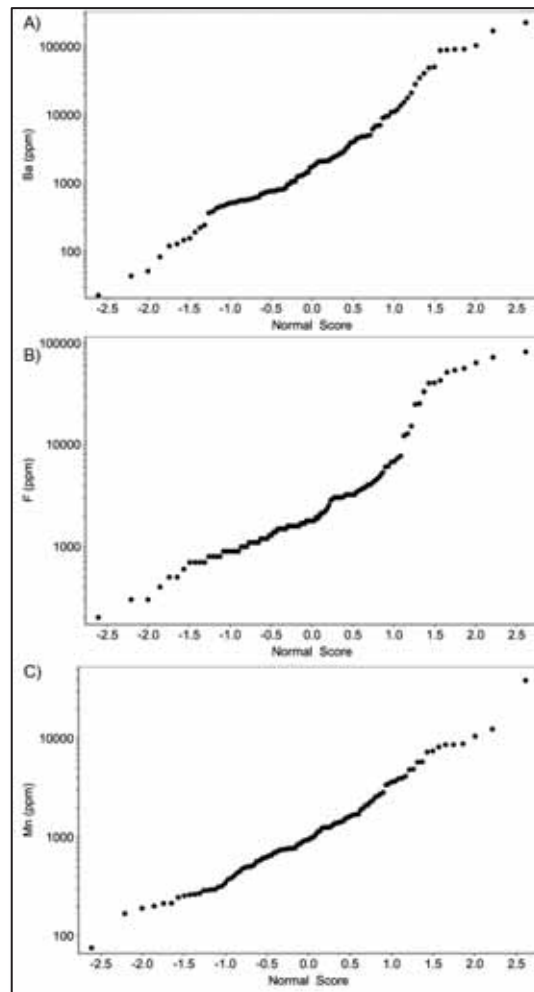


Figure 2.21: Probability plots of Ba, F, and Mn whole-rock data.

Variation outside the orebody

Coherent volcanics proximal to the E1 North orebody are commonly characterised by abundant carbonate veins, as well as an anastomosing pattern of magnetite-pyrite $\pm$ chalcopyrite alteration (Fig. 2.7I). The anastomosing texture is likely caused by magnetite-sulfide $\pm$ carbonate (calcite, siderite, ankerite or dolomite) veins or veinlets with wider alteration halo of the same assemblage, and the causative veins are occasionally visible. Further from the orebody, this stage 2 and 3 carbonate veining lacks significant sulfide or magnetite alteration, and is visible throughout the E1 Group mine lease. The veins are generally irregular in shape and vary in size from 1 mm to >2 m.

The orebody transitions southwest to a zone of pyrite-rich alteration (Fig. 2.19B). Continuing out from the pyrite zone and about 150 m southwest of the E1 North

orebody on the west limb of the E1 North antiform, a distinct zone of abundant coarse magnetite - pyrite -apatite veins and replacement is present (Fig. 2.19B). Apatite abundance is significantly higher in this zone (locally up to 2 wt% P) than in the orebody itself. Most of this alteration is related to Stage 2a, though it is possible that some of the magnetite and pyrite are from later stages. It is speculated that the orebody had higher concentrations of apatite during Stage 2, but it was overprinted by later mineralisation.

Whole-rock geochemical analysis indicates that barium concentrations, which were not fully tested during the drilling program, remain anomalous (>1750 ppm) up to 100m from the E1 North orebody (Figs. 2.19–2.20). Barite has not been detected in significant quantities outside the orebody, and it is likely that distal barium is hosted in K-feldspar or micas.

Whole-rock geochemical analysis of fluorine, which was also not assayed during drilling, indicates that anomalous (>1800 ppm) fluorine enrichment may extend over 100m from the orebody (Fig. 2.19). Wedepohl (1995) reported an average fluorine crustal abundance of 611 ppm, with a maximum average of 800 ppm in granitic crust. Almost all samples tested in this study contain >900 ppm, suggesting that the ore fluids were very Ba-F-rich, or that background values in the Ernest Henry–E1 area are higher than average crust.

Interpretations

Variations in mineralogy and element distribution within the orebody are mostly likely caused by a combination of changes in ore fluid conditions and host rock composition. This assumes that the ore-stage and pre-ore assemblages are genetically linked. The limited extent of barite-fluorite alteration with respect to the orebody is probably due to their relatively low solubilities. Alternatively, barite alteration may also be locally restricted by available sulfate at the time of deposition, but this does not explain the coincident limit of high F (>4 wt%) alteration. Concentration of these two elements around the northeast-trending shears and faults (Faults 2 and 3) and E1 North Antiform at E1 North, and near the hinge of the E1 South Antiform, suggests that these structures probably provided conduits for the Ba-F-bearing fluids.

A clear metasedimentary rock compositional control on mineralogy and element zonation is evident based on the relative lack of barite, and relative abundance of arsenopyrite and pyrrhotite, in the carbonaceous metasiltstone and schist at E1 South. The reducing nature of these host rocks likely removed oxidized sulfur from the mineralising fluids. The presence of abundant magnetite and chalcopyrite in both the marble and metasiltstone, however, indicates that the redox state of the host rock was not a vital factor in controlling ore distribution. The cause of Mn abundance in the upper portion of the E1 North orebody is not obvious. It is possible that this may reflect protolith composition, as the marble in this zone is less barite-fluorite-altered. Alternatively, it may represent a distinct zonation in the temperature or composition of the hydrothermal fluid. Ehrig et al. (2015) reported, based on core logs, a similar spatial zonation of barite-fluorite to siderite at the Olympic Dam IOCG deposit.

The transition from magnetite-chalcopyrite-barite-fluorite ore to magnetite-apatite-pyrite alteration southwest of the E1 North orebody (Fig. 2.19) may represent a temporal zonation. It is speculated that stages 2c and 3 mineralisations obliterated much of the Stage 2a apatite and pyrite in the orebody, while Stage 2a magnetite was probably remobilized by Stage 2c and not removed. It is possible that at least some of the Stage 3 fluorite in the orebody was formed by replacement of fluorapatite and F-rich biotite. It is not clear why Stage 3 mineralisation did not heavily overprint the magnetite and apatite zones (Fig. 2.19), but it may be the result of a lower-temperature, less-extensive, system during ore formation.

Discussion

Stratigraphic correlations of the E1 Group host rocks

The upper and lower horizons of metasedimentary rocks at E1 are similar to marbles and metasiliclastic rocks of the Corella Formation (1750–1720 Ma; Blake and Stewart, 1992; Foster and Austin, 2008) and possible equivalents (Doherty and Staveley formations; Foster and Austin, 2008; Carson et al., 2011) elsewhere in the Eastern Fold Belt. In the volcanic Zr/Ti vs Nb/Y diagram (Fig. 2.6B), the previously-logged trachyte and metabasalt are plot in, or close to, the andesite to andesitic basalt and andesite domains. Their compositions are different from the Toole Creek Volcanics of Cover Sequence 3, with higher Nb/Y ratios and significantly higher Zr/Ti ratios. Instead, their geochemical characteristics are virtually identical to the Mount Fort Constantine

Volcanics (Fig. 2.6B) of upper Cover Sequence 2 (Blake et al., 1997; Page and Sun, 1998; Foster and Austin, 2008). Additionally, the porphyritic and amygdaloidal textures of the E1 Group metavolcanic rocks described above are also similar to the textures of the Ernest Henry Mount Fort Constantine Volcanics (Fig. 2.5B–C). Therefore, it is proposed that the metavolcanic rocks at the E1 Group are part of the Mount Fort Constantine Volcanics. Regionally, the Mount Fort Constantine Volcanics are temporally equivalent to Corella Formation (Page and Sun, 1998; Mark et al., 2000; Foster and Austin, 2008).

Previously, the origin of the Mount Fort Constantine Volcanics as intrusive or extrusive was ambiguous (Page and Sun, 1998; Mark et al., 2000; Foster and Austin, 2008). We propose a volcanic origin for at least some of the Mount Fort Constantine Volcanics based on the following textural evidence at E1: 1) the presence of porphyritic and amygdaloidal clasts in the metavolcanic breccias (Fig. 2.5E), 2) local autobreccia of coherent rocks, and 3) a lack of aphanitic cooling margins at coherent/incoherent igneous contacts. These are typical textures for volcanic rocks (McPhie et al., 1993). Additionally, irregular and abrupt thickness changes in the metasedimentary and metavolcanic rock may represent localized volcanic flows.

The E1 Group is hosted in the same Mount Fort Constantine Volcanics and Corella Formation rocks of Cover Sequence 2 as the Ernest Henry deposit to the west, though their relative stratigraphic level within these formations is not clear. While some IOCGs to the south, such as Osborne, Monakoff and Eloise, are hosted in Cover Sequence 3, others like Mount Elliot-SWAN are hosted along the Cover Sequence 2 / Cover Sequence 3 contact (Duncan et al., 2014). Clearly, stratigraphic positioning in Cover Sequence 2 or Cover Sequence 3 is not a significant control on IOCG mineralisation in the district. With that said, the contact itself may be an important structural control (e.g. McClellan et al., 2010; Duncan et al., 2014).

Absolute timing of E1 Group mineralisation

The 1456 ± 44 Ma age of the E1 Group Stage 3 monazite overlaps in error with a titanite U-Pb (1514 ± 24 Ma; Mark et al., 2006b) age of pre-ore potassic alteration from Ernest Henry (Fig. 2.22). It also overlaps in error with the youngest plutons of the Isan Orogeny: the 1501 ± 9 Ma Capsize Granodiorite, and the 1493 ± 8 Ma Yellow Waterhole Granite; Page and Sun, 1998). Although syn-ore molybdenite Re-Os ages

from Mount Elliott (1513 ± 5 Ma; Duncan et al., 2011) and Ernest Henry (~ 1525 Ma; Mark et al., 2004) are distinctly older, the E1 Group age also overlaps with the molybdenite Re-Os age of 1487 ± 5 Ma for mineralisation at the Lady Ella IOCG prospect just south of Mount Elliott (Duncan et al., 2011). The oldest possible monazite ages at E1 may therefore indicate the maximum age of mineralisation around 1500 Ma.

The youngest possible monazite age of 1410 Ma, based on the 10 points in Figure 2.13B, may represent a younger resetting event; the highly anomalous, concordant, ages <1350 Ma are also likely reset. Although BSE imaging showed homogeneous monazite crystals, it may be the case that some of the discordances and younger ages were caused by mixing of monazite domains of different ages; most crystals were too small to ablate in different spots, and in some instances U/Th ratios varied down-ablation hole (not shown). The high closure temperature of monazite ($725 \pm 25^\circ\text{C}$; Parrish, 1990) precludes thermal resetting, but minor hydrothermal alteration could result in Pb-loss (e.g. Williams et al., 2011). It is possible that the monazite U-Pb age at E1 Group may represent a mixture of both the late Cu-Au mineralising event around 1500 Ma—synchronous with younger IOCGs such as Ernest Henry and Mount Elliott—as well as with a resetting event much later (>100 Myr) than main Cu-Au mineralisation (e.g. the Oak Dam IOCG deposit, Gawler Craton; Davidson et al., 2007). Resetting of the monazite may have been related to late magmatism. Although no intrusions younger than ~ 1500 Ma have been found in the Cloncurry district, Griffin et al. (2006) found small detrital zircon populations sourced from the Eastern Fold Belt with concordant ages between 1490–1420 Ma, and 1340–1280 Ma. They proposed that the ages could represent primary igneous crystallization. It is possible, though unlikely, that there are undiscovered 1490–1420 Ma intrusions in the EFB. The <1400 Ma monazite ages may therefore indicate that the E1 Group of deposits were partly reset by hydrothermal fluids related to such intrusions.

Nevertheless, the maximum ~ 1500 Ma age of E1 Group monazite, suggests that the deposit is part of the syn-Williams-Naraku Batholith group of IOCGs, which includes Ernest Henry, Monakoff, Mount Elliott, and Eloise. This is compatible with a regional D₄ timing of mineralisation proposed in Chapter 3.

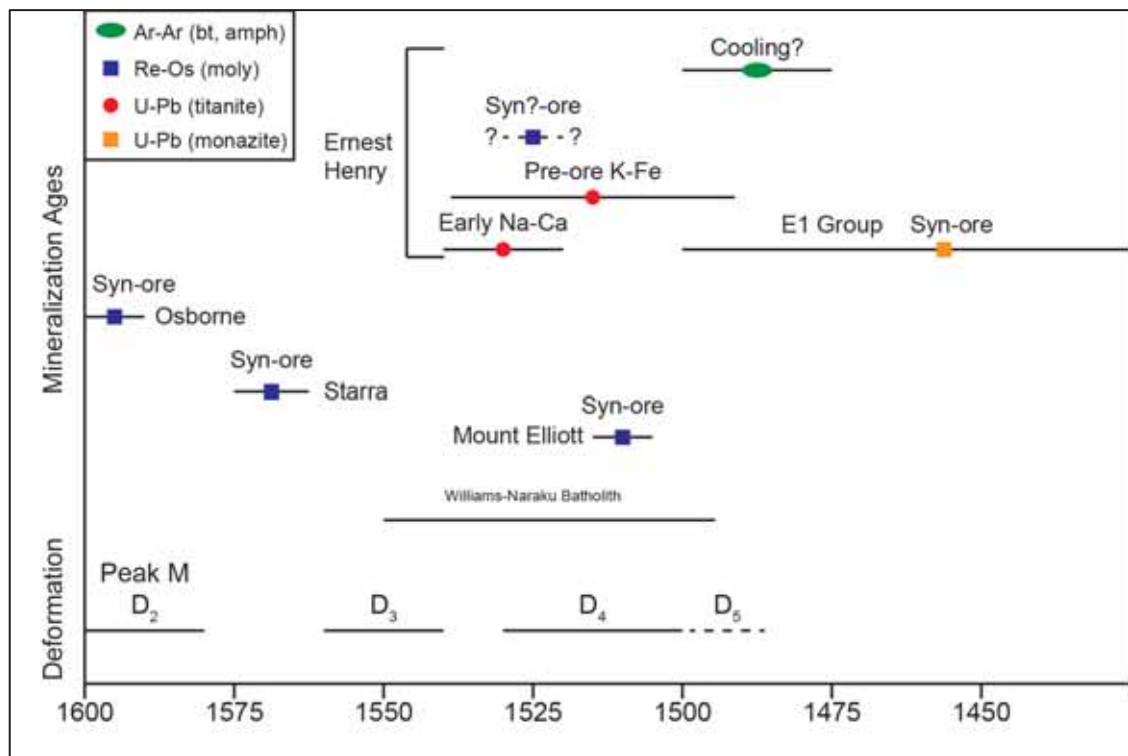


Figure 2.22: A comparison of reported mineralisation ages in Cloncurry IOCGs. See text for references.

Epigenetic origin of banded magnetite at the E1 Group

Following the geological evidence presented above, we propose the following evidence of epigenetic origin for magnetite present in the E1 Group system.

1. Magnetite abundance (>30%) in laminated metasedimentary rocks decreases away from the core of the E1 North orebody and grades into less-altered marble containing chloritised actinolite porphyroblasts (Fig. 2.5F).
2. Abundant magnetite (locally up to 78 wt% Fe₂O₃) is present in both the matrix and clasts of metavolcanic breccias (Figs. 2.5D, 2.7H), which is atypical for intermediate volcanic rocks. The only possible sources of secondary magnetite in the metavolcanic rocks are therefore from remobilization of Fe in adjacent metasedimentary rocks, or from an external source. The former source is unlikely, as this would require transport distances greater than 10 m; this is orders of magnitude greater than the cm-scale movement suggested for magnetite-sulfide remobilization of ironstones in the Starra and Osborne systems (Oliver et al., 2008). Furthermore, the metasedimentary rocks themselves are still highly magnetite-enriched (>70

wt%), which is opposite to the depletion expected if magnetite were mobilized from the metasedimentary rocks into the metavolcanic rocks.

3. Northeast-southwest-trending faults at E1 North appear to focus magnetite and chalcopyrite alteration (Fig. 2.19B), suggesting they served as a conduit for fluids to transport these minerals from elsewhere, rather than from local remobilization of sedimentary iron. The faults cut the folds and therefore cannot be pre-Isan Orogeny basin-bounding faults.

An epigenetic origin was also proposed by Coleman (2015), who analysed trace-elements in both laminated and infill magnetite from Ernest Henry and the E1 Group, and magnetite from fresh, typical BIF from Western Australia. He found that the E1 Group laminated magnetite exhibited similar Si-Al-V-Ti-Mg-Zn-Cr-Co signatures to E1 Group infill magnetite, but was different from magnetite the Western Australia BIF. He concluded that most magnetite present in the system was hydrothermal in origin with only minor detrital magnetite. When coupled with the observations that Cloncurry District IOCGs occur at varying stratigraphic levels, and in various types of host rocks, these lines of evidence suggest that most of the IOCG-hosting iron-rich rocks in the region are epigenetic.

Significance of discordant breccias at the E1 Group and Ernest Henry

The Ernest Henry deposit is unique among other IOCGs in the region for being completely hosted within hydrothermal breccias (Mark et al., 2000). This feature has led to targeting of regionally abundant albite-magnetite-rich breccias by explorationists; such breccias turned out to be mostly barren or only lightly mineralised.

The discordant breccias present in the E1 Group are consistent with the “Corella Breccia” described in Ryburn et al. (1988) and Marshall (2003). The term was applied to psuedobreccias formed by extreme boudinaging of Corella Formation, as well as to polymictic breccias containing clasts of Corella metasedimentary and intrusive igneous rocks, with the matrix containing hydrothermal minerals (Marshall, 2003). The E1 Group breccia is clearly more similar to the latter polymictic style. The E1 Group breccia is similar to the Ernest Henry ore breccia in terms of clast composition (sedimentary rocks and porphyritic volcanic rocks with K-feldspar, albite, and hematite alteration) and overall degree of clast support, but it is slightly more angular and

variable in size, and contains relatively finer-grained (<5 mm) cement than the Ernest Henry breccia (up to 1 cm). Unlike the Ernest Henry ore breccia, the E1 Group breccia is virtually barren and contains only minor mineralisation, disseminated in the breccia or in carbonate veins that cut across the breccia.

Aside from the Ernest Henry ore breccia, Mark et al. (2000) reported barren, albitised breccias around the orebody that are virtually identical to the discordant breccia present at the E1 Group (Fig. 2.5M). Like the breccia at the E1 Group, these breccias are overprinted by chalcopyrite mineralisation (Mark et al., 2000b). Considering that crystallization duration for granites (<10 Myr; Patterson et al., 1992) can be less than the uncertainties of Proterozoic ages, it is possible that the “Corella Breccias” which formed between 1530–1520 Ma represent many separate hydrothermal brecciation events, each associated with temporally indistinguishable, yet distinct, magmatic events. The Ernest Henry ore breccia may represent one of these “Corella” brecciation events. It is not entirely clear why this particular breccia became mineralised, but it may be because other systems lacked Cu-Au, an additional fluid, or adequate structural conduits to drive mixing and ore precipitation (e.g. Mark et al., 2006a; Rusk et al., 2010; Williams et al., 2015).

Classification of the E1 Group in the iron oxide-Cu-Au family

The E1 Group shares multiple characteristics with true IOCGs (e.g. Ernest Henry, Olympic Dam, Salobo and Candelaria): a Cu-Au-Ba-F-P-U-REE-Co-Mo geochemical assemblage, albite and magnetite-biotite-K-feldspar alterations, and fault-shear zone associations (Table 2.6).

Table 2.6: Characteristics of major IOCG and IOCG-related deposits

District	Deposit	Metals	Enrichments	Dominant ore	Dominant gangue	Mineralisation styles	Host rocks	References
Gawler Craton	Olympic Dam	Cu, U, Au, Ag	Fe, Ba, F, P, LREE, Co, Mo	Chalcopyrite, bornite, chalcocite, uraninite	hematite (upper), magnetite (lower), quartz, sericite, carbonate, fluorite, barite	matrix-supported hydrothermal breccia, crackle-breccia and veins	brecciated granite, metasedimentary and metavolcanic rocks	Roberts and Hudson, 1983; Reynolds, 2000
Candelaria-Punta del Cobre	Candelaria	Cu, Au, Ag	Fe, Zn, Mo, LREE	Chalcopyrite	magnetite, hematite, pyrite, actinolite, biotite, K-feldspar, carbonate, epidote	layer/matrix-controlled to massive; brecciation and veins	siltstone, andesite, dacite, sedimentary breccia	Marschik, et al 2000; Marshik and Fontboté, 2001
Carajás	Salobo	Cu, Au	Fe, F, P, U, REE, Co, Mo	Bornite, chalcocite, chalcopyrite	magnetite, biotite	massive	amphibolite, metagraywacke, quartzite, banded ironstone	Requia and Fontboté, 2000; Requia et al, 2003
Cloncurry Syn-Williams-Naraku Batholith	El Group	Cu, Au,	Fe, Ba, F, P, U, LREE, Co, Mo	Chalcopyrite	magnetite, carbonate, barite, fluorite, biotite	layer/matrix-controlled to massive replacement; some veins	metavolcanic breccia, metatuff, marble, metapsammite, metasiltstone	this study
	Ernest Henry	Cu, Au,	Fe, Ba, F, P, U, LREE, Co, Mo	Chalcopyrite	magnetite-hematite, carbonate, fluorite, barite	matrix-supported hydrothermal breccia, crackle-breccia and veins	brecciated intermediate metavolcanic rocks, metapsammite, marble, metasiltstone, metashale	this study; Mark et al., 2006b
	Monakoff	Cu, Au,	Fe, Ba, F, P, U, LREE, Co, Mo	Chalcopyrite	magnetite, fluorite, barite, carbonate	massive to layered replacement; dilational infill	banded ironstone?	Williams et al., 2015
	Mt. Elliott-SWAN	Cu, Au	Fe, P, F, Co, Ni, LREE, Te, Se	Chalcopyrite	magnetite, pyrrhotite, pyrite, diopside, andradite, calcite	open space infill, breccia, massive skarn	carbonaceous metapelites, metagreywackes, amphibolites	Wang and Williams, 2001
	Eloise	Cu, Au	Fe, Ag, Co, Ni, Zn, F, P	Chalcopyrite	pyrrhotite, pyrite, magnetite, albite, amphibole, biotite, quartz, calcite, chlorite,	breccias, veins, replacement bodies	amphibolite, quartz-biotite-schist, garnet psammite	Baker, 1998
Cloncurry Pre-Williams-Naraku Batholith	Osborne	Cu, Au	Fe, Co, Bi, W, Se, Hg, Te, Cl, Sn, P, B, Mo	Chalcopyrite	magnetite, carbonate, pyrrhotite	massive to layered replacement; breccia and veins	feldspathic metapsammite, ironstone	Adshead, 1995 Fisher and Kendrick, 2008; Oliver et al., 2004
	Starra	Cu, Au	Fe, Co, W, Sn, F, Mo, Y, REE	Chalcopyrite, bornite, chalcocite	magnetite, quartz, carbonate, anhydrite, hematite	massive to layered replacement and brecciated	psammite, albitised metasiltstone, schist, amphibolite, ironstone	Rotherham, 1997; Oliver et al., 2004 Duncan et al., 2014

However, the E1 Group has some unique features when compared to IOCGs from the southern Cloncurry District IOCGs (Starra, Osborne, Mount Elliott-SWAN, Eloise), which lack substantial Ba-U enrichment (Table 2.6). Unlike the E1 Group, Osborne and Eloise are not enriched in REE, though these elements are abundant at Mount Elliott and enriched at Starra (Table 2.6). The geochemistry of the E1 Group is also distinct from true IOCG deposits such as Olympic Dam, Prominent Hill, Salobo, Candelaria, and Ernest Henry (Groves et al., 2010). For example, the E1 Group has much higher Ba (up to 22 wt%) and F (up to 8%) abundance than Ernest These deposits. Its U and total REE (~1500ppm) content, however, are much lower than Olympic Dam (~5000ppm; Oreskes and Einaudi, 1990). It is possible that the E1 Group and the nearby Monakoff (e.g. Williams et al., 2015) deposits represent geochemical end-members of the Cu-Au-U-REE-Ba-F IOCG assemblage with very high Ba-F content.

Mineralogically, the E1 Group is similar to other IOCG deposits in the Cloncurry District in that it contains abundant magnetite and some apatite and pyrite (Table 2.6). Indeed, most of the Fe-oxide Cu-Au orebodies in the region are magnetite-dominated; the Starra and Osborne deposits and Airport prospects, which also contain substantial hematite, are exceptions to this. The E1 Group also hosts early sodic and ferric/ferrous-potassic (-P) alteration assemblages typical of most IOCGs. Interestingly, the paragenetic sequence of the E1 Group is very similar to those of the nearby Ernest Henry and Monakoff IOCGs (Fig. 2.10) – all three are characterised by potassic-ferric/ferrous alteration followed by Ba-F-U-REE-enriched mineralisation. The main difference is that Monakoff lacks appreciable early sodic-calcic alteration.

In contrast, the E1 Group is notably different from other Cloncurry District IOCGs in several aspects. For example, the southern deposits are generally less sulfate-rich, though Starra does contain some anhydrite and minor barite. Additionally, although the E1 Group is hosted mainly in carbonate-rich rocks, it lacks appreciable calcic (garnet, pyroxene) alteration like the skarn-rich Mount Elliott deposit, which has been classified as a skarn-like IOCG (Wang and Williams, 2001; Groves et al., 2010). When compared to deposits in other districts, the E1 Group is unique in that it lacks the abundant amphibole, associated with early sodic alteration, found in Ernest Henry, Olympic Dam and Sossego (Moreto et al., 2015). The E1 Group is similar to Olympic Dam, in that some ores contain abundant barite (up to 38 wt%) and fluorite (up to 17 wt%). The E1

Group and Ernest Henry, however, are both dominated by magnetite whereas Olympic Dam is hematite-dominated except in the deepest part of the system.

True IOCG deposits exhibit strong structural control (Groves et al., 2010). This control is exemplified by the presence of IOCG systems adjacent to, or within, fault and shear zones, such as in the case of Ernest Henry, Candelaria, Starra, Osborne, Monakoff, and Salobo (Adshead-Bell, 1998; Marschik and Fontboté, 2001; Requia et al., 2003; Mark et al., 2006b; Fisher and Kendrick, 2008). Although E1 Group mineralisation is dominantly controlled by protolith, the ore fluids were introduced to the receptive host rocks through shearing, multiple faults, and fold hinges, suggesting a high degree of structural control on the system. The chemical similarities between the E1 Group, Ernest Henry, Olympic Dam and Salobo suggest that breccia mineralisation textures are not a useful defining feature of IOCG-style deposits. Rather, they are probably determined by deposit-scale variations in the nature (brittle or ductile) and degree of structural deformation of the host rocks (see Chapter 3).

To summarise, the E1 Group exhibits all of the major characteristics of true IOCG deposits, including Ba-F-U-REE enrichment, Na-K-Fe alteration, strong structural control, and potentially temporal association with felsic intrusions, but varies considerably in chemistry and mineralogy from the most well-known IOCG deposits.

Implications for IOCG Genesis and Exploration

The similarities in paragenesis and ore chemistry between the E1 Group, Ernest Henry and Monakoff suggests these systems formed from a similar type of hydrothermal fluid that was present over an area of 120 km² between the deposits, thus making the area highly prospective for additional exploration. These similarities also imply that brecciation is not necessary for the formation of small and medium-sized orebodies. Indeed, large, mineralised hydrothermal breccia systems like Ernest Henry are the exception rather than the norm in the Eastern Fold Belt. Replacement of shear zones and chemically reactive host rocks is a more common IOCG phenomenon as evidenced by numerous moderately-sized orebodies like the E1 Group, Osborne, Starra and Monakoff. Brecciation, however, is likely to be important for generating high enough permeability to form IOCGs with size and grades comparable to Ernest Henry. The absence of brecciation at the E1 Group and Monakoff may help explain their high barite and fluorite concentrations. Barium and fluorine in Stage 2 K-feldspar and fluorapatite

indicate that both elements were present in the hydrothermal fluid(s) before and during ore deposition. It is hypothesized that protracted replacement at the E1 Group over multiple paragenetic stages, presumably associated with minor volume change, led to increasing total Ba-F content over time. This is consistent with the observed tendency for fluorite to replace F-rich biotite in the E1 Group ores, as well as with the apparent lack of fluorapatite in ores, which was probably also replaced by fluorite. In contrast, brecciation and infill during ore formation at Ernest Henry probably caused a much greater increase in the overall volume of the system (e.g, Oliver et al., 2006), and therefore diluted these elements over multiple stages in a more open system.

Fluorine and barium are potential vectoring elements to the E1 Group orebody. Anomalously-high fluorine is traceable for >100 m around the orebody, and it probably occurs mostly in apatite and biotite. Ernest Henry and the E1 Group are both characterised by magnetite-apatite haloes extending over 200 m outside of the orebody. Barium is also above background levels for at least 100 m outside of the E1 Group ore zone.

Conclusions

The E1 Group of iron oxide-Cu-Au deposits is hosted in a sequence of metatuff, marble, metavolcanic breccia, metasiltstone, metashale, and variably-porphyritic and amygdaloidal metavolcanic rocks of the ~1740 Ma Corella Formation and Mount Fort Constantine Volcanics of upper Cover Sequence 2, which was intruded by diorite, then brecciated, then intruded by dolerite prior to mineralisation. The geometry of the deposit is characterised by north-northwest-plunging folds that are cut by faults and shear zones coincident with mineralisation. The E1 Group has a Cu-Au-Ba-F-Mn-U-REE-As-Mo-Co-rich ore assemblage, similar to the nearby Ernest Henry IOCG deposit, but the mineralisation style of the E1 Group is dominantly characterised by layer- and matrix-controlled replacement of metasediment and metavolcanic rocks, whereas Ernest Henry is entirely hosted in a breccia. The alteration paragenesis occurred in three major stages, with the second stage divided into three substages: 1) early albitisation, 2a) ferric/ferrous-potassic magnetite-biotite-apatite-K-feldspar-pyrite, 2b) intermediate albitisation, 2c) early carbonate flooding and mineralisation, and 3) late carbonate-barite-fluorite flooding and main mineralisation. Whole-rock geochemistry and MLA analysis shows that the E1 Group orebody contains significantly more barite and

fluorite alteration (associated with Stage 3) than most IOCGs, and at E1 North both are most abundant in the deeper portion of the orebody. Barium and fluorine concentrations in the sampled area exceed average crustal values, suggesting either a source rich in Ba and F, or an anomalously high regional background.

An epigenetic origin, at 1456 ± 44 Ma, is proposed for both the E1 Group mineralisation and the magnetite in the banded, iron-rich host rocks, based on a combination of drill core and thin section observations, and geochemical data. Despite the contrasting mineralisation style between the E1 Group and the classic IOCG Ernest Henry, the former fits within the family of iron oxide-copper-gold deposits *sensu stricto*, and is more similar to Ernest Henry than to the Osborne or the Starra deposits in the Cloncurry district. E1 Group mineralisation is mostly dependent on a combination of structures and host rock permeability and chemical suitability. The E1 Group contains comparable copper resources to Starra, and a similar amount to Osborne (though the latter two systems are more Au-rich), indicating that brecciation is not necessary to produce moderately large copper orebodies in the Cloncurry District. Furthermore, the pre-mineralisation timing of hydrothermal breccias at E1 suggests that similar breccias in this area are not related to mineralisation, and that the Ernest Henry breccia represents a separate event. Alternatively, it is possible that there were multiple stages of Cu-Au-bearing fluids in the area, but that the early breccias did not focus the metals. Barium and fluorine enrichment at E1 may be the result of temporally protracted enrichment through replacement, as opposed to Ernest Henry-style brecciation that may have diluted these elements in a more open system. The similarity in ore chemistry and parageneses of Ernest Henry, E1 and Monakoff suggests these deposits were formed from similar types of hydrothermal fluids, consequently making this area highly prospective for additional deposits.

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Chapter 3

Delineating the structural controls on iron oxide-Cu-Au deposit genesis through implicit modeling: A case study from the E1 Group, Cloncurry District, Australia

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Abstract

Iron oxide-Cu-Au (IOCG) deposits encompass a range of orebody shapes, including stratabound replacement ores and hydrothermal breccias. We use the implicit method to make a detailed 3-D geological model of a stratabound IOCG in the Cloncurry district, the E1 Group, to elucidate structural controls on mineralisation. This model is compared to the nearby, world-class, Ernest Henry breccia-hosted IOCG deposit. Copper mineralisation in the E1 Group occurs as structurally-controlled, mainly stratabound, replacement bodies hosted in metasedimentary and metavolcaniclastic rocks intercalated with barren meta-andesite. Replacement bodies in the E1 Group conform to a series of north-northwest plunging folds formed in regional D₂ during peak metamorphism. Folding was followed by local D₃ / regional D₄ shortening that formed a dextral, transpressional Riedel brittle to ductile system along the regional Cloncurry Fault Zone. Modeling suggests that much of the Cu-Au mineralisation is controlled by synthetic R structures associated with this Riedel system. The deformation sequence at Ernest Henry is comparable, but differences in host rock rheology, permeability and fluid pressure may explain the variation in ore body types and total Cu-Au resource between the two deposits. The results carry implications for other districts containing these styles of IOCG mineralisation.

Introduction

Although fluid sources and genetic models for iron oxide-Cu-Au (IOCG) deposits are debated at the global scale (e.g. Barton and Johnson, 2000; Hitzman, 2000; Pollard, 2000; Williams et al., 2005; Hunt et al., 2007; Groves et al., 2010), IOCGs *sensu stricto* are primarily controlled by splays or intersections of regional faults and shear zones (Hitzman et al., 1992; Groves et al., 2010). However, knowledge about the structural controls of these deposits is less advanced than, for example, epigenetic gold deposits. A comparison between the major IOCG districts (Fig. 3.1) including the Gawler Craton and Cloncurry District, Australia (e.g. Oreskes and Einaudi 1990; Oreskes and Einaudi 1992; Haynes 2000; Belperio et al., 2007; Mark et al., 2006a; Oliver et al., 2004, 2006, 2008; Rubenach et al., 2008; McLellan et al., 2010), the Fennoscandian shield, Scandinavia (Billström et al., 2010), Punta del Cobre, Chile (Marschik and Fontboté 2001), and Carajás, Brazil (Ronzê et al., 2000; Grainger et al., 2008), reveals some similar structural settings for IOCG-style orebodies. These settings include hydrothermal breccias, veins or replacement bodies associated with the intersections

between faults and shears and specific rock types, and location within dilational fault or shear jogs. Some rock types (e.g. calcareous or carbonaceous sedimentary rocks) can act as ideal chemical traps, or may focus permeability by brecciating. Fe-oxide-Cu-Au deposits appear to have formed both at relatively shallow (<5 km) depths, as in the case of Olympic Dam (Oreskes and Einaudi, 1992; Haynes et al., 1995), and at deeper levels (~10 km), in the case of Ernest Henry (Kendrick et al., 2007). Some of the major IOCG districts, such as the Fennoscandian shield, Carajás, and Cloncurry, are characterised by protracted periods of metamorphism, magmatism and metasomatism that enhance existing ores and generate new orebodies (Kirchenbaur et al., 2016; Macmillan et al., 2016; Billström et al., 2010; Oliver et al., 2008). Thus, understanding the relative timing of IOCG mineralisation with respect to regional deformation events is critical for developing genetic models that include fluid transportation conduits and trapping mechanisms.

The Cloncurry District of northwest Queensland, Australia, hosts numerous IOCG deposits, all associated with shear zones (e.g. Baker and Laing 1998; Coward 2001; Davidson et al., 2002; Duncan et al., 2014). The recently discovered E1 Group of IOCG deposits (10.1 Mt at 0.73 % Cu, 0.22 g/t Au), located 40 km northeast of Cloncurry (Fig. 3.2), has not been extensively studied and may offer new insights into regional structural controls and genesis of IOCG deposits. The E1 Group comprises three distinct orebodies: E1 North (the largest), E1 East, and E1 South. The orebodies were discovered in 1990 by Western Mining Corporation, but were not extensively drilled out until the early 2000s by EXCO Resources. The E1 Group is located 8 km east from the world-class Ernest Henry system which has total resources of 226 Mt at 1.1% Cu and 0.51 g/t Au (Rusk et al., 2010), and is the largest Cu-Au deposit in the Cloncurry District (Mark et al., 2006a). The area surrounding the E1 Group and Ernest Henry is characterised by sparse outcrop, and as a result past exploration has been heavily dependent on geophysical techniques in order to resolve regional- and deposit-scale structures that host the IOCG mineralisation.

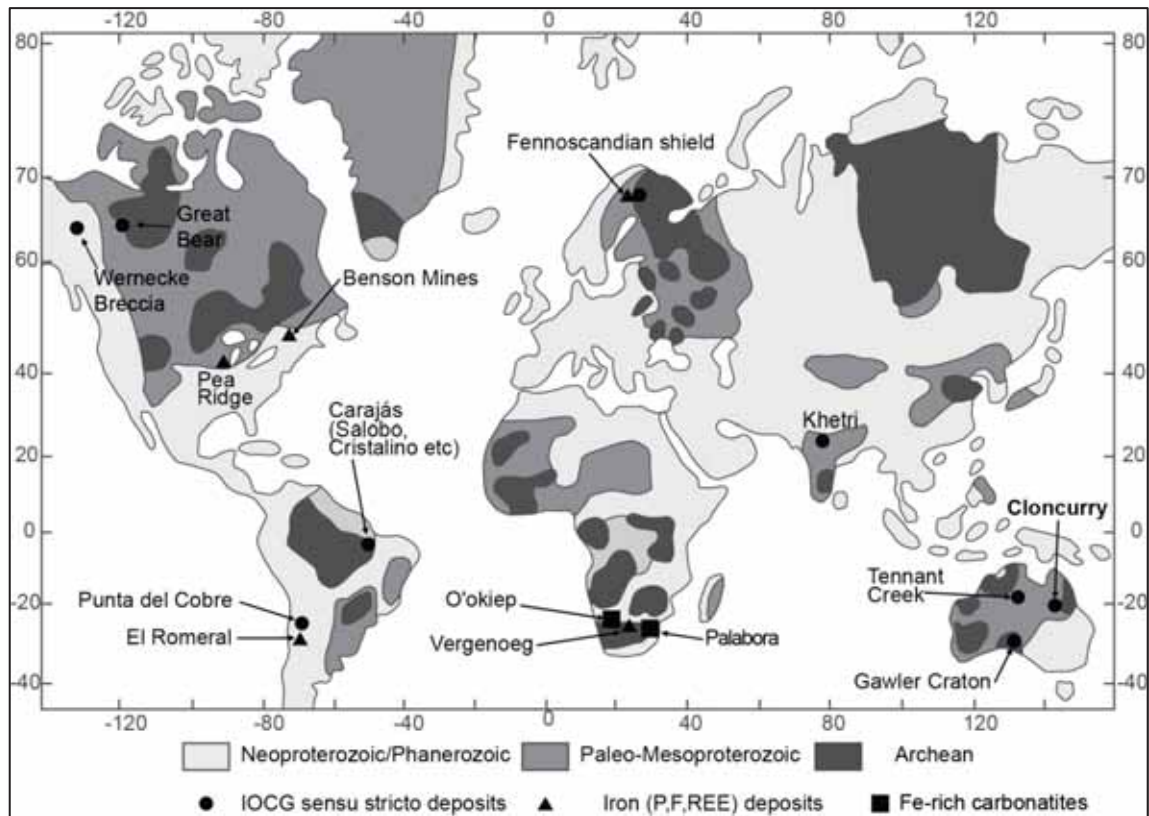


Figure 3.1: Global distribution of IOCG and related deposits, based on the modified map and classification scheme of Groves et al., (2010). Study area labelled in bold typeface. The Fennoscandian shield contains both IOCG and Iron oxide-apatite (IOA) deposits, and the symbols are placed side-by-side.

Implicit geological and geochemical modeling are powerful tools that can aid in rapid characterisation of the disposition of orebodies, particularly those with limited outcrop in which cross and plan sections must be synthesized from drilling and geophysical datasets (e.g. Hill et al., 2014). A geological model of the E1 Group could contribute to the understanding of mineralisation in this area where the subsurface geology is poorly constrained. Using three-dimensional (3-D) modeling derived from drill core logging, open pit mapping and aeromagnetic data, this study presents the structural characteristics, deformation history, and structural controls on mineralisation of the E1 Group of IOCG deposits. These aspects are compared to those of the nearby breccia-hosted Ernest Henry system in order to infer the controls on the different mineralisation styles.

Regional Geology

The E1 Group of IOCG deposits is located 40 km northeast of Cloncurry in the Selwyn Zone of the Proterozoic Mount Isa Inlier of northwest Queensland (Fig. 3.2). The Mount Isa Inlier is conventionally subdivided into the Western Fold Belt, Kalkadoon-

Leichhardt Belt, and Eastern Fold Belt tectonic domains (Fig. 3.2; Blake and Stewart 1992). The Inlier is prospective for Cu, Au, Pb, Zn, Ag, U, REE, Mo, but deposit styles vary substantially between belts (Murphy et al., 2011). The Western Fold Belt is dominated by Mount Isa-style Cu and Pb-Zn deposits, while the Eastern Fold Belt and Kalkadoon-Leichhardt Belt host varying styles of Cu-Au and BHT and SEDEX Pb-Zn $\pm$ Ag mineralisation, of which many of the Cu-Au deposits are grouped into the IOCG classification (Williams et al., 2005; Groves et al., 2010).

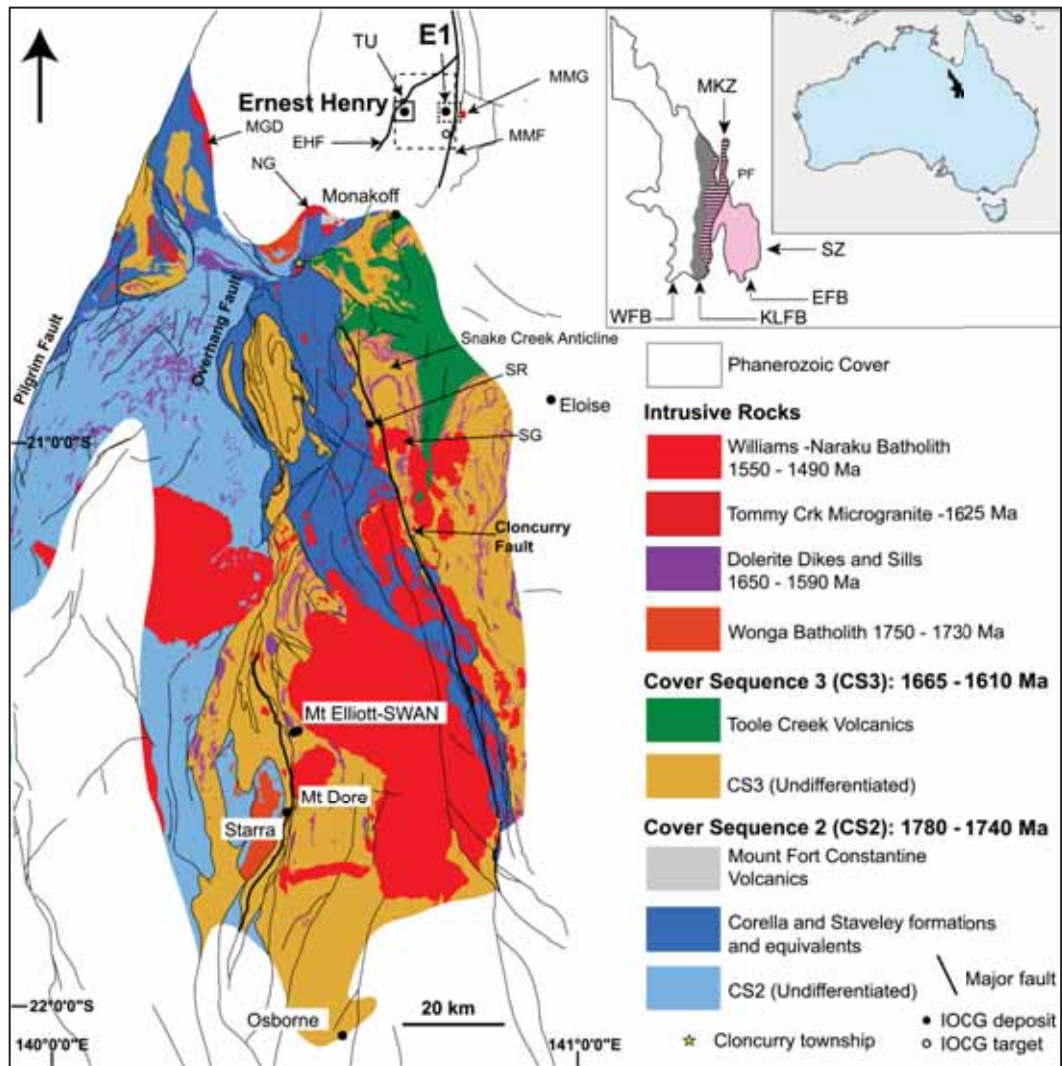


Figure 3.2: Interpreted bedrock geology and structures of the Eastern Fold Belt east of the Pilgrim Fault (the Selwyn Zone). The inset shows the major domains of the Mount Isa Inlier. Geology polygons and structure polylines are from the Geological Survey of Queensland (2011). Structures below cover were interpreted in the same report from geophysical datasets. The solid-, dashed- and dotted-outlined boxes indicate the areas represented in Figures 3.8, 3.9 and 3.10, respectively. GDA 94 projection EFB, Eastern Fold Belt; MKZ, Mary Kathleen Zone; SZ, Selwyn Zone; KLFB, Kalkadoon-Leichhardt Fold Belt; WFB, Western Fold Belt; MMG, Mount Margaret Granite; PF, Pilgrim Fault; MMF, Mount Margaret Fault; EHF, Ernest Henry Fault; MGD, Mavis Granodiorite; NG, Naraku Granite; SR, Suicide Ridge; SG, Saxby Granite; TU, Third Umpire target.

Cover sequence deposition and early intrusions

The sedimentary and volcanic country rocks of the Eastern Fold Belt were deposited between 1875 and 1610 Ma in an intracratonic rift setting (Blake, 1987 and references therein; O’dea et al., 1997). They overlie the ~1900 Ma basement rocks of the Barramundi Orogen and are divided into three major unconformable cover sequences (Fig. 3.3; Page and Williams, 1988; Blake and Stewart, 1992).

Cover Sequence 1, composed mostly of mafic-felsic extrusive rocks, was deposited from 1870–1840 Ma (Wyborn and Page, 1983). Following a significant hiatus, mudstones, sandstones, carbonates, and evaporites of Cover Sequence 2 were laid down between 1780 and 1740 Ma. In the area around the E1 Group and Ernest Henry, Cover Sequence 2 rocks are represented by the intermediate Mount Fort Constantine Volcanics and Corella Formation carbonates and siliclastic rocks; they formed synchronously from 1750–1740 Ma (Page and Sun, 1998; Foster and Austin, 2008). Equivalents of the Corella Formation, including possibly the Staveley Formation, may be as young as 1720 Ma (Betts et al., 2011). After deposition of Cover Sequence 2, granites of the ~1740 Ma Wonga Batholith were intruded mostly in the western portion of the Eastern Fold Belt (Wyborn et al., 1988). Cover Sequence 3 sedimentary rocks and mafic volcanics were deposited between 1690 and 1650 Ma (Foster and Austin, 2008; Rubenach et al., 2008). Mafic dykes and sills were also intruded during this time period (Rubenach et al., 2008). The Ernest Henry Diorite suite crystallized around 1650 Ma (Page and Sun 1998) in the region around Ernest Henry. Scott et al., (1998), Jackson et al., (2000), Betts and Giles (2006) and Neumann et al., (2009) present an alternative stratigraphic framework for the entire Mount Isa Inlier, and Betts and Giles (2006) consider the Western and Eastern fold belts to be broadly stratigraphically correlated in the form of superbasins. Those authors have grouped the formations of Cover Sequence 2 into the Leichhardt Superbasin, while those of Cover Sequence 3 are divided into the Calvert Superbasin (Llewellyn Creek Formation-Mount Norna Quartzite) and Isa Superbasin (Toole Creek Volcanics and Staveley Formation). Similar correlations have also been proposed by Foster and Austin (2008).

Isan Orogeny: deformation and metamorphism

The post-1900 Ma deformation history of the Mount Isa Inlier is dominated by the 1650–1500 Ma Isan Orogeny (Rubenach et al., 2008). Deformation and metamorphism related to this orogeny is complex in the Eastern Fold Belt, and there is no consensus on

the timing and number of individual events. Most studies in the Eastern Fold Belt have focused on the well-exposed areas south and west of Cloncurry (Fig. 3.2) such as the Selwyn zone, Snake Creek Anticline, and Mary Kathleen Domain (e.g. Looseveld and Schreurs 1987; Adshead-Bell 1998; Rubenach and Lewthwaite 2002; Giles et al., 2006; O’dea et al., 2006; Rubenach et al., 2008; Abu Sharib and Bell 2011). Those workers generally concluded that at least four major deformation events took place in the region (Fig. 3.3). Rubenach and Lewthwaite (2002) and Giles et al., (2006) describe an early (1680–1640 Ma, Rubenach et al., 2008) extension-related event (denoted D_{bp} by Rubenach et al., 2008), resulting in a bedding subparallel foliation (Fig. 3.3). This extensional event was followed by three or four major crustal shortening events (Mark et al., 2000; Blenkinsop et al., 2008; Rubenach et al., 2008; Abu Sharib and Bell, 2011).

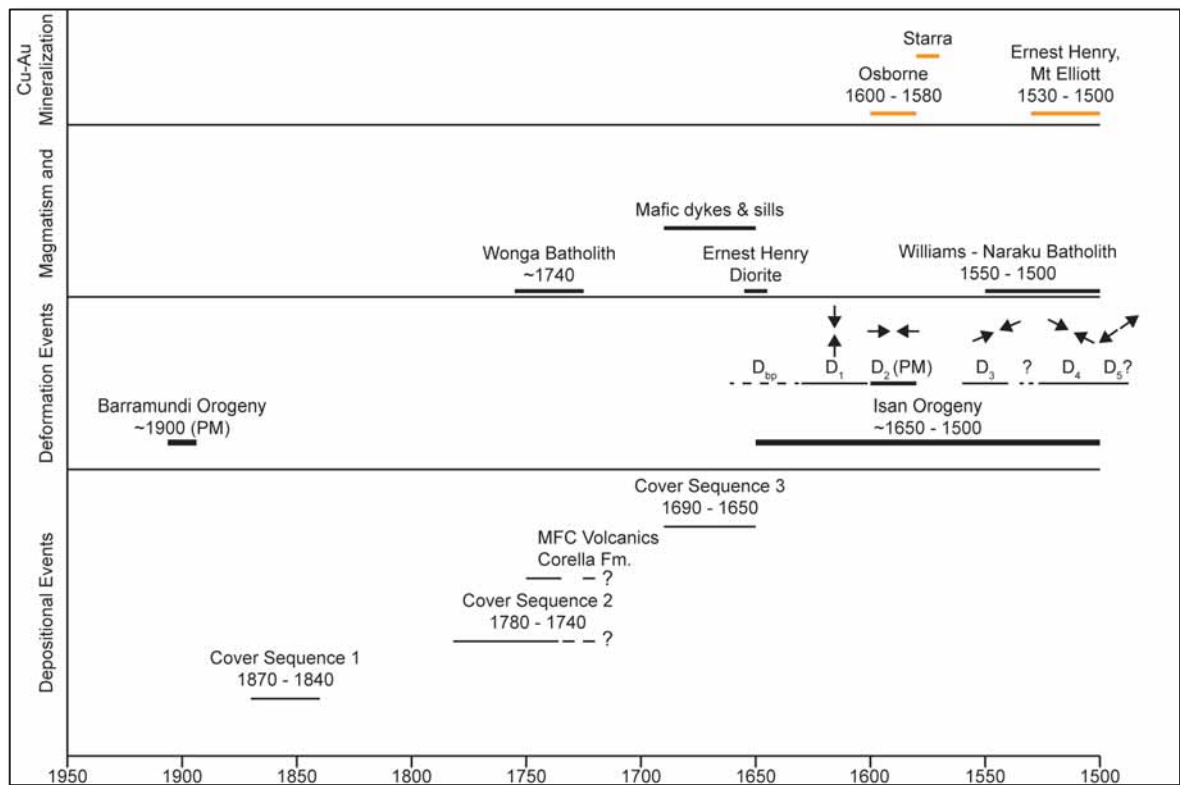


Figure 3.3: Diagram showing the major depositional, deformation, magmatic and mineralization events in the Eastern Fold Belt of the Mount Isa Inlier after 1900 Ma. See text for references. PM, Peak metamorphism.

The D_1 event (1630–1600 Ma; Rubenach et al., 2008) is poorly preserved, and is characterised by east-west folds and steep, east-west S_1 foliation (Bell 1983; Adshead-Bell 1998; Bell and Hickey 1998; Rubenach and Lethwaite 2002; O’dea et al., 2006; Rubenach et al., 2008). The dominant north-south-trending, steep, and upright to vertical folds and fabric recognizable widely throughout the Mount Isa Inlier resulted

from the D₂ (1600–1580) event at amphibolite facies peak metamorphic conditions (Page and Sun 1998; Giles and Nutman 2002; Foster and Rubenach 2006; Rubenach et al., 2008). This was followed by D₃ (1550 Ma; Page and Sun 1998; Rubenach et al., 2008; Duncan et al., 2011) which is characterised by north-northwest-south-southeast-trending folds with steeply dipping axial surfaces and penetrative crenulation of S₂ (Rubenach et al., 2008). Northeast-southwest-trending folds with steep axial surfaces are considered by Rubenach et al., (2008) to be a late D₄ event synchronous with intrusion of the ~1527 Ma Saxby Granite; D₄ may have continued until ~1500 Ma (Davis et al., 2001; Duncan et al., 2011). Some authors (e.g. Beardsmore 1992; Austin and Blenkinsop 2010) have described an even later (≤ 1500 Ma) dominantly brittle event (D₅) characterised by northeast-southwest extension. Major regional structures such as the Cloncurry and Pilgrim faults (Fig. 3.2) likely originated as basin-bounding faults during extension that were subsequently reactivated as reverse or transform structures during the Isan Orogeny (Blenkinsop et al., 2008; Austin and Blenkinsop 2010).

As a result of poor outcrop, deformation in the area northeast of Cloncurry has not been extensively studied, except at isolated deposits such as Ernest Henry (Twyerould 1997; Mark et al., 2000; Coward 2001). Figure 3.4 displays the local deformation schemes interpreted by these authors as correlated to the regional deformation history south of Cloncurry.

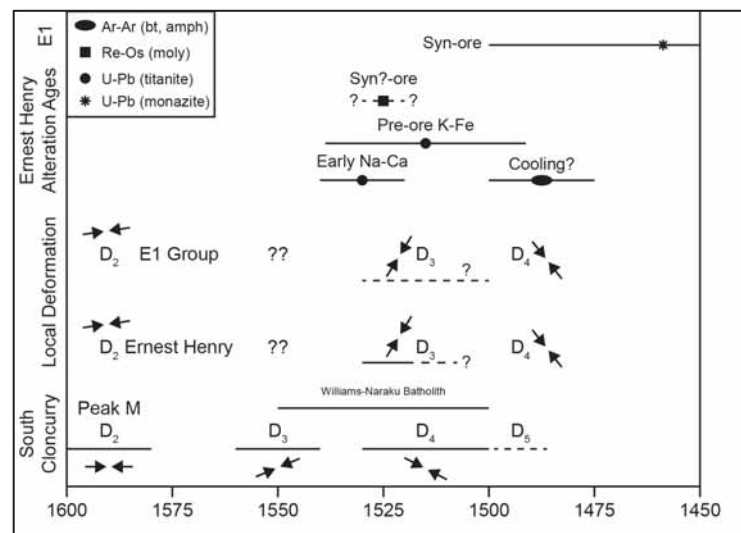


Figure 3.4: A comparison of reported local deformation schemes at Ernest Henry and the E1 Group, with the regional events shown in Figure 3.3. See text for references.

The Ernest Henry deposit is characterised by northeast-southwest-trending brittle to ductile zones (Fig. 3.5A) that are splays of a regional northeast-southwest structure, known as the Ernest Henry Fault (Fig. 3.2). Twyerould (1997) interpreted mineralisation to be of regional D₃ or D₄ timing (Fig. 3.4), and in a compressional setting. The shear zones may be focused around the hinge of a northeast-plunging fold developed in D₂ (Twyerould 1997). Coward (2001) conducted a detailed structural study of the system and interpreted the northeast-southwest-trending structures of the area to have formed during local D₂, including the shear zones which bound the ore breccia (Fig. 3.5). These shears were reactivated and overprinted by local D₃ extensional shearing during mineralisation. The local D₄ event was dominated by brittle reactivation of D₃ faults. Mark et al., (2006b) recognized only the D₁–D₃ events, and correlated them directly to the regional sequence; they interpreted mineralisation as syn-D₃.

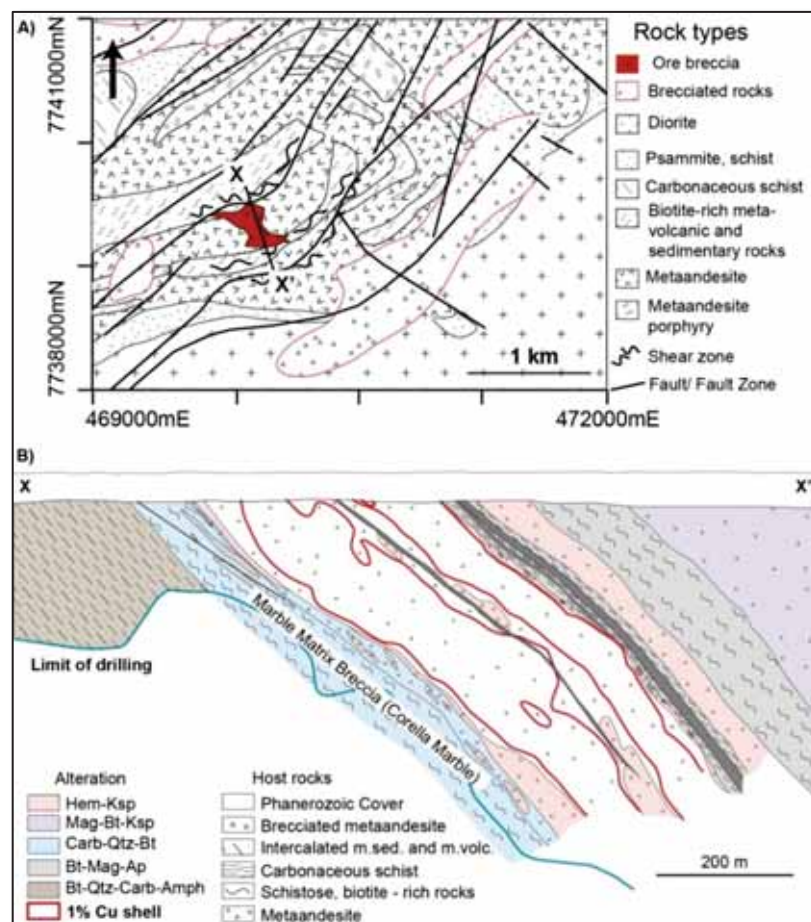


Figure 3.5: Geological map and cross section of the Ernest Henry IOCG deposit. A) Plan view (~50 m ASL) composite based on Twyerould (1997) and Mark et al., (2006b). B) Long section through the orebody modified, with permission, from Coward (2001). Rock type groupings vary between authors. The strongly-foliated, biotite-rich, rocks in plan section (A) correspond with the metasedimentary and metavolcanic rocks in (B). Brecciated rocks in (A) include fractured equivalents of all other rock types. ASL, above sea level.

Late intrusions and IOCG mineralisation

Following peak metamorphism in the Isan Orogeny, voluminous A-type granitoids of the Williams-Naraku Batholith (1550–1490 Ma; Fig. 3.3) were intruded throughout the Eastern Fold Belt (Page and Sun 1998). The closest Williams-Naraku intrusion to the E1 Group is the Mount Margaret Granite, 2 km east of the deposits (Fig. 3.2); it is dated at 1530 Ma (Page and Sun 1998). No other granites are spatially associated with Ernest Henry or the E1 Group; the nearest other granite pluton, the Naraku Granite, crops out 20 km southwest (Fig. 3.2). IOCG-style mineralisation in the Mount Isa inlier occurred over ~100 Myr (1595–1500 Ma): Osborne formed during peak metamorphism at ~1595 Ma (Gauthier et al., 2001) and Starra at 1568 ± 7 Ma (Duncan et al., 2011). Both deposits are interpreted to have formed from metamorphic fluids (Fisher and Kendrick 2008; Duncan et al., 2011). Other IOCGs in the district, such as Ernest Henry and Mount Elliott, formed much later between 1530–1500 Ma (Wang and Williams 2001; Mark et al., 2006b; Duncan et al., 2011), overlapping in time with intrusion of the Williams-Naraku Batholith. These granites have been postulated as one potential source of Cu-Au-bearing fluids for the younger IOCGs (Kendrick et al., 2007; Oliver et al., 2008; Williams et al., 2015).

Host Rocks and Paragenetic Sequence of the E1 Group

The E1 Group is hosted in a sequence of Corella Formation metasedimentary rocks intercalated with intermediate Mount Fort Constantine metavolcanic rocks, both of Cover Sequence 2 (Chapter 2). The host rocks do not crop out and are unconformably overlain by 30–50 m of Mesozoic sedimentary rocks. The metasedimentary rocks comprise marbles, psammites, and carbonaceous metasiltstones and pelites (Fig. 3.6A–C). The metavolcanic rocks consist of basaltic meta-andesite to meta-andesite with variable porphyritic, amygdaloidal and massive textures, as well as metavolcanic breccia and metatuff (Fig. 3.6D–E). The rocks are similar to those that host the nearby Ernest Henry deposit. This metavolcano-sedimentary rock package is intruded by diorite (Fig. 3.6F), which is likely related to the Ernest Henry Diorite suite (~1650 Ma; Page and Sun 1998). Clasts of the diorite are present in albite-hematite-K-feldspar-biotite-altered, discordant, breccia (Fig. 3.6G–I), that cuts across the system (Fig. 3.6I). The discordant breccia is intruded by dolerite dykes of unconstrained age (Fig. 3.6J). Ores are hosted primarily in the metasedimentary rocks (excluding the carbonaceous

pelite), but strongly-sheared metavolcanic rocks are also mineralised in the E1 North Shear zone.

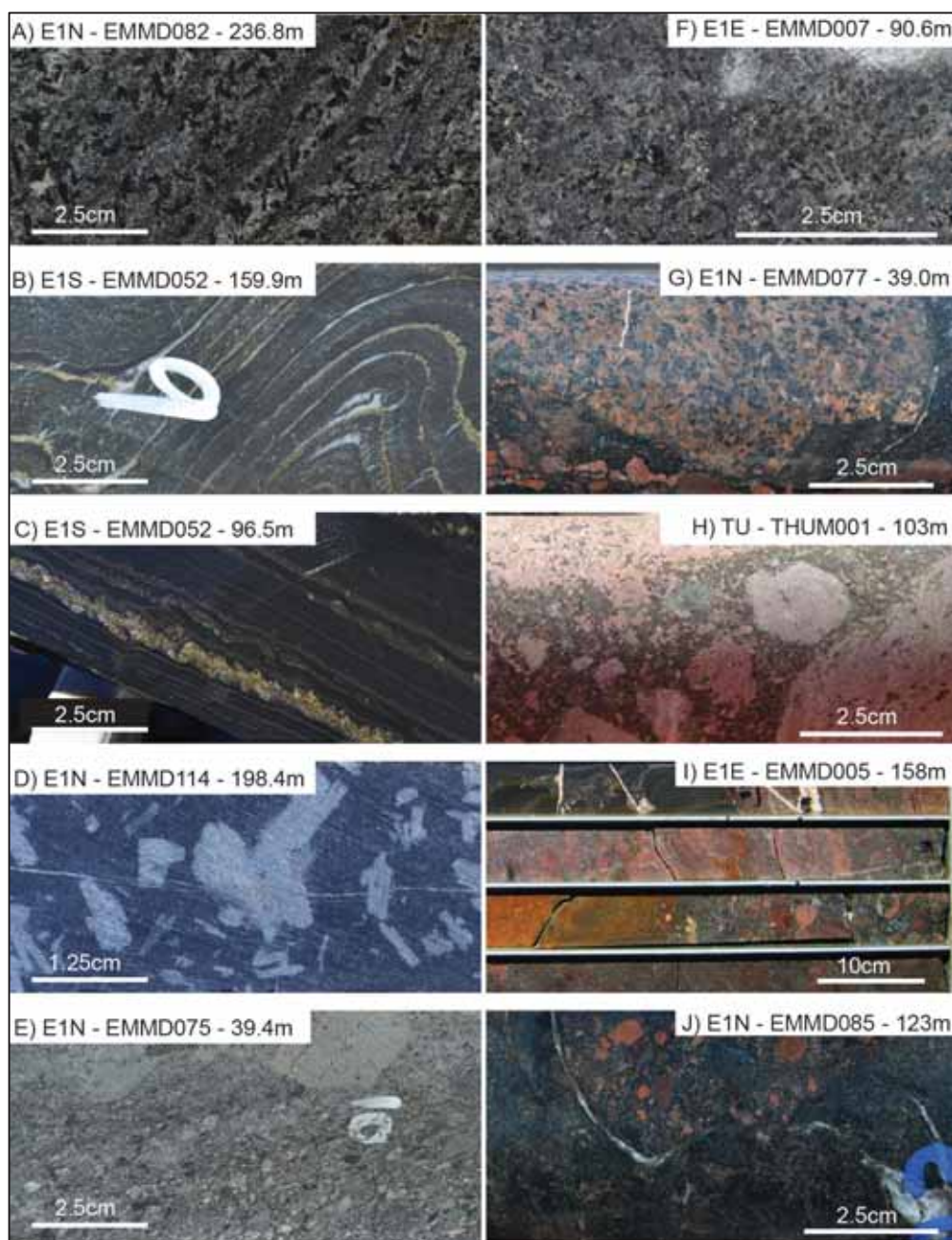


Figure 3.6: Drill core photographs of E1 Group host rocks. A) Porphyroblastic marble with disseminated magnetite and sulfide alteration. Porphyroblasts are chlorite after actinolite. B) Carbonaceous metasilstone with pyrite-carbonate-quartz alteration and veining. Note dilational fold microreefs infilled with carbonate and quartz. C) Carbonaceous schist/phyllite with similar pyrite-carbonate-quartz alteration. D) Representative plagioclase-phyric meta-andesite in the metavolcanic rocks above and below the marble unit in Fig. 3.7. Note slight albite(-hematite) alteration of phenocrysts. E) Metatuff. F) Diorite inferred to be from the Ernest Henry Diorite suite. G) Diorite clast in discordant breccia. H) Less altered discordant breccia from Third Umpire prospect north of Ernest Henry. The matrix is composed mainly of albite, amphibole and pyroxene. (I) Discordant contact of metasilstone (upper right part of core tray) with discordant breccia. (J) Dolerite with discordant breccia xenoliths. E1N, E1 North; E1E, E1 East; E1S, E1 South. Act, actinolite; Cal, calcite; Py, pyrite; Qz, quartz; Bt, biotite; Chl, chlorite; Ab, albite; K-spar, K-feldspar; Px, pyroxene; Dol, dolerite.

Mineralisation at the E1 Group is characterised by layer-controlled replacement of the metasedimentary rocks, accompanied by relatively minor veining (Chapter 2).

Alteration at the E1 Group is complex, and is grouped into three major paragenetic stages, with the second, pre-ore, stage comprising three substages (Chapter 2, Figs. 2.10–2.11). The stages are: 1) early sodic(-calcic), 2a) precursor ferric/ferrous-potassic-silicic, 2b) intermediate sodic (-Ti), 2c) early carbonate (-Fe-Mg) flooding and mineralisation, and 3) main Cu-Au-carbonate(-Fe-Mn)- barite-fluorite-U-REE mineralisation (Chapter 2). This sequence is comparable to that of the nearby Ernest Henry deposit, which suggests similar chemistry of the mineralising fluid(s) in both deposits (Chapter 2). Such similarity, however, does not necessarily indicate a common origin.

3-D Geological Modeling

The development of three-dimensional (3-D) implicit modeling software in the last decade has provided geologists with new means for quickly visualizing the geology of mineralised systems in 3-D space (e.g. Cowan 2003; Alcaraz et al., 2011; Hill et al., 2014; Stewart et al., 2014). The E1 Group represents an ideal study area to conduct implicit modeling for detailed subsurface geological characterisation, as it is sufficiently small and is represented by substantial assay and core photo databases.

Datasets

A 3-D geological model of the E1 Group was generated from a combination of diamond drill hole (DDH) logging, open pit mapping, and ground and aerial magnetic surveys (Figs. 3.7–3.9). Twenty-three diamond holes were physically logged and observations from these holes were used to log lithologies of remaining 260 diamond holes using the core photo database. Structural measurements from oriented drill core were made using a goniometer, and β - α measurements were converted to dip/dip direction using GEOCalculator software (Holcombe, 2013). Geophysical datasets were provided by the mine operator and include a regional aerial magnetic survey with 50 m flight and 500 m tie-line spacing (Fig. 3.8), as well as a ground magnetic survey across the E1 Group with 50 m line spacing (Fig. 3.9). All drill hole and geophysical datasets were converted to GDA 94 projection.

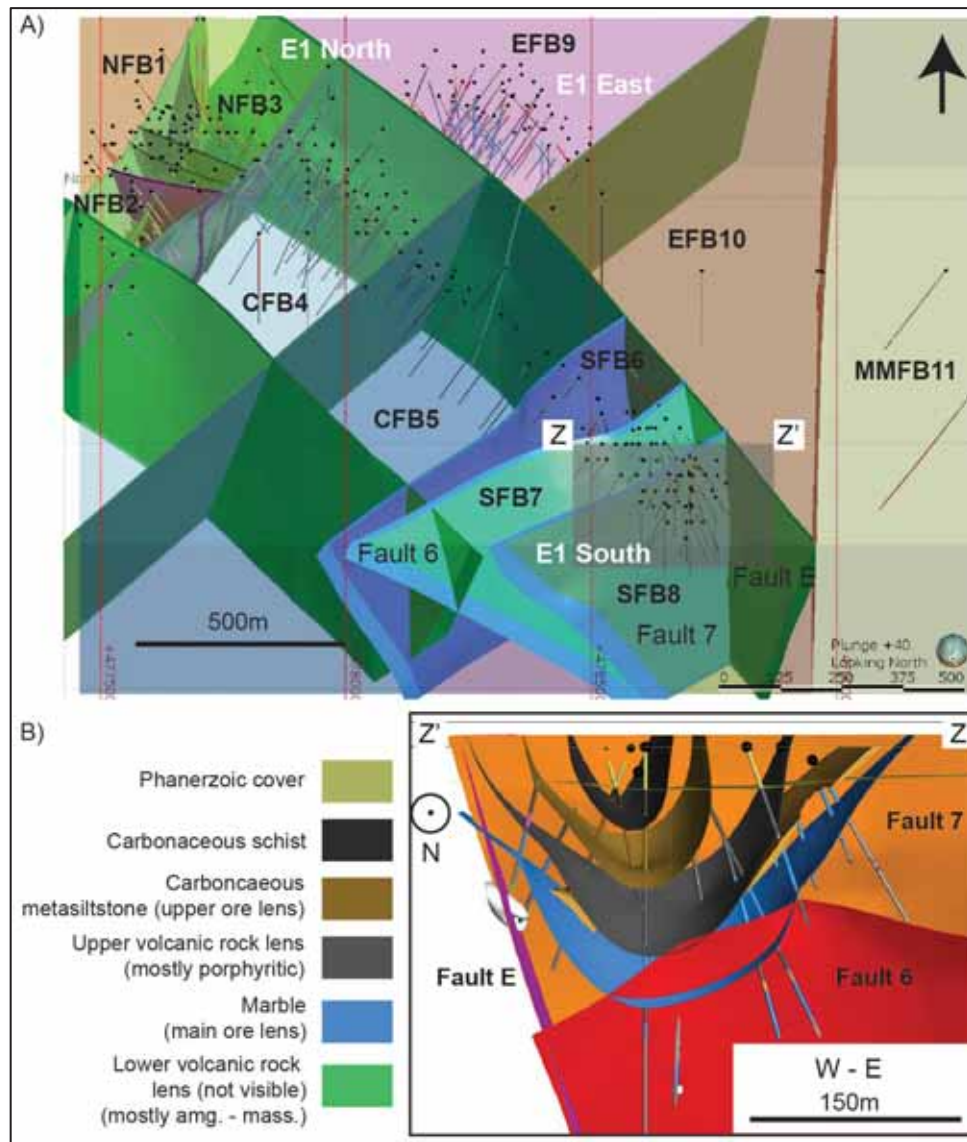


Figure 3.7: A) Rendered image of the diamond drill hole dataset used for geological modeling, along with the modeled 'Fault Block' volumes generated from interpreted faults (see Fig. 3.10). Geochemical modeling parameters vary for each fault block (see Table 3.2). B) Vertical, west-east cross section of the E1 South synform (location shown in A), showing an example of isosurfacing in the South fault blocks with the 'Stratigraphy' function in Leapfrog (isosurfaces are not shown in (A)). See Fig. 3.6 for host rock descriptions. FB, fault block; N, north; S, south; E, east; C, central; MM, Mount Margaret.

Geological modeling parameters

Geological and numerical geochemical modeling were conducted in Leapfrog Geo 2. Geological contact surfaces for the metasedimentary and metavolcanic rock sequence were modeled using the Stratigraphic Sequence function (Fig. 3.7B). Discontinuous metatuff lenses in this stratigraphy were modeled as veins. The diorite, discordant breccia, and dolerite lithologies were modeled in that order as intrusions cutting across the stratigraphy. Extensive shearing and metasomatism in the western portion of the E1 North orebody has obscured clear identification of protoliths; as a result, some of the

rocks in this area were classified as ‘sheared sedimentary rocks’ (Fig. 3.10) when continuous layering was observed, or as ‘sheared sedimentary and volcanic rocks’ when layering was discontinuous or relict volcanic textures were observed (Fig. 3.10). The discordant nature of the shear zones necessitated modeling of these zones as intrusions, and structural anisotropic trends were applied to the shear zones in order to accurately represent their orientations. The model was subdivided into 11 fault blocks (Fig. 3.7A). A cutaway of the model is displayed in Figure 3.11.

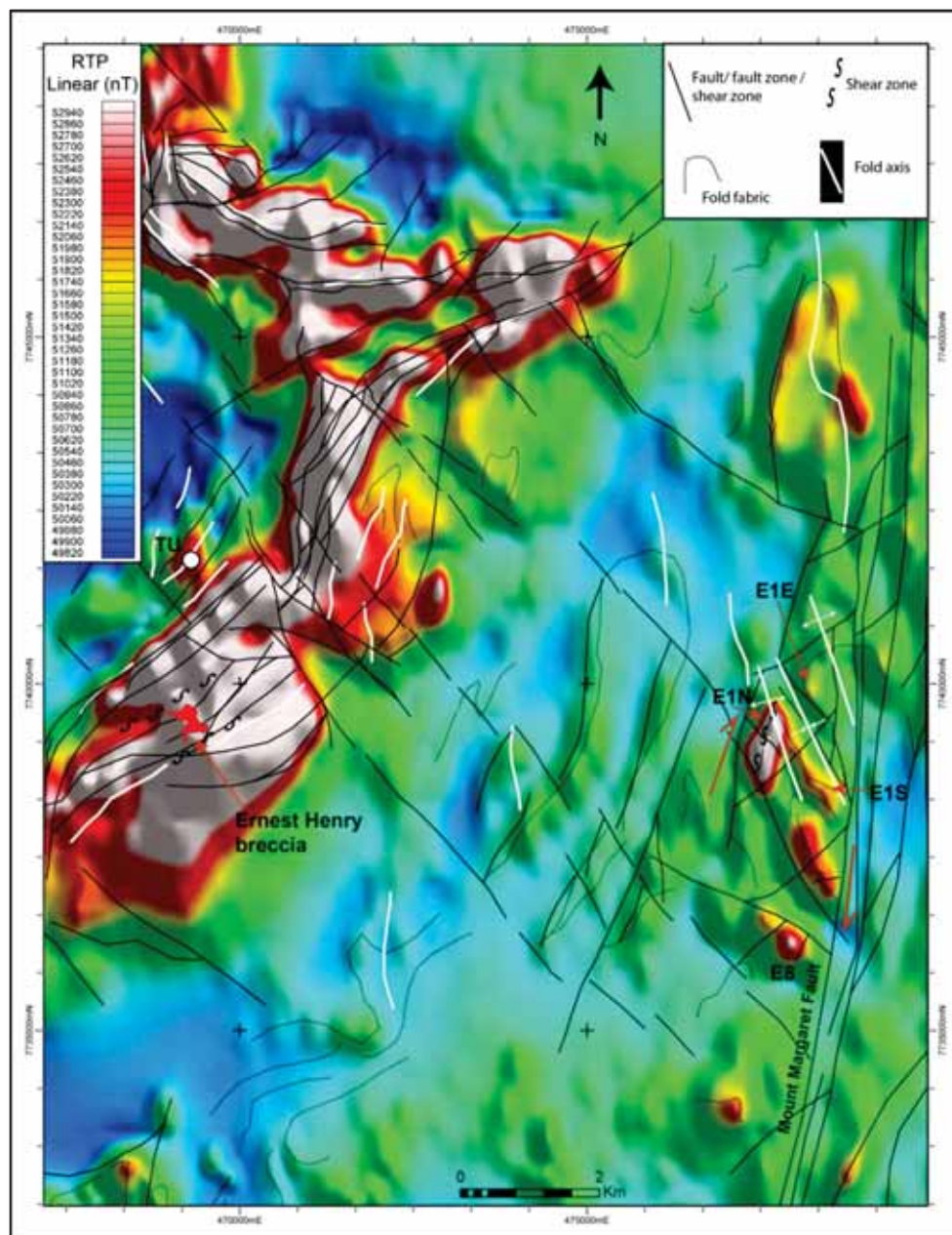


Figure 3.8: Structural interpretation of the Ernest Henry-E1 Group area. Reduced to Pole (RTP) aerial Total Magnetic Intensity (TMI) image. Data from Xstrata Copper Exploration (Glencore). Converted to GDA 94 projection.

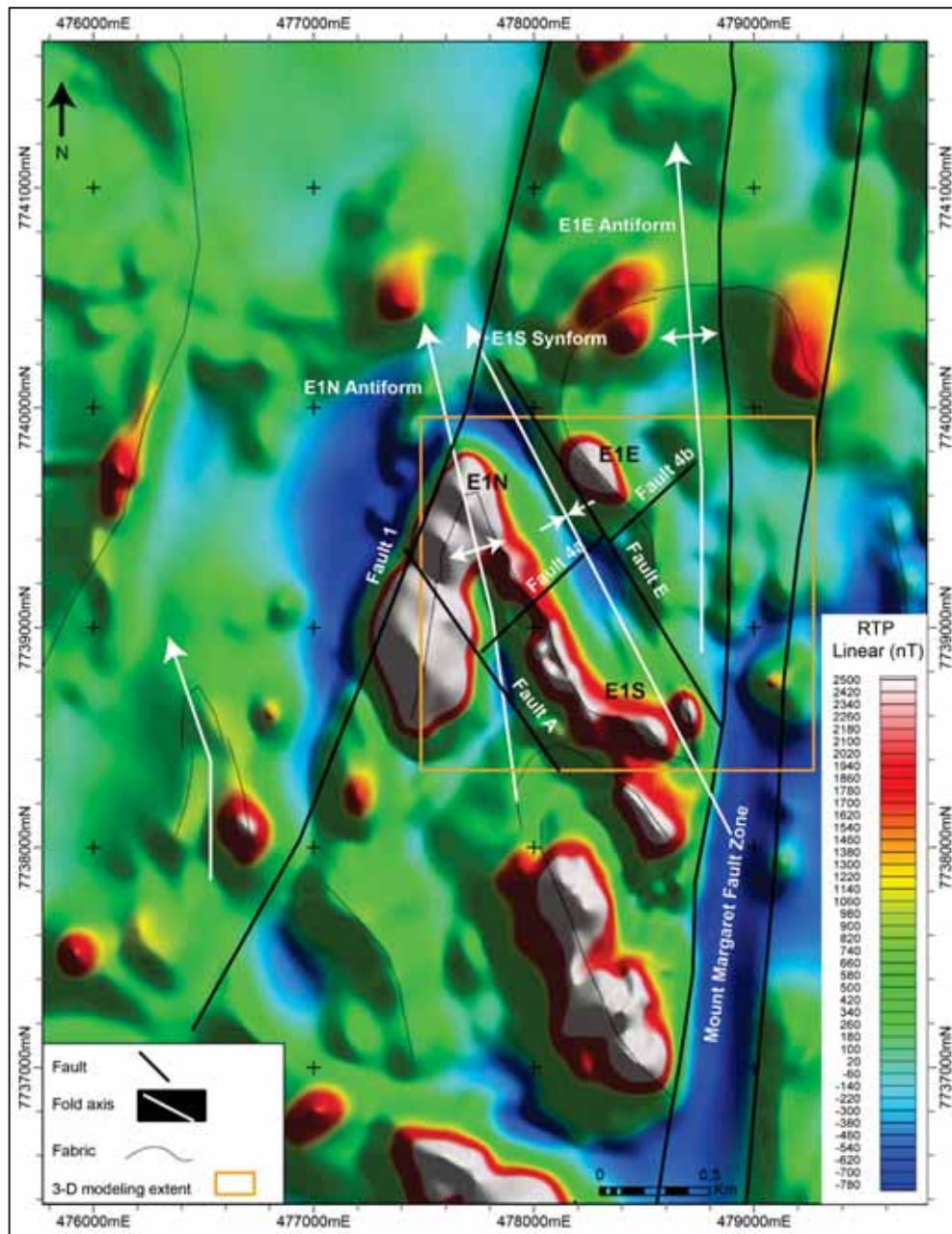


Figure 3.9: Structural interpretation of E1 Group area. Based on RTP aerial TMI survey conducted using 50 m flight line and 500 m tie-line spacing with 25 m clearance. Data from Xstrata Copper Exploration (Glencore), and converted to Geocentric Datum of Australia (GDA) 94 projection. E1N, E1 North; E1S, E1 South; E1E, E1 East.

E1 Structural Geology

The E1 Group does not outcrop, and as a result the understanding of its structures comes mostly from 3-D modeling derived from drill core and limited mapping of the orebody periphery in the E1 North open pit.

Deposit geometry and macrostructures

The topography of the Proterozoic-Mesozoic unconformity forms a ~10 m culmination over the E1 North orebody. The general geometry of the E1 Group orebody is characterised by northwest- to north-northwest plunging similar, open folds with near-vertical axial surfaces (Figs. 3.10–3.12). E1 North is hosted near the hinge of a north-northwest-plunging antiform, and the eastern limb of the antiform transitions into the west limb of the northwest-plunging E1 South synform which contains the E1 South orebody. The metasedimentary rock layers thin substantially on the limb connecting the folds, and the marble layer appears to pinch out on the west limb of the E1 North Antiform although it may be obscured by the intense shearing and metasomatism in that zone. Drilling indicates that the E1 East orebody dips steeply to the east, and regional aerial magnetic data suggest that it is part of the overturned southwest limb of the north-northwest-plunging E1 East Antiform (Fig. 3.9). This antiform continues from the east limb of the E1 South Synform and the thickness of the metasedimentary rocks increases between E1 South and E1 East. The metavolcanic sequence present between the marble and metasilstone units at E1 North and South is mostly absent at E1 East with the exception of some isolated pods of porphyritic metavolcanic rocks.

The folds are cut by several faults of multiple generations (Table 3.1). The E1 North Antiform is cross-cut by a series of northeast-southwest-trending, northwest-dipping, shear zones collectively referred to as the E1 North Shear Zone (Figs. 3.13; 3.14A–B). The most intense shearing in this zone is mostly developed in marble, metatuff and metavolcanic breccias, but some shear fabric is also developed in the coherent porphyritic and amygdaloidal metavolcanic rocks (Figs. 3.13C; 3.14A; 3.15B). A combination of high strain and metasomatism associated with the E1 North Shear Zone, coupled with significantly deeper weathering, have inhibited clear protolith identification within some portion of the shear zone (e.g. Figs. 3.15B; 3.17C). As a result, it is not certain whether the Corella marble horizon pinches out on the west limb of the antiform, or is simply obscured by alteration and shear fabrics (see next section). Drill core observations from within the shear zone yield shear senses in multiple directions, possibly due to reactivation, causing ambiguity regarding the deposit-scale sense of movement. However, an isolated lens of mineralised Corella marble adjacent to the main lens probably moved down and to the west with respect to the main horizon, suggesting a normal component of shear.

Table 3.1: Summary of the E1 Group deposit-scale structures

Structure	Width (m)	Dip (°)	Dip Direction (°)	Length (m)	Type	Displacement (m)	Evidence for movement	Earliest local timing	Local reactivation timing / Type	Association with ore or alteration	Timing relative to ore	Regional timing	Comments
Fault 1	≤1	~85	107–125	>1 x 10 ⁴	normal and dextral slip	unclear	steep dip, association with steeply-dipping veins; breccia offsets	likely D ₃	unclear, possibly D ₄	bounds mag-ap zone	syn	D ₄	may have been active in D ₂ , based on lateral extent
Fault 2	≤1	~70	294–266	~900	normal	~10	steep dip, association with steeply-dipping veins; modeled rock offsets	D ₃	D ₄ / reverse, possibly dextral	partly coincident with Cu; bounds mag-ap zone	syn; react. post syn;	D ₄	-
Fault 3	≤1	~70	307–294	~500	normal and dextral? slip	~10		D ₃	D ₄ / reverse, possibly dextral		react. post	D ₄	-
Fault 4 a–b	≤1	76	307	>2 x 10 ³	possibly sinistral?	10–20	modeled offset of metasiltstone	likely D ₃	unclear, possibly D ₄	not coincident	syn to post	D ₄	inconsistent sense of offset
Fault 5	≤1	70	130	>950	mainly reverse?	>>10 dip-slip, unclear strike-slip	modeled offset of metasedimentary rocks	D ₄	unknown	offsets Cu and alteration	post	D ₅	variable thickness of metasedimentary rock layers inhibits sense of strike-slip movement
Fault 6	≤1	50	130–145	>900	reverse and sinistral	>30 dip-slip, ~30 strike slip		D ₄				D ₅	-
Fault 7	≤1	62	140	>640	reverse and dextral	<10m		D ₄				D ₅	-
E1N Shear	~200	~70	~295	>500	normal	unclear	steep dip and offset of marble, association with steeply-dipping veins and shear fabric	D ₃	associated faults: F1, F2, F3, react. in D ₄	coincident with Cu and mag-ap zone	syn	D ₄	brittle-ductile structure related to F1, F2, F3
Fault A	unclear	74	237	>1.5 x 10 ³	unclear	unclear	N/A	D ₃	unclear	unclear	syn?		recognized in aeromag and drill core intersects
Shear B	≤2	76	36	~240	strike-slip?	minor, <1	does not offset F1-F3	D ₃	unclear	coincident with Cu and mag	syn		conjugate to E1N Shear and F1–F3
Shear C	≤3	72	32	~250		minor, <1	does not offset F1-F4	D ₃					
Shear D	≤4	71	16	~260		minor, <1	does not offset F1-F5	D ₃					
Fault E	≤5	73	242–228	2 x 10 ³	mainly strike-slip; sinistral (early) and dextral (late)	>100?	modeled offset of metasedimentary rocks; aeromag	D ₃	D ₄ / dextral	not coincident, truncates E1 South orebody; unclear if it truncates F5–F7	syn to post	D ₄	offset of rock layers is sinistral, but offset of F4 is dextral
MM / C FZ	10 - 20	sub-vert.	N/A; trends ~N-S	>5 x 10 ⁴	normal; later reverse, strike-slip	>>100	aeromag; Austin and Blenkinsop, 2010	syn-dep.	D ₂ / reverse D ₃ / dextral D ₄ and post D ₄ / unclear	not coincident	pre syn post	D ₂ D ₄ D ₅ and post-D ₅	offsets Mesozoic cover; pre-Isan basin-bounding fault

Mag, magnetite; ap, apatite; MM / C FZ, Mount Margaret / Cloncurry Fault Zone; dep., depositional; react., reactivated

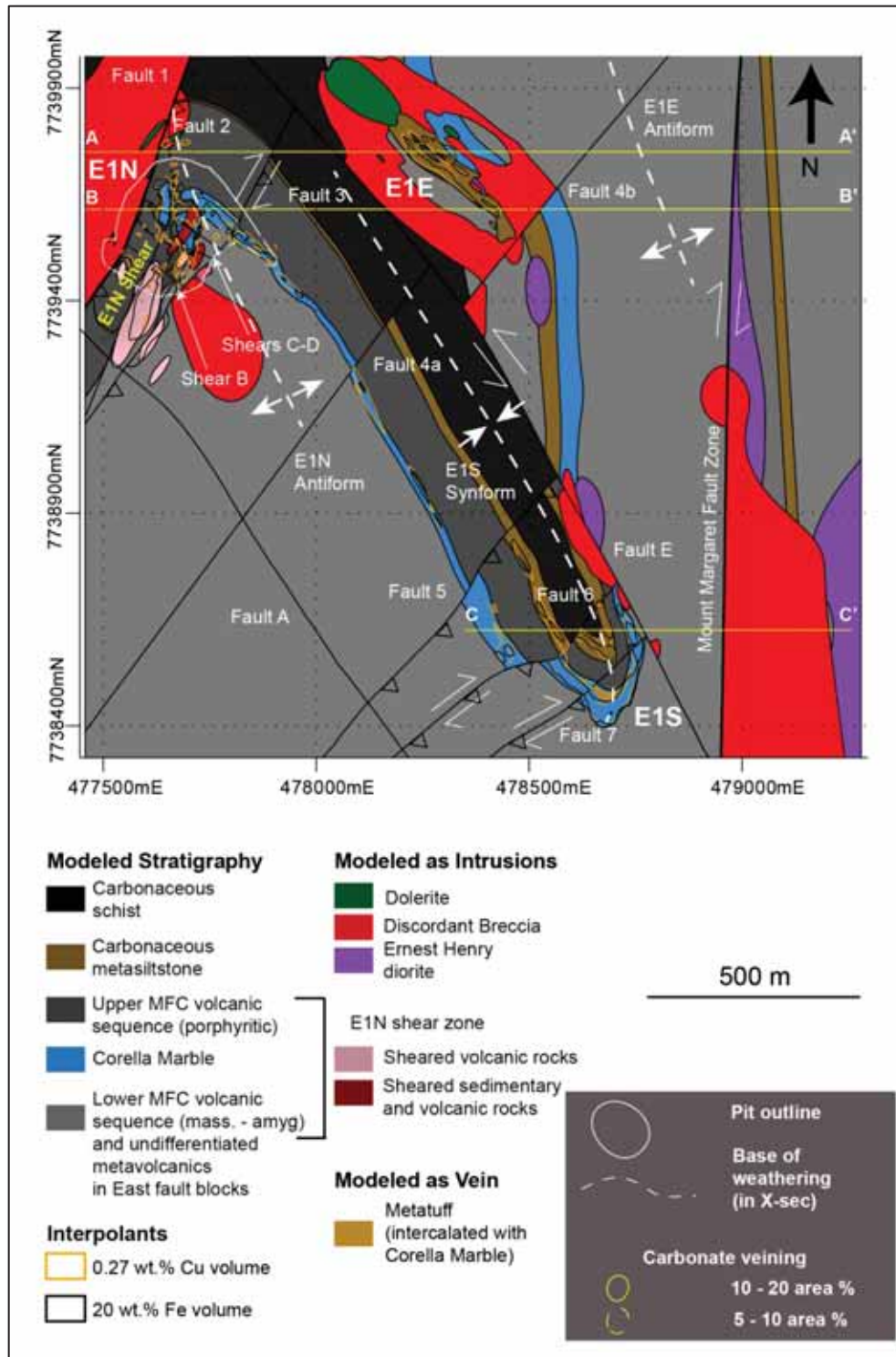


Figure 3.10: 2075 m RL / 75 m ASL plan section of the E1 Group rendered from the 3-D geological model (extent shown in Fig. 3.9), showing the rock types, major folds, faults, and shear zones of the E1 Group. The metatuff is conformable, but was modeled as a 'Vein' in the Leapfrog software because of its lateral discontinuity. Copper and iron outlines are sections rendered from the modeling interpolants in Fig. 3.18. GDA 94 projection. RL, relative level mine datum; ASL, above sea level.

The E1 North Shear Zone is coincident with mineralisation and, southwest of the orebody, alteration in the shears transitions from laminated magnetite-barite-fluorite-chalcopyrite ore into massive magnetite $\pm$ apatite $\pm$ pyrite (Fig. 3.14). Shear zones B–D (Fig. 3.10; Table 3.1) trend northwest-southeast and dip $\sim 70^\circ$ northeast; they are nearly perpendicular to the E1 North Shear Zone. These shears do not offset the E1 North Shear Zone, and are therefore interpreted to represent shear zones conjugate to the E1 North Shear Zone. The conjugate structures are also coincident with mineralisation observed in the open pit (Fig. 3.13A) and modeled Cu-Fe mineralisation (see next section; Figs. 3.14B; 3.18H). The presence of these conjugate shear zones implies a component of strike-slip movement in the E1 North Shear Zone. The E1 North Shear Zone and its conjugate shear zones (shears B–D; Fig. 3.10) are bounded by parallel northeast-southwest-trending faults with variable dip-slip and strike-slip components (Figs. 3.13D; 3.14A–B). The faults coincide with changes in rheology caused by abrupt transition from magnetite dominated to albite-quartz dominated alteration. Fault 1 dips steeply southeast at 85° , while Fault 2 and Fault 3 dip 60° – 70° northwest. Fault 1 is clearly traceable in reduced to pole total magnetic intensity (RTP-TMI) for over 2 km north and south of E1 North (Fig. 3.9). Modeling of rock type offsets indicates reverse net slip of up to 20 m along these faults. Fault 3 is also characterised by ~ 20 m of dextral movement.

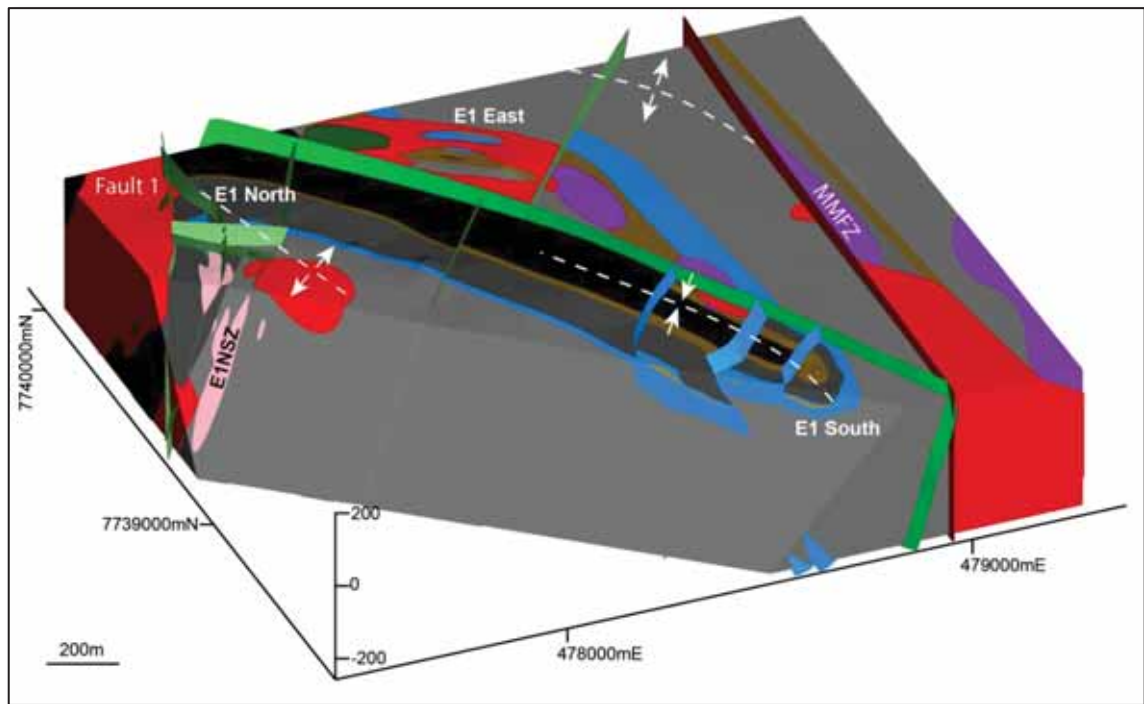


Figure 3.11: Three-dimensional cutaway of E1 Group 3-D geological model, showing the major D_2 folds that define the E1 North and E1 South orebody geometries. Red faults are syn- D_2 or pre- D_2 . Green faults are syn- (local) D_3 and later. Blue faults are syn- (local) D_4 and later. Vertical axis is elevation above sea level (m). See Fig. 3.10 for legend. GDA 94 projection.

E1 South Faults 5–7 (Figs. 3.10; 3.14D; Table 3.1) exhibit reverse and strike-slip separation, and dip from $\sim 80^\circ$ to 60° to the southeast. Kinks in Faults 5 and 6 are interpreted to have been caused by rheological contrast between the ductile marble and brittle coherent metavolcanic layers. Unlike the E1 North faults, these structures do not coincide with high Cu-Fe concentrations or shear zones, and they offset all alteration. A major northwest-southeast trending fault (Fault E; Fig. 3.10) separates E1 East from E1 North and South. Truncation of the metasedimentary rock horizon hosting the E1 East and E1 South orebodies by Fault E suggests strike-slip movement along this structure of hundreds of meters. Fault A (Fig. 3.10) is inferred mainly from aeromagnetism and its offset is not clear. Faults 4a and 4b likely represent a single northeast-southwest structure offset by Fault E.

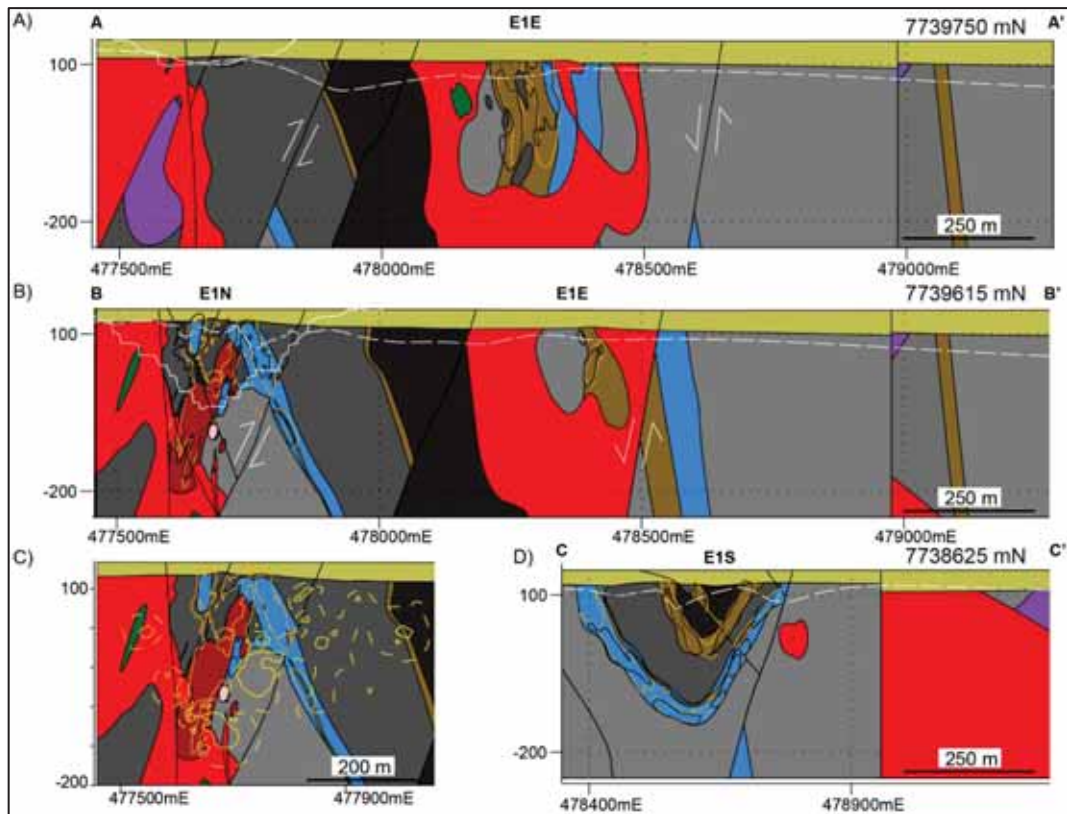


Figure 3.12: Cross sections of the E1 Group Geological model along lines shown in Fig. 3.10. A) A–A', E1 East. B) B–B', E1 North. C) Inset of B–B' showing contours of abundance of carbonate veining. D) C–C', E1 South. Vertical axis is elevation ASL (m). See Fig. 3.10 for legend. White solid and dashed lines are the E1 North open pit outline and depth of highly-weathered rock, respectively.

The detailed structure of E1 East is not well-constrained, but core logging indicates that the metasedimentary rocks are strongly sheared throughout the system. The scale and sense of the shearing are not clear. Copper-iron interpolants at E1 East (see 3-D Concentration Distribution section) follow the distribution and attitude of the metasedimentary rocks, and no northeast-southwest-trending structures are apparent, suggesting that the E1 East shear zone parallel to bedding on the western limb of the E1 East Antiform. The upper volcanic rock layer (Figs. 3.7; 3.10) which separates the Corella marble and metasiltstone horizons at E1 South is mostly absent at E1 East, and the entire metasedimentary rock sequence is nearly twice as thick at E1 South. Isolated pods (> 20 m) of cohesive metavolcanic rocks within the metasedimentary rocks at E1 North and East (texturally identical to the continuous sequences) may represent large-scale boudins within this shear zone (Fig. 3.14C).

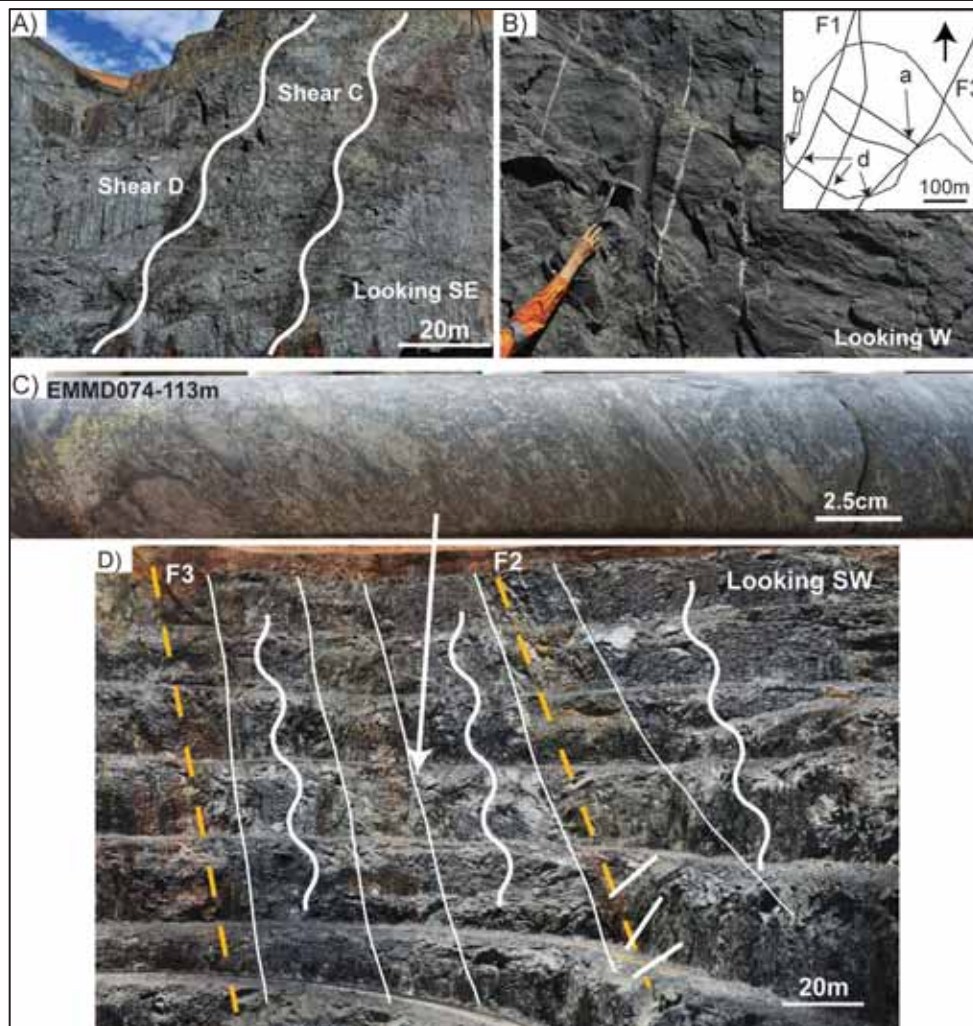


Figure 3.13: E1 North fault and shear structures visible in the E1 North open pit. A) Fault/shear zones C and D (see Fig. 3.10). Dark material is magnetite alteration. B) Sub-vertical carbonate $\pm$ fluorite $\pm$ barite $\pm$ sulfide tension veins near Fault 1. C) Photograph of a drill core intersection of sheared metavolcanic breccia in the E1 North Shear Zone. D) Three magnetite-pyrite-apatite-altered shear zones (white outline) of the E1N Shear Zone exposed in the southwest wall of the E1 North open pit. Arrow indicates approximate location of the drill core intersect in (D). These correspond to the modeled linear zones of high (> 20 wt%) Fe shown in Figs. 3.14A–B and 3.18H. Straight white lines indicate $\sim 45^\circ$ dipping carbonate veins associated with Fault 2. The orientation of these veins and those in (B) suggest extensional or normal movement along the faults and shear zones during mineralisation (local D_3); reverse movement took place in local D_4 after mineralisation.

Meso- and micro-scale structures

Ductile structures are prevalent in metasedimentary rocks throughout the study area.

Close to open, asymmetric folds with < 10 cm to > 10 m wavelengths are common. The northwest-southeast to southwest-northeast trend of their hinge surfaces (Fig. 3.16B) is consistent with that of the E1 North Antiform and E1 South Synform and they are considered to be parasitic. The variations in dip and strike of some of the axial surfaces may be due to refolding (see Deformation sequence below). Sporadic flaser cross-bedding (Fig. 2.5G; Chapter 2) found in E1 East metasedimentary rocks indicates that some bedding is overturned by < 10 m-scale folding. Disharmonic folding of siliceous

and pelitic layers within the metasiltstone has formed dilational zones in the fold hinges infilled with carbonate, quartz and sulfide (Fig. 3.6B). Microfaulting is abundant in the metasedimentary rocks and is typically associated with boudinage of siliceous layers in between calcareous and pelitic layers. The geometry of, and distance between, boudins at the drill core scale are variable, with thicker beds with relatively narrow (< 5 cm) zones of infill between boudins, (Fig. 3.15A) and others completely fragmented into breccia-like textures surrounded by shear fabric. These pseudo-breccia textures are nearly identical to those observed in the Marble Matrix Breccia at Ernest Henry (Twyerould 1997; Marshall and Oliver 2008), and are common in Cover Sequence 2 rocks across the Eastern Fold Belt. The boudins are typically sheared and imbricated. Foliation is widespread across the E1 Group and is generally restricted to metasedimentary rocks except in high-strain zones like the E1 North Shear Zone. The foliation is defined by mica but in highly-mineralised zones it is defined by sulfide and magnetite alteration. Kinematic indicators in coarse-grained clastic rocks (Fig. 3.15B) indicate that much of this foliation in the E1 North Shear zone formed by normal shearing, but the nature of foliation in marble and other metasedimentary rocks is less clear.

Veins are ubiquitous across the deposit, but contain less ore compared to bedding and foliation replacements. Early, small (< 10 cm), irregular, Stage 1 albite and Stage 2 K-feldspar veins are common, and are less voluminous than later stages. Stage 2 magnetite and biotite veins are typically less than 1 cm thick, although the boundary between magnetite veins and magnetite alteration is usually impossible to distinguish. Indeed, much of the magnetite is characterised by massive texture and cannot be linked to obvious conduits at sub-meter scales. Albite, K-feldspar, hematite and biotite veins are generally absent in the discordant breccia, though it is extensively altered by these same minerals. Stage 2c and Stage 3 carbonate veins are found throughout the mine lease and extend beyond drilling; they are volumetrically the dominant vein stages. They range in apparent width in drill core from sub-millimeter to > 5 m. Within and proximal to the ore zone, the Stage 3 carbonate veins host barite, fluorite, chalcopryrite, and pyrite. Carbonate, fluorite and barite in these veins are typified by large (10–50% of the vein width), euhedral crystals; the relative locations of these minerals within veins varies considerably (e.g. Fig. 2.7, Chapter 2). Where growth directions of these minerals are visible, they are generally normal to the vein wall (not shown). Carbonate veins are

most abundant in the brittle metavolcanic rocks and discordant breccia, and can transition into breccias near the contacts of mineralised metasedimentary rocks (Chapter 2; App. E). Stage 3 carbonate veins typically form conjugate sets and the orientation of carbonate veins is shown in Figure 3.16D. These veins are typically subvertical, though some are moderately dipping, and some of the larger veins (up to 1 m thick) appear to be linked to Faults 1 and 3 in E1 North (Fig. 3.13D). However, the veins frequently reopen, partially, the fractures of earlier feldspar, magnetite and biotite veins and metamorphic fabrics resulting in visually variable orientations (not shown). Some microveins, defined herein as having widths less than 5 mm, follow bedding and are difficult to distinguish from layer-parallel alteration when obscured by sulfide selvages.

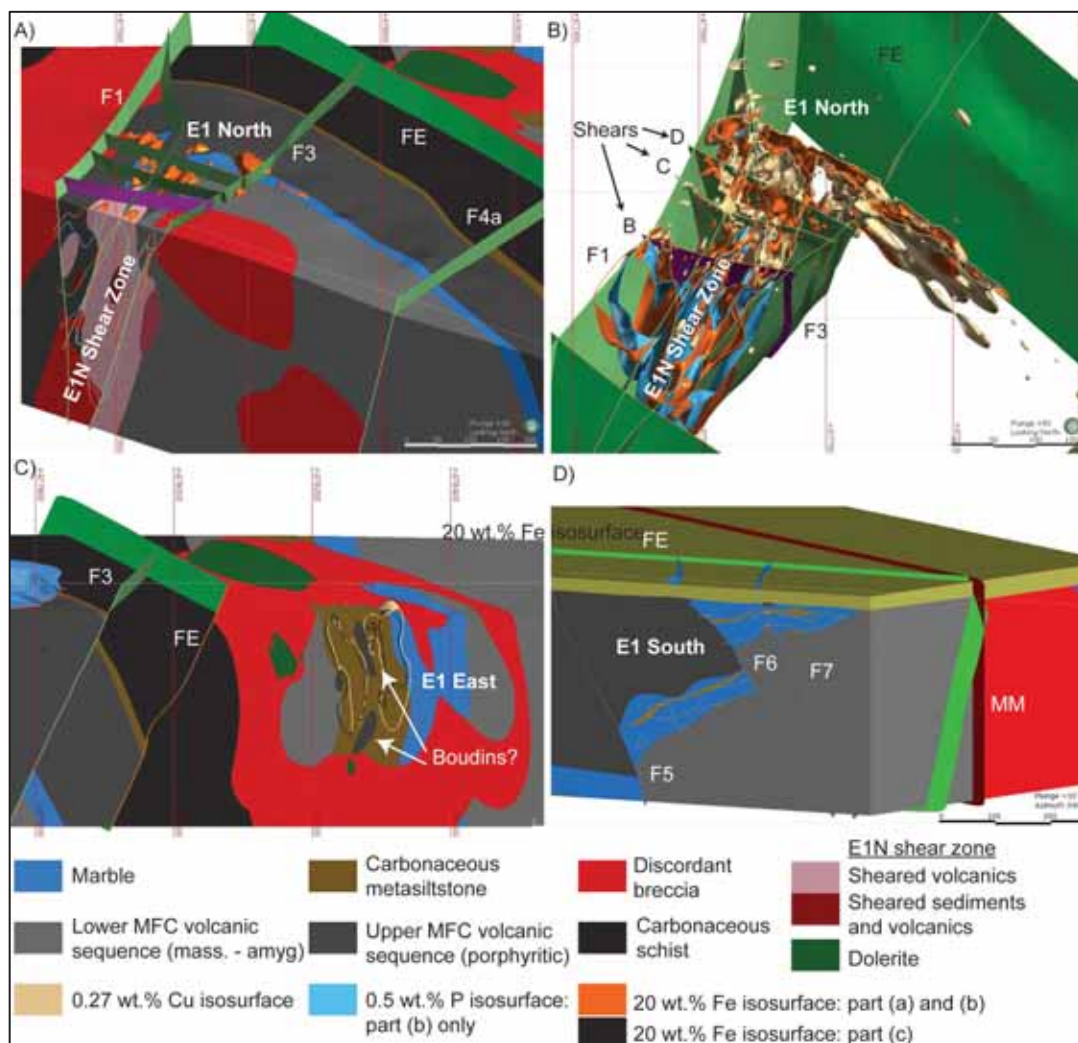


Figure 3.14: Deposit-scale structures of the E1 Group. A) E1 North Shear Zone and associated Fe-P (magnetite-apatite) alteration zones. B) Horizontal slice showing zonation along E1 North Shear Zone from Cu orebody to Fe-P (magnetite-apatite) zone. C) Slice through E1 East orebody showing boudinaged? porphyritic metavolcanic rocks within the metasiltstone ore lens. D) Slice, looking 040, through E1 South showing offset of Cu-Fe mineralisation by D₄ Faults 5–7. Note that Cu concentrations are higher below the metatuff lens. GDA 94 projection.



Figure 3.15: Small-scale structures. A) Boudinage of silica-rich layers in siliceous marble. Note carbonate-fluorite-pyrite-chalcopyrite veins forming boudin necks. B) Sheared metavolcanic breccia? or siliceous metasedimentary rock. Groundmass is entirely pyrite-magnetite-chalcopyrite-barite-albite-fluorite-altered. C) Dilation in magnetite-altered marble with magnetite-pyrite-chalcopyrite infill, associated with faulting and shearing? Ccp, chalcopyrite; Mag, magnetite; Bar, barite; Fluo, fluorite; Py, pyrite. The kinematic indicators are sinistral but the lack of oriented core inhibits determination of their true sense.

Deformation Sequence

The deformation events presented in this section refer to local events in the E1 area, except in instances where a regional correlation is explicitly made. Correlations between E1 and regional deformation are discussed later.

D₁ and D₂ and earlier deformation events

The earliest deformation in the E1 Group area is represented by foliation sub-parallel to compositional layering preserved in some pelitic metasiltstones (Fig. 3.17A), and is interpreted as an S₁ fabric formed during local D₁. This fabric is largely obscured by D₂ and D₃ fabrics. The most prominent D₂ structure is the Mount Margaret Fault, which is

a first-order, north-south-trending, structure clearly visible in aerial RTP-TMI over 20 km north and south of the E1 Group (Fig. 3.8). It is the only structure in the vicinity of the E1 Group that clearly offsets the Mesozoic cover. Blenkinsop et al., (Fig. 10A; 2008) implied, based on geophysical interpretations, that the Mount Margaret Fault represents a northern equivalent of the regional Cloncurry Fault structure, which probably originated as a syn-depositional basin-bounding normal fault and was subsequently reactivated as a major thrust during regional D₂ and later episodes of the Isan Orogeny (Austin and Blenkinsop 2008; Blenkinsop et al., 2008; Austin and Blenkinsop 2010). The possibility that Fault 1 was also active during D₂ cannot be precluded. D₂ also formed the S₂ foliation which is dominant throughout the E1 Group area. S₂ foliation is defined by mica cleavage in pelites as well as flattening and alignment of metavolcanic breccia clasts and amygdules (Fig. 3.17B). Fine-grained (< 100 µm), highly-deformed quartz veins, up to 1–2 cm thick, are present in some schists and are folded into alignment with S₂, and are interpreted to represent pre- to early syn-metamorphic veining. S₂ trends north-northwest-south-southeast and dips subvertically either east-northeast or west-southwest (Fig. 3.16A), and is typically parallel to axial surfaces of parasitic macrofolds observed in drill core (Fig. 3.17D). Primary flow textures are preserved in most plagioclase-rich metavolcanic rocks, implying that they were not highly penetratively strained during D₂. Development of S₂ foliation was concurrent with formation of the deposit-scale folds, which were caused by east-northeast-west-southwest crustal shortening. The orientation of S₂ and the folds are similar to D₃ fabric reported by Rubenach et al., (2008); this event, however, did not produce major folding in the Eastern Fold Belt and D₂ structures at the E1 Group most likely correspond to regional D₂ and peak metamorphism. The lack of unaltered host rocks in the E1 Group drilling area has inhibited estimation of the peak metamorphic grade reached in the deposit, but it is inferred to be amphibolite facies like Ernest Henry 8 km to the west (Mark et al., 2006b).

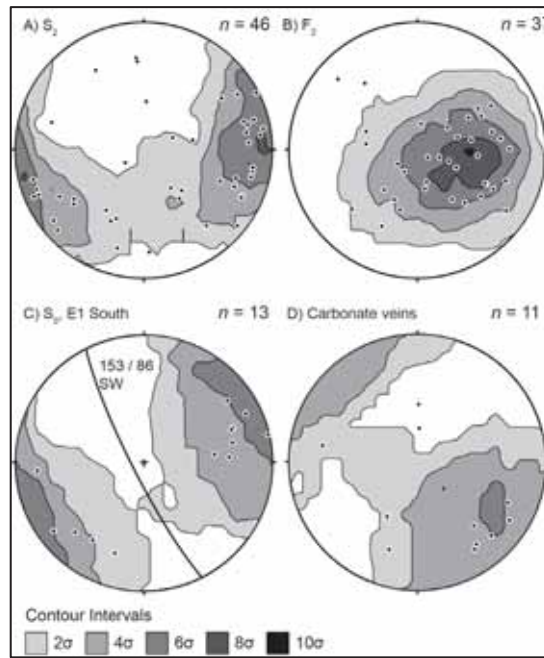


Figure 3.16: Poles of drill core structures plotted on equal-area southern hemisphere projection stereoplot. Contours based on the Kamb (1959) method. A) Poles to S_2 fabric associated with D_2 , generally axial planar to F_2 folds. B) Poles to F_2 fold axes. C) Poles to bedding from both limbs of the E1 South synform and calculated axial plane of the synform. D) Poles to orientations of Stage 3 carbonate veins.

D_3 deformation event

The E1 North Shear Zone, which cuts across the E1 North Antiform formed during D_2 , represents a D_3 structure. The limited amount of ductile strain and abundance of veins in the metavolcanic rocks suggest that the E1 North Shear Zone, its bounding faults, and associated Stage 3 veins are a collective brittle-ductile zone. Stage 3 carbonate veins exposed in the E1 North open pit near Fault 3 are mostly subvertical and dip southeast (Fig. 3.13B), though some of the larger veins (up to 1 m thick), observed in drill core and modeled, dip $\sim 60^\circ$. Other large veins form perpendicular to Fault 2 and dip $\sim 45^\circ$ west-southwest (Fig. 3.13D). These orientations indicate mostly normal sense movement under locally extension-dominant stress regimes, and the veins are interpreted to represent mainly extension vein structures associated with the steep shear zones and faulting in the E1 North Shear Zone; they are not, however, purely extensional. Asymmetric boudinage is common throughout metasedimentary rocks in the E1 Group, but it is not clear at the drill core scale if it is related to extension or compression. The extensional movement of the E1 North Shear Zone and related faults can be explained by accommodation of sinistral movement of Faults E and A in response to dextral movement along Fault 1 and the Mount Margaret Fault caused by northeast-southwest shortening. S_2 foliation is crenulated by S_3 fabric (Fig. 3.17), and F_2

folds are refolded. Within the E1 North Shear Zone, S_2 is sheared and locally completely overprinted by S_3 shear fabric (Fig. 3.17). E1 East metasedimentary rocks are also strongly sheared but the kinematics in this area are not constrained, though the distribution of ores suggest that shearing was parallel to the northwest-southeast trend of the E1 East Antiform in which the orebody is hosted (Fig. 3.10).

Unlike the strongly-foliated metavolcanic breccias, the discordant feldspar altered breccias cutting across the system are generally only locally deformed and contain clasts of actinolite-porphyroblastic metasedimentary rocks, indicating that this breccia formed after D_2 and peak metamorphism. Weak foliation (S_3 ?) is developed in the biotite-rich matrix of the discordant breccia, and clasts are very locally strongly foliated. The contact of the breccia with intact wall rock is strongly sheared at E1 North, and the breccia is discordant with D_2 folds, therefore it is likely that brecciation occurred after D_2 and prior to or during D_3 .



Figure 3.17: Representative deformation fabrics. A) S_1 compositional layering, or possibly S_0 / S_1 composite layering, in graphitic chlorite metasiltstone, crenulated by S_2 and S_3 . B) S_2 flattening of metavolcanic breccia clasts. Note the white haloes in clasts caused by magnetite destruction. C) S_3 shearing of S_2 -foliated metavolcanic rocks. Groundmass is mostly magnetite with blebby sulfides. Note phenocrysts in “clasts”. The magnetite may replace a S_3 shear fabric resulting in pseudobreccia in porphyritic metavolcanic rocks, or may replace a primary breccia matrix. Continued on the next page.

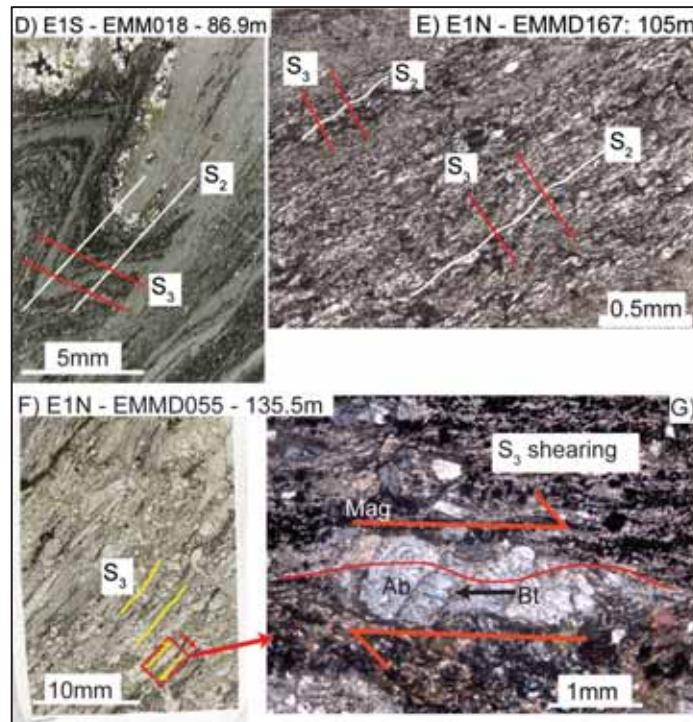


Figure 3.17 (cont.): D) and E) S_2 fabric in carbonaceous schist axial planar to folding, crenulated by S_3 . F) S_3 shearing of plagioclase-phyric meta-andesite. G) Photomicrograph of area noted in (F), showing dextrally-sheared albitised plagioclase phenocrysts; cross polarized light. Pre-ore biotite veins antithetic to the shear suggest syn-shearing timing. Opaque mineral is pre-ore magnetite with minor hematite.

D₄ and later deformation events

The northeast-trending faults bounding the E1 North Shear Zone were reactivated in oblique-slip movement with dominantly a reverse-slip component during D₄. Faults 4–7 formed at this time with similar orientations, and also experienced both reverse and sinistral or dextral movement (Fig. 3.10). The reactivation of these faults suggests shortening was approximately south-southeast to north-northwest. Dextral offset of Fault 4 by Fault E (Fig. 3.10) suggests that the latter was also reactivated following D₄. The D₄ faults offset alteration and post-date mineralisation, though some zones of supergene enrichment in Co and Mo are clearly associated with these structures (see next section; Fig. 3.18). Strike-slip movement along Faults 1 and 2 is minimal as they do not laterally offset the conjugate shear zones or mineralisation. Offset of the Mesozoic sedimentary rocks by 10–20 m at the Mount Margaret Fault indicates that this structure was reactivated up to the Mesozoic.

3-D Concentration Distribution Modeling

Datasets

Geochemical modeling interpolations of the Cu, Au, Fe, S, P, Co, Mo, U and La concentration shells presented in this study are based on assay data provided by the

current mine operator, which consists of a pre-open pit DDH and RC (Reverse Circulation) multi-element suite including all of the aforementioned elements, as well as a dataset from blast hole sampling for E1 North open pit which includes Cu, Au, Fe, S, and Co. The assays were prepared by triple-acid (HCl, HNO₃, and HClO₄) digestion and analysed via inductively-coupled plasma atomic emission spectroscopy (ICP-AES) for Au and trace elements at ALS Laboratories in Townsville, Australia. Copper was analysed by inductively-coupled plasma atomic absorption spectrometry (ICP-AAS). Assay interval lengths generally vary between 1 m and 2 m for DDH and RC samples, and many visually unmineralised intervals were not sampled. Blast hole samples represent homogenised averages of the entire hole length, which varies from 8 m to over 20 m. While down-hole sample resolution is lower in the blast holes compared to the DDH and RC holes, the former are spaced < 5 m in all directions and provide much higher spatial resolution in the E1 North orebody. Phosphorus, U and La were not analysed in blast hole samples, but a comparison of Cu interpolants incorporating and excluding blast hole data demonstrates that major structures can still be resolved with only DDH and RC drilling, and meaningful interpretations can be made. Below-detection values are not listed in the database and could not be distinguished from unsampled intervals. For this reason, below-detection values were not replaced and all missing values were omitted from interpolation. Summary statistics of the assay data are available in Appendix E. Energy-Dispersive Spectroscopy (EDS) was conducted on a JEOL JXA-8200 Superprobe at the James Cook University Advanced Analytical Centre to help identify the host minerals of the modeled elements.

Concentration interpolation parameters for the E1 Group

Numerical implicit modeling of geochemical assay data was conducted using the Multi-domained Interpolation function. Leapfrog uses fast-Radial Basis Functions (RBF) for implicit modeling, as described in detail in Stewart et al. (2014). The output of fast-RBFs is comparable to ordinary and dual kriging (Stewart et al., 2014). Table 3.2 displays the interpolation parameters used for all elements in this study. In addition to these parameters, a structural anisotropic trend was applied to each interpolant to reflect the stratabound morphology of the orebody. The orientation of the trend is derived directly from the combination of meshes of the modeled metasedimentary rock units that host the ores, as well as from meshes of the mineralised D₃ structures observed at E1 North. Isosurfaces of the output interpolants are presented in Figures 3.18–3.19.

Table 3.2: Radial Basis Function Interpolation Parameters for the E1 Group

Element	Variance	Sill	Base Range (m)				Nugget	Alpha
			North and East fault blocks	Central fault block	South fault blocks			
Cu	3.51	0.5		400				
Fe	0.606	100		500				
P	2.6	4×10^6		200				
S	3.27	9		200				
Co	1.7	2×10^5	132	132	200	0	3	
Mo	4.53	6000		132				
U	3.62	3×10^5		500				
La	3.38	2×10^5		132				

Isosurface values for copper and gold were selected as the cutoff values between economic and sub-economic concentrations used by the mining company. These cutoffs are probably orders of magnitude higher than thresholds between regional background and anomalies, but they have been chosen because the elements are of economic interest. Cutoff values for copper and gold are 0.27 wt% and 0.23 g/t, respectively. Cobalt, Mo, U and La follow approximately log-normal distributions (Appendix E) and are characterised by < 10% outliers, enabling anomalous isosurfaces to be calculated using the median + 2MAD (median absolute deviation) method (Reimann et al., 2005). This yields anomalous lower thresholds at 74 ppm, 25 ppm, 23 ppm and 66 ppm, respectively. Thresholds of these elements calculated using the box plot inner fence method (Tukey, 1977) were around an order of magnitude (e.g. Co 300 ppm) higher than their average crustal abundances and, at best, represent maximum background cutoffs. The lower thresholds determined from the median + 2MAD method are preferred. Iron, S, P do not follow normal or log-normal distributions and their lowest isosurface values were arbitrarily set to their mean concentrations in ore-concentration (> 0.27 wt% Cu) zones (17 wt% Fe, 2000 ppm P, 2.8 wt% S).

Interpolation results

Structurally-trended concentration isosurfaces of Cu, Au, Fe, S, P, Co, Mo, U and La are presented in Figures 3.18–3.19. These are overlain in the plan and cross sections in Figures 3.10–3.12. Cobalt, Mo, and U (Fig. 3.18E–G) coincide with the Cu-Au orebody, while Fe, P, La and S (Fig. 3.18A; C–D) overlap but show significant zonation from northeast to southwest away from the ore zone. The Fe, Cu and S interpolants

(Fig. 3.18A, C, H) strongly coincide with E1 North Shear Zone structures, including shears C and D (Fig. 3.18H); the Cu and Au interpolants follow the E1 South Synform and E1 North Antiform down-plunge (Fig. 3.19). Although the resolution of the P assay is lower, it is high enough to resolve association with the E1 North Shear Zone southwest of the orebody (Fig. 3.18C). All elements are enriched within the Corella marble horizon extending from E1 North to E1 South. The Co anomaly (≥ 74 ppm; Fig. 3.18E) extends beyond mineralisation for up to 20 m in the more stratabound zones of the orebody, but extends along strike of the E1 North Shear Zone for over 150 m. Anomalous La and U (> 66 ppm and > 23 ppm, respectively) are modeled up to 250 m and 180 m respectively along the shear zone, and are restricted to 20–40 m outside the Cu orebody at E1 East and South (Fig. 3.18D, G). The Mo anomaly (> 25 ppm; Fig. 3.18F) is present up to 50 m outside mineralisation at E1 North, but is restricted to < 20 m elsewhere in the E1 Group.

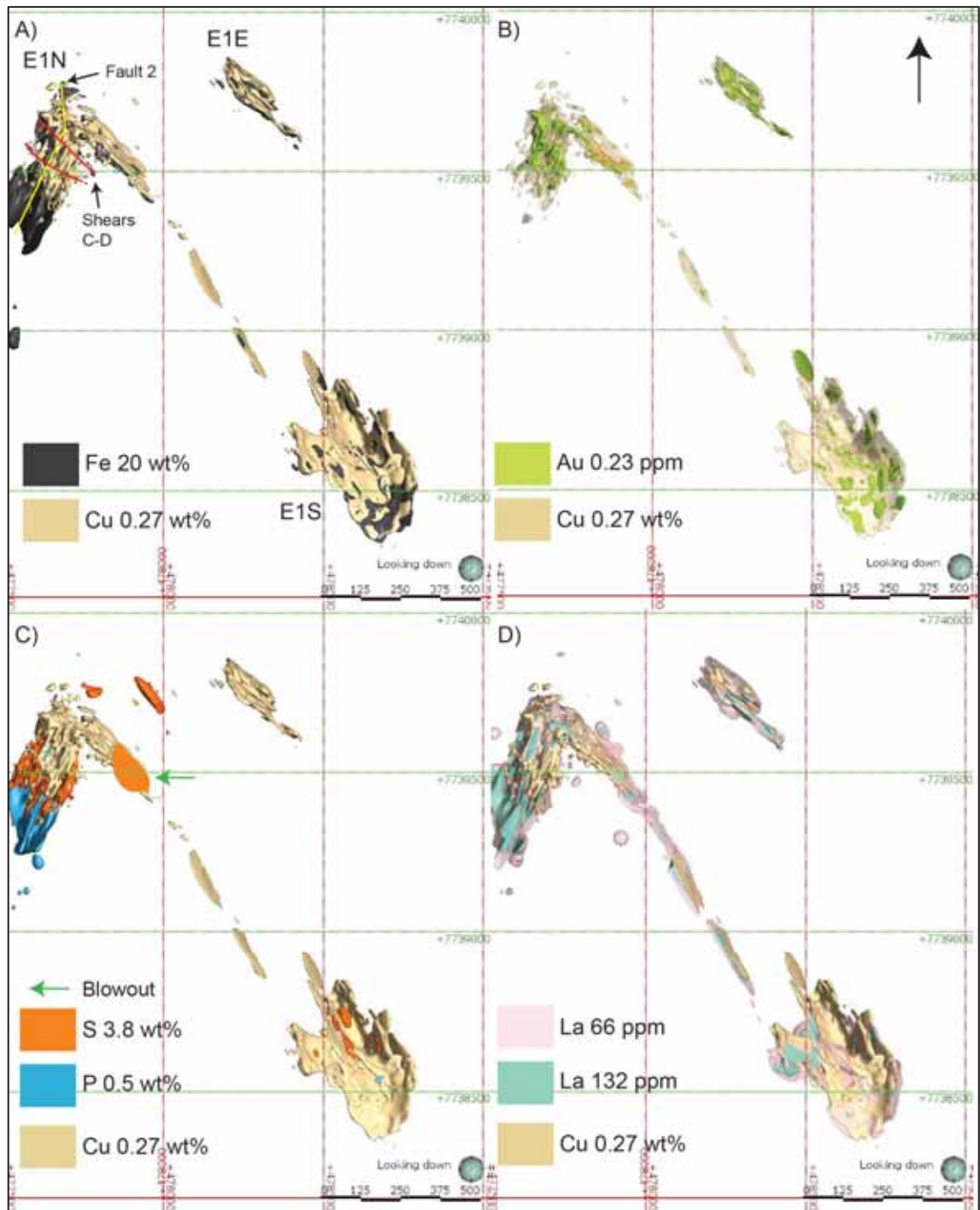


Figure 3.18: Plan view of isosurfaces of structurally-trended interpolants. Note the higher resolution at E1 North for Cu, Fe, S, and Mo as a result of additional blast hole data. Copper and gold isosurface values are based on mining cutoff concentrations, while S, P, and Fe are based on the mean concentrations of these elements in ores. Isosurface values for La, Co, Mo and U are based on anomalous cutoffs determined using the median + 2MAD (median absolute deviation) method (Reimann et al., 2005). A) Cu and Fe isosurfaces. B) Cu-Au. C) S and P. D) La isosurfaces at anomalous and 2x anomalous values. UTM grid is in meters. GDA 94 projection. Continued on the next page.

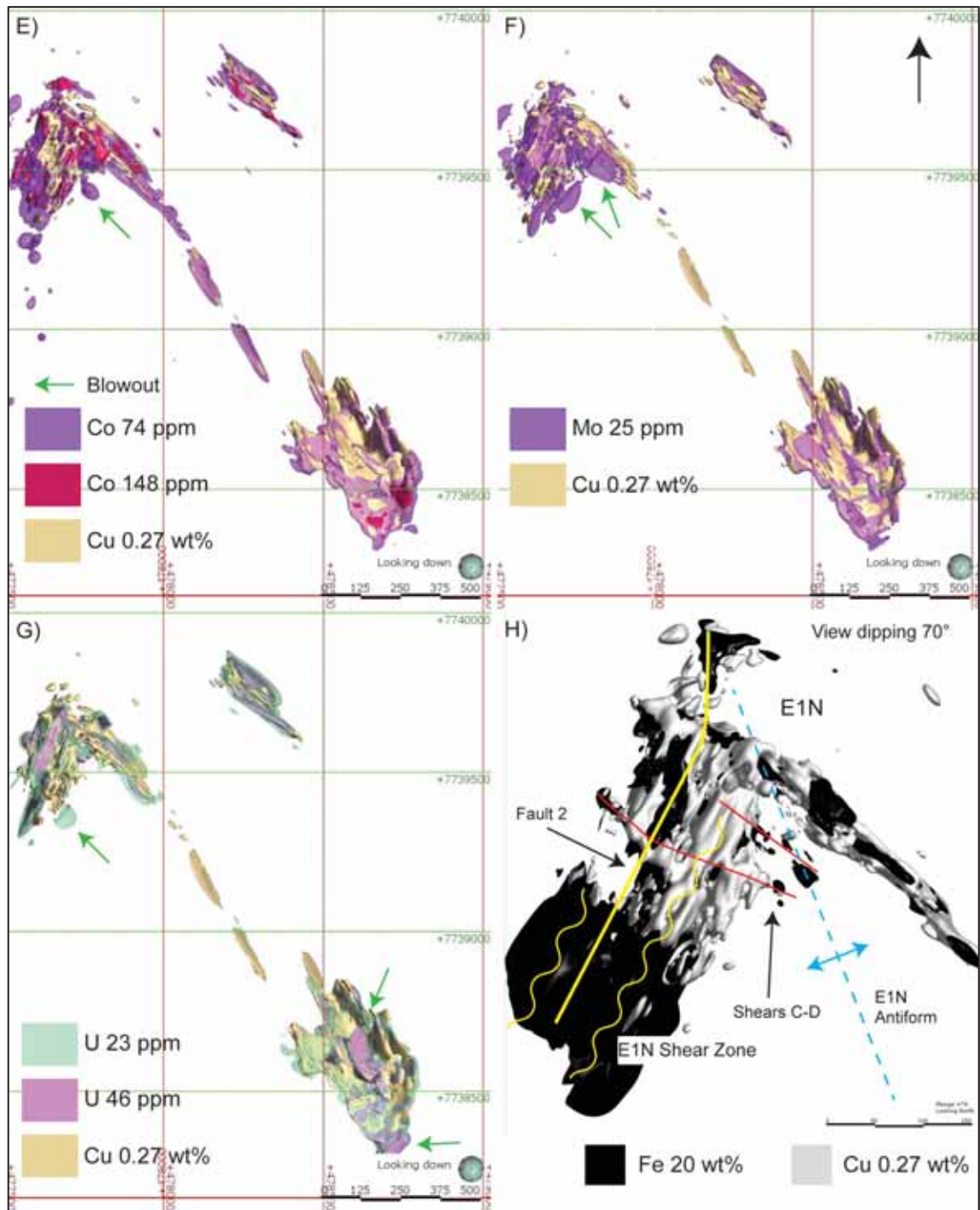


Figure 3.18 (cont.): E) Co isosurfaces at anomalous and 2x anomalous values. F) Mo. G) U isosurfaces at anomalous and 2x anomalous values. H) Close-up view, dipping 70°, of E1 North orebody showing the Cu-Fe trends coincident with Fault 2 and Shears C–D. Blowouts (green arrows) in S, Co, Mo, U are artificial and extend into the unaltered cover sedimentary rocks. This is caused by the interpolation models having the same extents as the geological model in which they are subdomained. Leapfrog cannot clip the interpolants to a particular surface or volume.

Interpretations

Drill core, petrographic, and EDS observations enable the modeled element distributions to be linked to specific alteration phases. Drill core logging indicates that the interpolated high-S zone corresponds to pyrite alteration, while the Fe-P-rich zone is characterised by widespread coarse-grained, euhedral magnetite-apatite $\pm$ pyrite replacement. Energy-dispersive spectroscopic analysis demonstrates that the high La anomaly is hosted within apatite and trace monazite. In the ore zone there is less apatite and REE alteration is also contained in bastnäsite and monazite. Uranium and S are enriched to over 200 ppm and 10 wt%, respectively, in the carbonaceous metapelite at E1 South. Such high S content is attributable to the $\sim$ 5 vol% pyrite content of this rock, which may be diagenetic in origin but has since been recrystallized. Uranium is naturally high in carbonaceous metasedimentary rocks (Vine and Tourtelot, 1970), which may explain the elevated values. Enrichment of Co, Mo and U near the basement-cover unconformity (the ‘blowout blobs’ in Fig. 3.18) is likely due to supergene remobilization. These elements are also anomalous in soil samples at the surface above 30–50 m of thick cover (R. Lilly, pers. comm.). Molybdenite is rare in the deposit, and Mo and Co-rich phases have not been observed in EDS analysis, suggesting that they are hosted mostly within another phase.

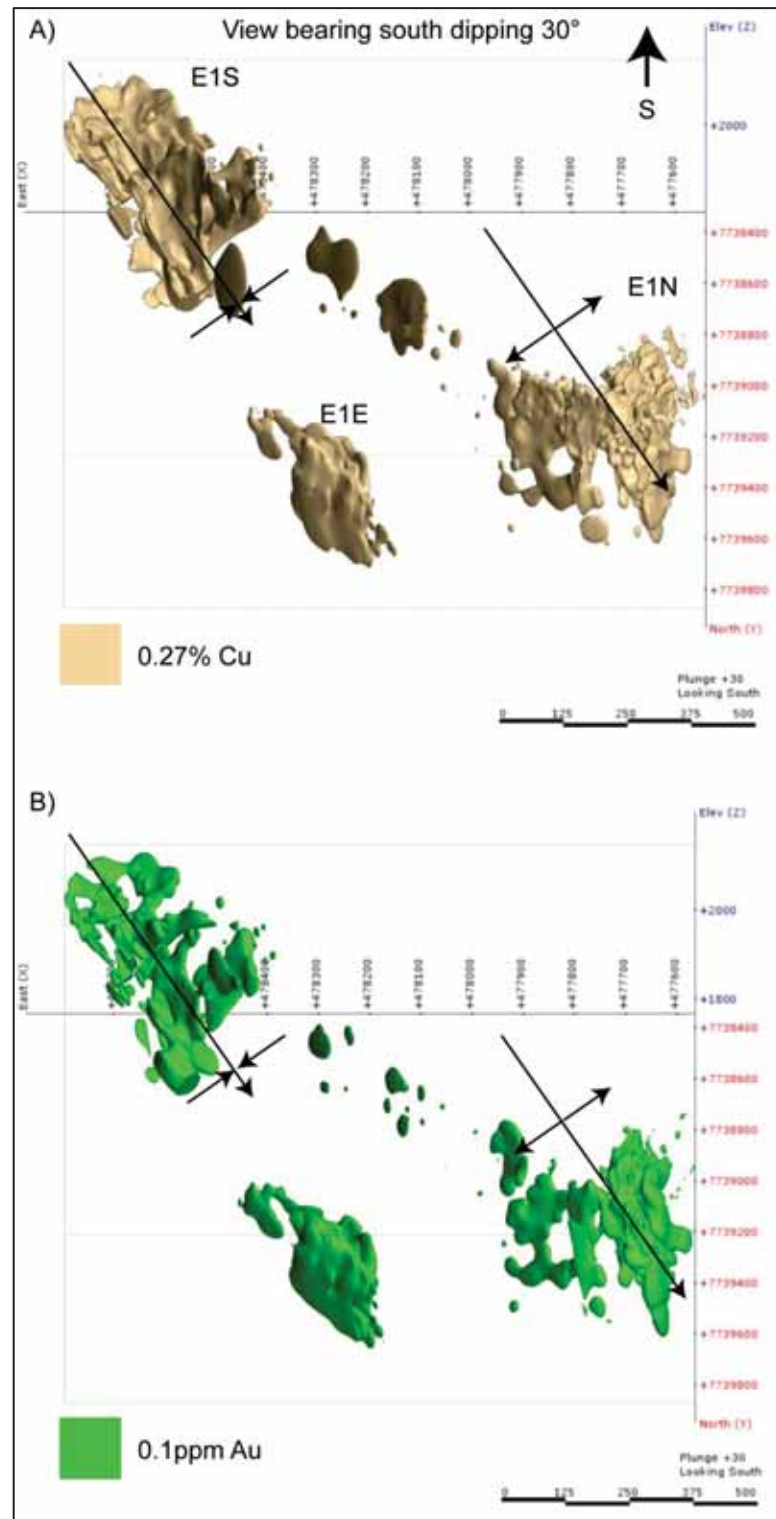


Figure 3.19: 3-D renders of the 0.27% Cu (A) and 0.1ppm Au (B) interpolants; view is bearing south (opposite to Figure 3.18) and dipping 30°. Both interpolants are clearly controlled strongly by the plunge and attitudes of the E1 North Antiform and E1 South synform. The orebodies are open at depth. GDA 94 projection.

Discussion

Relative timing of alteration and mineralisation

At the deposit scale, interpolated Cu and Fe element concentration shells and observed magnetite-rich zones form clear lineaments associated with the E1 North Shear Zone and conjugate shear zones B–D, indicating that these local D₃ structures were likely active during at least Stage 2 alteration and Stage 3 mineralisation (Figs. 3.13; 3.14; 3.18; 3.20). This is consistent with microscale observations of Stage 2 biotite veins cutting across antithetically to dextrally-sheared, albitised (Stage 1), plagioclase phenocrysts (Fig. 3.17G), which indicates a pre- to syn-local D₃ shearing timing for Stage 1 albite alteration, and syn-shearing timing for Stage 2 alteration (Fig. 3.20). Furthermore, hematite alteration associated with Stage 1 is aligned to the shear fabric (Fig. 3.17G), which is also consistent with a pre to syn-shearing timing for Stage 1. Stage 2 quartz associated with Stage 2 magnetite is locally deformed at grain boundaries and provides further evidence of on-going deformation during alteration. Faults 4 to 7 are not associated with alteration or veins and offset the former, indicating that local D₄ took place after mineralisation (Fig. 3.20). Additionally, a lack of abundant horizontal veining associated with Faults 1–3 suggests that the reverse movement on these structures during local D₄ was not associated with any substantial hydrothermal activity and alteration.

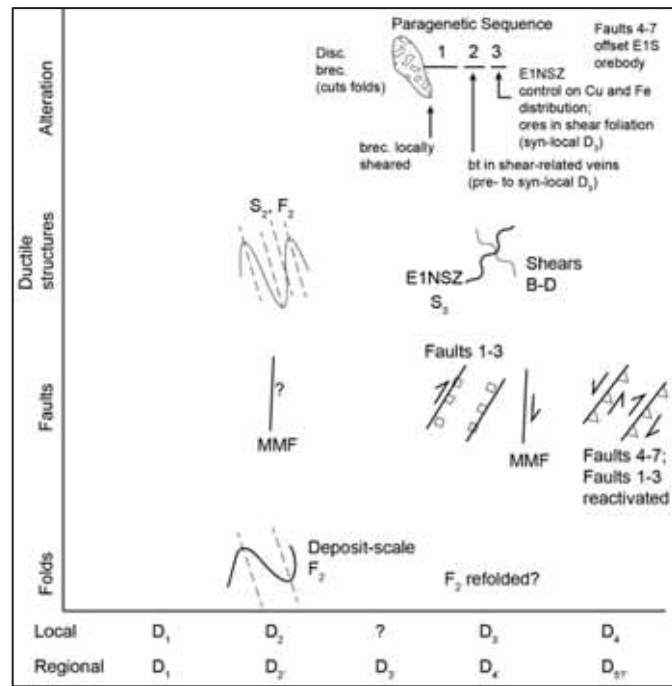


Figure 3.20: Integrated structural and alteration schematic of the E1 Group. The local deformation sequence is correlated to the regional sequence. E1NSZ, E1 North Shear Zone; Disc. brecc., discordant breccia; bt, biotite.

Structural controls on mineralisation in the E1 Group

Structural permeability in the E1 Group is provided mainly by fold hinges and shear zones. Mineralisation is focused at/near the hinges of the E1 North Antiform and E1 South Synform, and the paucity of major mineralised structures at E1 South suggests that dilation in the synform hinge itself acted as a major fluid focusing zone during mineralisation. This is in agreement with the presence of small-scale dilations in the hinges of <1m parasitic folds at E1 South. These dilations focus hydrothermal carbonate, quartz and pyrite. The bounding of the E1 metasedimentary rock horizons by relatively impermeable metavolcanic rocks may have enhanced focusing of fluids into these dilational zones. Intersection of the E1 North Antiform, in particular the marble horizon that defines it, with the E1 North Shear Zone (Fig. 3.14) is the most likely explanation for higher ore concentration and tonnage at E1 North (Table 1.1) compared to East and South. It is also possible that the E1 North antiform experienced more dilation than E1 South, but this does not explain the extent of alteration along strike of the southwest limb. The E1 North Shear Zone focuses alteration along strike, nearly parallel to the limb of the antiform, for more than 1 km. Alteration along the shear zone changes from the apatite ± magnetite zone in the southwest, to the magnetite zone, pyrite zone, and finally the magnetite-barite-fluorite-carbonate-chalcopyrite ore zone near the hinge of the E1 North Antiform. The orientation of the shear zone appears to be

mostly controlled by the west limb of the antiform. It is possible that strain partitioning along this shear zone may have been enhanced by the discordant breccia body that is partially fault-bound to the west by Fault 1 (Fig. 3.10). This breccia is relatively undeformed compared to the adjacent strongly-sheared metavolcanic breccias and metasedimentary rocks in the E1 North Shear Zone. The breccia also shows strong albite-K-feldspar-alteration, which was more likely to fracture than rather than shear except at localized high-strain zones < 5 m wide.

The northeast-southwest trending shear zones at E1 North are not recognized at E1 East. Interpolation of Cu concentration suggests that the orebody trends in the same direction as the host limb of the E1 East Antiform. However, it is notable that the E1 East ore zone occurs adjacent to the onset of major curvature in this antiform. Shearing parallel to layering is abundant in drill core and probably acted as the major fluid conduit at E1 East. The contact between metasedimentary and metavolcanic rocks, regardless of stratigraphic conformity, is not a significant control on mineralisation at the deposit scale, as high ore concentrations (> 1 wt% Cu) are typically found over 5–10m away from contacts at E1 South (Fig. 3.12D).

At the deposit scale, the 3-D geochemical models suggest that ores not directly associated with a specific structure are restricted mostly to the Corella metasedimentary rocks. This may suggest that metasedimentary composition and bedding are major mineralisation controls. The chemical favourability of carbonate rocks for sulfide alteration is well-documented in skarns (Meinert, 1992). Evidence of these controls at smaller scales can be observed in preferential alteration along beds, including flaser crossbedding. Although bedding contacts are not a major control at the deposit scale, lamination-parallel microveining (< 5 mm width) is common and may have acted as a major fluid pathway. These microveins are difficult to distinguish from coarse-grained (> 2 mm) alteration without petrographic analysis. It is possible that the microveins open along bedding sub-parallel S_1 , and that S_1 itself has enhanced bedding permeability. Locally, high ore concentrations are carried by thick (> 30 cm) carbonate veins that typically reopen earlier veins of quartz, albite and K-feldspar. The carbonate veining and localized brecciation is more abundant in the more competent coherent metavolcanic rocks, but these veins and breccias are only slightly mineralised. Disseminated carbonate alteration haloes are associated with some carbonate veins, but

at the drill core scale these haloes are only sporadically associated with strong magnetite-chalcopyrite alteration. It may be that these larger veins were either not a major conduit for mineralisation, or that the system at that time was characterised by relatively low water-rock ratios. Boudin necks and microfaults within the metasedimentary rocks focus alteration and are typically infilled by carbonate, chalcopyrite and pyrite veining with wide (~1 cm) chalcopyrite-pyrite selvages.

Timing of IOCG mineralisation in Cloncurry

Understanding the relative timing of mineralisation with respect to formation of structural conduits is critical for improving IOCG genetic models. At the Ernest Henry deposit, mineralisation is interpreted to have taken place after peak metamorphism (D₂) and during both local and regional D₃ (Twyerould, 1997; Coward, 2001; Mark et al., 2006b). These relationships are consistent with the E1 Group orebody having formed during local D₃. Ernest Henry alteration has been dated via Re-Os (molybdenite) by Mark et al., (2004) and via U-Pb (titanite) by Mark et al., (2006b). These data are shown in Figure 3.4, together with correlations between the E1 Group and Ernest Henry and regional deformation histories. Both dating methods constrain the timing of ore genesis at Ernest Henry to 1530–1500 Ma.

Ernest Henry and the E1 Group share local D₃ mineralisation timing and regional D₃ kinematics. The absolute age of Ernest Henry, however, is closer to regional D₄ (Figs. 3.3–3.4). The 1456 ± 44 Ma U-Pb monazite age reported for the E1 Group in Chapter 2 suggests that it formed coevally with the 1550–1490 Ma Williams-Naraku suite; it overlaps in time with Ernest Henry. The discrepancy between the relative and absolute timing of these deposits with respect to regional D₃ and D₄ could be explained in two ways. First, regional D₃ may not be focused significantly in the E1 Group–Ernest Henry area. Variability in the intensity of regional D₃ and D₄ fabrics and structures have been documented by other authors (e.g. Rubenach and Barker, 1998; Austin and Blenkinsop, 2010; Duncan et al., 2014), especially in the vicinity of the Cloncurry Fault (Austin and Blenkinsop, 2010). Second, it is possible that the direction of shortening in regional D₄ is heterogeneous over the distance between the Snake Creek Anticline and the E1 Group. Such heterogeneity has been documented across the Mount Isa Inlier by Abu Sharib and Bell (2011), who describe zones of dominantly east-west shortening, north-south shortening, and northeast-southwest shortening. Furthermore, the diorite bodies around Ernest Henry and the E1 Group may account for some strain heterogeneity. The

latter is more localized, especially in the northern part of the Inlier where Ernest Henry and the E1 Group are located. The preferred explanation is a combination thereof, in which regional D₃ strain was not focused in the E1 Group–Ernest Henry region, and the direction of subsequent regional D₄ shortening shifted from northwest-southeast in the Snake Creek Anticline, to northeast-southwest. Thus, despite being characterised by kinematics similar to regional D₃, the E1 Group probably formed during regional D₄. The post-mineralisation, local D₄, structures thus formed in a regional D₅ event which has been recognized by some workers (Fig. 3.3; Austin and Blenkinsop, 2010; Duncan et al., 2014). At Ernest Henry evidence for this is observable as late, northeast-southwest-trending reverse faults transecting the orebody (Coward, 2001), as well as gentle folding of the orebody about an east-northeast-west-southwest-trending hinge (Fig. 3.21C).

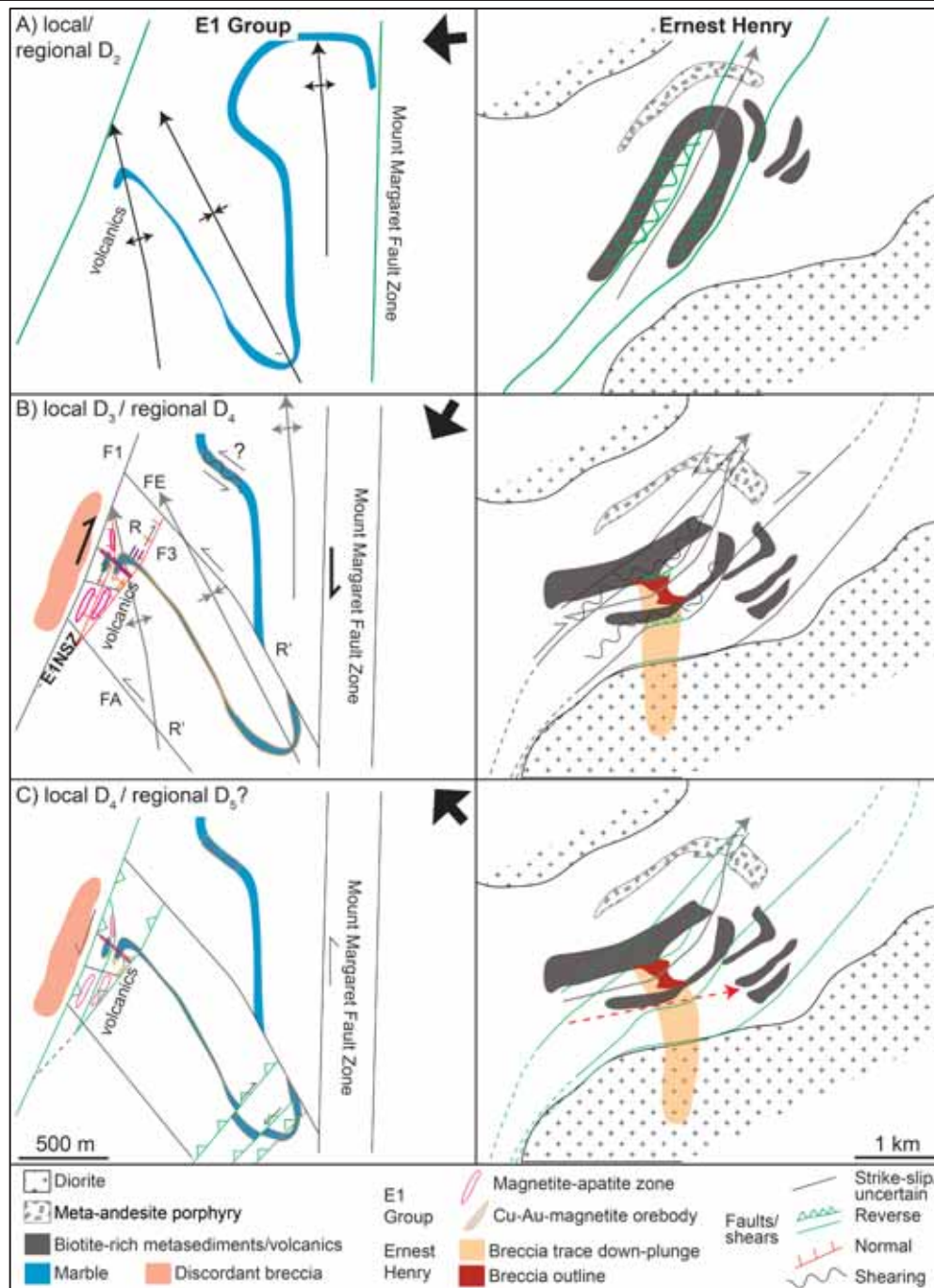


Figure 3.21: Conceptual model (plan view) of the structural history of the E1 Group and Ernest Henry deposits. Large black arrows are σ_1 direction. A) Regional D_2 folding generates pre-mineralisation tectonic fabric. At E1, Fault 1 and Mount Margaret faults probably activated as thrusts during this time. At Ernest Henry, sedimentary rocks are folded around Ernest Henry Diorite, and the orebody-bounding shear zones, possibly parallel to existing sediment layers, are initiated. B) In local D_3 / regional D_4 , the shortening direction (indicated by the black arrows) shifts northward causing dextral reactivation of D_2 faults at E1. Sinistral northwest-trending faults are formed, and E1 North shear zone develops as probably normal-dextral conjugate structures, with shear zones mainly focused along the marble horizon between more competent breccia and volcanic rocks. At Ernest Henry, D_2 shear zones reactivated in a reverse flower structure in response to probably dextral shearing along the main shear zone around the competent diorite bodies. During this time, mineralisation takes place in both systems. At Ernest Henry, competent volcanics between sheared metasedimentary rocks deform in a brittle manner and brecciate with sufficient fluid overpressure. At E1, strain is mostly focused in the metasedimentary rocks and volcanic breccias. C) After local D_3 , northwest-southeast-directed shortening (local D_4) causes reverse faulting at E1, and northeast-southwest-oriented gentle folding of the Ernest Henry orebody.

Comparison of the structural controls on the E1 Group and Ernest Henry deposits

The structural setting of the Ernest Henry deposit has been extensively analysed, and deposit-scale controls on mineralisation are well-constrained (Twyerould, 1997; Mark et al., 2000; Coward 2001; Mark et al., 2006b). However, camp- and regional-scale controls have not been well-studied in this area due to the paucity of outcrop. Although structural controls in ore deposits are typically complex and somewhat unique to each system, similarities and differences can be found between Ernest Henry and the E1 Group which may help to explain structural factors influencing the style of IOCG mineralisation in a given district: i.e., breccia-hosted Ernest Henry-style orebodies compared to shear-replacement E1 Group-style orebodies. In the case of these two deposits, at least four major factors combined to influence their location and mineralisation styles throughout their structural evolution: 1) structural ground preparation through D₂ folding and faulting, and alteration, 2) local normal or reverse faults/shear zones, formed within larger wrench shear systems, enabling dilation and fluid influx, 3) strain partitioning caused by rheological contrast between volcanic and sedimentary protoliths and, 4) fluid overpressuring.

The major folds hosting Ernest Henry and the E1 Group were developed prior to mineralisation. The hanging wall and footwall shear zones that bound the Ernest Henry orebody are splay structures related to a larger, northeast-southwest-trending, brittle to ductile zone that developed in east-west shortening during regional D₂. The shear zones provided the structural framework for later syn-mineralisation deformation (Twyerould, 1997; Coward, 2001). The northeast-southwest-trending orientation of these shear zones, along with the possible fold hinge they form around, are not consistent with north-northwest-south-southeast D₂ fabrics. This suggests that they may have been rotated during local D₃ (Fig. 3.21C). At the E1 Group, D₂ formed the north-northwest plunging E1 North Antiform with its western limb trending northeast-southwest.

During local D₃ / regional D₄, the D₂ structures in both deposits were reactivated with components of dip- and strike-slip movement, leading to dilation that could focus mineralising fluids (Fig. 3.21). In the E1 Group, the north-northeast-south-southwest-trending Fault 1 and Mount Margaret Fault structures probably experienced dextral and reverse slip in response to northeast-southwest shortening, resulting in formation of a transpressional Riedel brittle to ductile system (Cloos, 1928; Riedel, 1929; Davis et al., 2000) (Fig. 3.21B–C). Less competent sedimentary and volcanoclastic rocks

experienced shearing associated with this faulting. Faults A and E may have formed as sinistral antithetic R' brittle to ductile zones to this wrench system, while the E1 North Shear Zone and associated conjugate structures may have formed as synthetic R brittle to ductile zones. The orientations of Faults A and E are northwest-southeast-trending, rather than northeast-southwest (in an ideal Riedel system). This is probably caused by utilization of the existing north-northwest-south-southeast trend of the major folds. Because of the pre-existing northeast-southwest trend of the west limb of the E1 North Antiform, the E1 North Shear Zone developed as both a R brittle to ductile zone and normal structure to accommodate northwest-southeast directed extension. At Ernest Henry, the northeast-southwest shortening associated with D₄ formed a series of moderately-dipping, reverse shear zones between the diorite bodies at Ernest Henry, resulting in dilation. In contrast to the E1 Group, the dilation caused brecciation of metavolcanic rocks by the Cu-Au-bearing fluids (Twyerould, 1997; Coward, 2001; Mark et al., 2006b). Overall, the E1 Group and Ernest Henry deposits record the same sequence of deformation events from at least D₂ onward. The mineralising event in D₄, however, resulted in contrasting orebody styles: hydrothermal breccia ores at Ernest Henry, and replacement ores at the E1 Group.

Protolith competency contrasts in Cover Sequence 2 rocks may have helped to focus the D₄ structures that host the Ernest Henry and the E1 Group deposits. In this part of the Eastern Fold Belt, Cover Sequence 2 is made up mostly of intercalations of the competent Mount Fort Constantine Volcanics and more ductile Corella Formation metasedimentary rocks. Cross sections of Ernest Henry (e.g. Twyerould, 1997; Coward, 2001) reveal marble and metasiltstone rock horizons in the footwall sequence that immediately underlie the ore breccia zone. The horizons are coincident with the shear zones that bound the orebody. These metasedimentary rocks are generally characterised by strong biotite and carbonate shear foliation; more silica-rich beds are boudinaged and brecciated (Twyerould, 1997). Marshall and Oliver (2008) suggested that this intercalation of metavolcanic rocks and Corella marble resulted in brittle strain developing in the former concurrently with ductile strain focusing in the latter.

The footwall metasedimentary rocks at Ernest Henry are comparable to those at the E1 Group, which suggests that these shear zones are likely controlled by the original stratigraphic position of the sedimentary and volcanic rocks. In both cases, D₄ shear strain was mostly partitioned into the ductile Corella marble and other metasedimentary

horizons between more competent coherent metavolcanic rocks and metasiltstones. Strain partitioning was facilitated in each system by the pre-existing northeast-southwest orientation of the sedimentary and volcanic rocks resulting from the D₂ folding. Although metasedimentary rocks focused most of the ductile strain in both deposits, these rocks are not mineralised at Ernest Henry. It is possible that juxtaposition of competent volcanic rocks (Fig. 3.5B) between the sedimentary rocks increased the amount of brittle strain focused into the former, leading to brecciation. This is in contrast to the E1 Group, where the volcanic rocks surround the sedimentary rocks, causing much less strain to develop in the volcanic rocks.

Relative fluid overpressure (where fluid pressure > lithostatic pressure) may also help explain the contrasting mineralisation styles between the E1 Group and Ernest Henry. These parameters, in addition to the fertility of the source fluid(s), may account for the higher tonnage and concentration of the latter. Oliver et al., (2006) demonstrated that the process of rapid, fluidized brecciation by potentially mineralising fluids could explain the breccia textures observed at Ernest Henry and other, barren hydrothermal breccias in the region. Marshall and Oliver (2008) implied that this process may have taken place at Ernest Henry, in part due to overpressuring by an impermeable footwall marble layer. The replacement of sheared marble and other metasedimentary rocks in the E1 Group, however, provide clear evidence that marble can also preferentially act as a sink of ore fluid metasomatism rather than a barrier.

It is likely that brecciation or replacement can take place depending on the relative permeability of the volcanic and metasedimentary rocks. This is governed by the partitioning of strain, as previously discussed, as well as by the degree of fluid overpressure. If strain rate is relatively low, the sedimentary rocks can accommodate most shear strain while the volcanic rocks remain mostly intact and relatively impermeable. However, if strain rate is high, or more strain is focused into the competent rocks, they may fracture and become relatively more permeable than the sedimentary rocks. If fluid pressure is also low enough, micropermeability within the shear zone will be sufficient enough to accommodate hydrothermal fluids, albeit with some fracturing and faulting. The volcanic rocks are less resistant to tension than the sedimentary rocks, and may consequently accommodate most of the strain caused by overpressure (e.g. Gessner et al., 2006; Gessner, 2009).

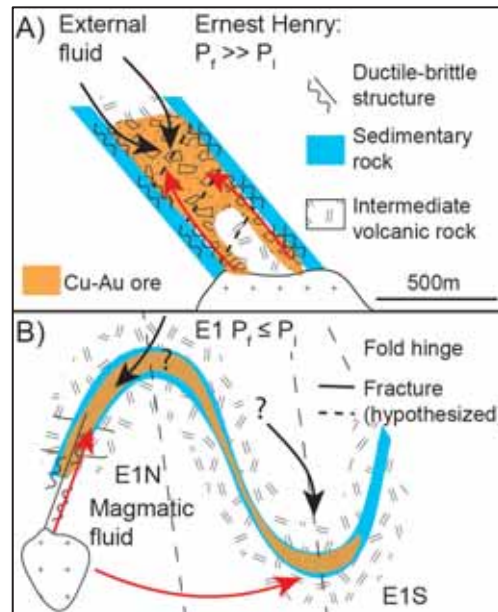


Figure 3.22: Cartoon of fluid and structural models for Ernest Henry and E1 Group mineralisation. A) At Ernest Henry, a combination of fluid pressures significantly higher than lithostatic pressure, and positioning of competent metavolcanic rocks between impermeable, ductile, metasedimentary rocks (mostly marble) leads to overpressuring of a magmatic-hydrothermal fluid and brecciation of the competent metavolcanic rocks. During this brecciation, an external fluid mixes with the magmatic fluid. B) At the E1 Group, the ductile metasedimentary rocks, bounded by brittle metavolcanic rocks, focus shearing and hydrothermal fluids, which are under comparatively less pressure (fluid pressure $\leq$ lithostatic pressure).

The degree of fluid overpressure in either system may be related to the overall size and H₂O content of the granitic intrusion that probably contributed to the mineralising fluids in both Ernest Henry (Twyerould, 1997; Mark et al., 2006b; Kendrick et al., 2007; Oliver et al., 2008) and the E1 Group (Williams et al., 2015). The P-T conditions at the time of fluid exsolution from the magma, along with the availability of ligands, Cl, and S for transporting and precipitating Cu and Au, are also important. Indeed, models for IOCG genesis in the region (e.g. Mark et al., 2006b; Kendrick et al., 2007; Williams et al., 2015) invoke the mixing of a magmatic fluid with another fluid (i.e. basinal or meteoric; Fig. 3.22), which may have carried much of the necessary sulfur, in order to generate Ernest Henry ore. The size of the E1 Group may be partly dependent on the degree of mixing between such fluids; brecciation may serve as an efficient mixing mechanism. However, the similar mineralogy and chemistry of the two deposits suggests that their fluid characteristics were comparable during mineralisation (e.g. Williams et al., 2015). The high tonnage and concentration of Ernest Henry compared to the E1 Group is probably a result of either higher overall permeability generated

through brecciation, or derivation from a larger or more fertile fluid and metal source(s). Furthermore, brecciation at Ernest Henry may have facilitated more fluid mixing, resulting in more available metals and/or sulfur. Mineralisation at the E1 Group was probably enhanced by the chemically favourable nature of marble for sulfide alteration.

Global comparisons

The E1 Group and deposits in its host district share many structural characteristics with Fe-oxide-Cu-Au deposits in the northern Fennoscandian shield and Carajás districts. Like the Cloncurry District, both regions underwent deformation, metamorphism and magmatism around the time of IOCG formation. Billström et al. (2010) provide a thorough summary of the tectonic and structural framework and IOCG deposits of the Fennoscandian shield, on which the following comparisons are based. The Fennoscandian shield and Cloncurry are both typified by protracted tectonic and hydrothermal histories spanning >200 Ma, resulting in a wide array of ore deposit styles. The Fennoscandian shield hosts several IOCG deposits, as well as the type-deposit for the related iron oxide-apatite (IOA) class of deposits: Kirunavaara. The Fennoscandian shield was dominated by rift tectonics and corresponding deposit types (e.g. syngenetic base metal, VMS and ultramafic intrusion-hosted Ni-Cu-PGE) from about 2500–1900 Ma. Following this, a subduction zone formed and collisional tectonics began, and lasted until as late as 1650 Ma. Fe-oxide-Cu-Au and orogenic-Au deposits formed in two episodes of deformation and metamorphism from 1900–1870 Ma and from 1810–1790 Ma; many IOCGs also formed between these major deformation events. Metamorphic grade varies mainly from greenschist to amphibolite facies, though some areas reached granulite facies. Like the E1 Group and Ernest Henry, many of the Fennoscandian shield IOCGs, such as Gruvberget, Tjärrojäkka, Rakkurijärvi, and Nautanen, are hosted in intermediate-mafic metavolcanic rocks. Nautanen ores are characterised by replacement textures, while the other deposits are dominated mostly by hydrothermal breccias. In some instances (e.g. Gruvberget) Cu-Au-breccias appear to overprint earlier massive magnetite alteration. All of the deposits are spatially associated with splays of regional structures. The Nautanen deposit is noted for being a type-example of shear zone-hosted ores in the district (Billström et al., 2010). The Nautanen deposit is therefore the most analogous orebody in the region to the E1 Group, as it is characterised mostly by replacement ores and ductile structures.

However, it is distinct from the E1 Group in that it may have formed prior to or during peak metamorphism (Martinsson and Wanhainen, 2004).

The Carajás district in Brazil hosts world-class IOCG deposits including Salobo and Sossego. These two deposits form part of the group of Archean (~2.5 Ga) Fe-oxide-associated Cu-Au $\pm$ Mo $\pm$ Ag $\pm$ U $\pm$ REE deposits (Grainger et al., 2008). The deposits are hosted mainly in a series of Neoproterozoic (2.75–2.68 Ga) intermediate-mafic metavolcanic and metasedimentary rocks interpreted to have been laid down in an intracratonic rift basin (Grainger et al., 2008), which is analogous to Cloncurry. As with the Cloncurry and Fennoscandian shield, metamorphism in this area reached greenschist to amphibolite facies, with local migmatite formation. The Igarapé Bahia-Alemão, Crisalino and Sossego-Sequerinho deposits are typified by breccia-hosted Fe-oxide-Cu-Au ores, while Salobo – the largest deposit in the district – is dominated by massive replacement magnetite-Cu-Au bodies (Requia et al., 2003; Grainger et al., 2008). Salobo is characterised by ductile-brittle shear zone controls, whereas the others deposits are mostly associated with brittle structures (Requia et al., 2003). Grainger et al., (2008) suggested that this may be the result of greater formation depth and metamorphic grade (amphibolite facies) at Salobo than at the other systems (greenschist facies). The Cinzento strike-slip fault system – one of the more prominent regional structures associated with these deposits – was active at 2.5 Ga (Pinheiro and Holdsworth, 1997). Requia et al., (2003) interpret multiple Re-Os (molybdenite) mineralisation ages at Salobo (2576 ± 6 and 2572 ± 8 Ma) to represent reactivation of the shear zone and brittle structures that control the orientation of the orebody.

From comparing the Fennoscandian shield and Carajás districts to the Cloncurry District, a clear association can be made between ductile or ductile-brittle structural settings, and the formation of replacement IOCG orebodies such as the E1 Group, Nautanen and Salobo. Multiple factors may explain the presence of both breccia-hosted and shear-hosted IOCG deposits in these regions. In the case of the Carajás District, the variation in deformation style between Salobo and other deposits may be attributable to the grade of metamorphism (Grainger et al., 2008), with Salobo forming in a higher-grade zone dominated by ductile strain. Another factor that may be important is the volume of fluids expelled from possible source magmas, as previously discussed for Ernest Henry and the E1 Group; more fluids can lead to higher fluid pressure, causing brecciation. However, the large size of the Salobo orebody (789 Mt at 0.96% Cu and

0.52 g/t Au; Souza and Vieira, 2000) indicates that shear zone replacement by magmatic fluids can form large IOCG deposits. Instead, the rate of fluid flow is probably more important, with breccia orebodies possibly characterised by higher rates. Lastly, late brittle deformation and mineralisation may take place in systems affected by earlier metasomatism. For example, Billström et al., (2010) suggested that earlier Na-Ca and/or magnetite/hematite alteration structurally prepared the host rocks of some deposits (e.g. Gruvberget-Cu?) in this district for hydrothermal brecciation by increasing their rigidity.

Regardless of structural regime, deposits in all three districts are commonly controlled by shifts in the competency of the host rocks. Examples of this are apparent at Salobo, where ores are hosted in a metagreywacke bounded by more competent quartzite and gneiss (Requia et al., 2003). In the Fennoscandian shield, deposits such as Nautanen and Aitik are hosted within schist surrounded by gneiss and granite (Billström et al., 2010). Overall, it is clear that the structural controls and setting of the E1 Group and Ernest Henry deposits are comparable to IOCGs in other provinces, and the results presented in this study may be applied to shear-hosted, replacement-style IOCG orebodies elsewhere.

Conclusions

Three-dimensional geological modeling and geochemical interpolation, when combined with drill core and open pit observations, can facilitate the spatial and temporal understanding of deposit evolution. The E1 Group of Fe-oxide Cu-Au deposits is characterised by four major deformational events recognizable at small scales through drill core logging, and at large scales through deposit-scale modeling. Although much of the mineralisation in the E1 Group is hosted within metasedimentary rocks, the E1 North orebody is substantially larger than other orebodies in the Group due to the intersection of the E1 North Shear Zone with the Corella marble horizon. Mineralisation took place during local D₃ / regional D₄ shearing and faulting in a transpressional Riedel brittle to ductile system associated with the major Cloncurry Fault Zone. At E1 North, this deformation was focused along the E1 North Shear Zone trending northeast-southwest and parallel with the west limb of the north-northwest plunging E1 North Antiform. Fluids at E1 South were focused in the hinge of the E1 South Synform.

Ernest Henry mineralisation also took place during local D₃ / regional D₄ and was focused in reverse sense shear zones.

Mineralisation at the Ernest Henry breccia-hosted deposit was facilitated by strain partitioning between ductile metasedimentary or biotite-rich metavolcanic rocks, surrounding a more competent sequence of Mount Fort Constantine metavolcanic rocks which deformed through fracturing. In contrast, at the E1 Group replacement deposit, only one layer of metasedimentary rock was aligned to northeast-southwest-trending shear zones, causing strain and mineralisation to focus mostly into the metasedimentary rock layer. Additionally, strain rate and fluid pressure may have been lower at the E1 Group than at Ernest Henry. The mineralising fluids permeated through shear zones and chemically replaced metasedimentary rocks in the rest of the system.

Relative permeability and degree of fluid overpressure (where fluid pressure > lithostatic pressure) are important characteristics influencing the formation of Ernest Henry-style IOCG breccia orebodies, as opposed to shear-zone replacement-style E1 Group orebodies. These are in addition to factors such as magma fertility, and the degree of mixing between multiple potential source fluids. In the northeast Cloncurry District, northeast-southwest-trending structures intersecting folded metasedimentary horizons, and hosted within conjugate-trending strike-slip structures, can form shear systems ideal for Ernest Henry and E1 Group-styles of mineralisation. Such structures would mostly likely be related to regional D₄. In some instances, juxtaposition of competent lithologies, such as metavolcanic rocks, between multiple metasedimentary rock horizons facilitates the brecciation necessary to form Ernest Henry-sized IOCG systems. The E1 Group and Ernest Henry-style orebodies occur in other districts including the Fennoscandian shield and Carajás. Replacement bodies like the E1 Group tend to form in ductile-brittle or ductile regimes, whereas breccia ores are more commonly, but not exclusively, associated with more brittle regimes. Rheology contrasts in the country rocks are important for focusing the structures that control these types of IOCG deposits.

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Chapter 4

The evolution and sources of mineralising fluids at the E1 Group IOCG deposits, Cloncurry District, Queensland, Australia

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Abstract

Proposed fluids and metal origins and ore precipitation mechanisms of iron oxide-Cu-Au (IOCG) deposits vary from both magmatic and non-magmatic hydrothermal sources, and at present the genetic model of this deposit class remains ambiguous. Combined, detailed, fluid inclusion and isotope studies of oxygen and sulfur in individual deposits can provide great insight into IOCG fluid evolution and possible sources. This study presents quartz and barite fluid inclusion data, coupled with isotopic studies of oxygen in quartz and magnetite, and sulfur in barite, chalcopyrite and pyrite from the E1 Group of IOCG deposits in the Cloncurry District, Australia.

Fluid inclusion analyses were conducted on pre-ore quartz (Stage 2a), associated with magnetite, on syn-ore barite (Stage 3), associated with chalcopyrite and fluorite, and on post-ore calcite (late Stage 3). Stage 2a quartz hosts two fluid inclusion assemblages (FIA): 1A and 1B. Assemblage 1A is characterised by primary, aqueous liquid-solid-vapour fluid inclusions. Many of the 1A inclusions are almost entirely occupied by halite and were heterogeneously trapped. Assemblage 1B is composed of secondary, liquid-vapour, inclusions too small to study.

Stage 3 barite hosts three FIAs: 2A, 2B and 2C. Assemblage 2A comprises primary, aqueous liquid-vapour, moderate to low salinity (< 15 wt% NaCl_{eq}), inclusions that homogenise between 160° and 190°C. Assemblage 2B is comprises a first generation of secondary, moderately saline (< 9 wt% NaCl; < 18 wt% CaCl₂), liquid-vapour inclusions. Assemblage 2C is a later secondary generation of liquid-vapour inclusions that were also too small to analyse. Late Stage 3 calcite, which precipitated sequentially after barite, hosts Assemblage 2D. This assemblage is made up of primary, moderately saline (< 7 wt% NaCl; < 16 wt% CaCl₂), liquid-vapour inclusions.

Stable isotopes of Stage 2a quartz-magnetite, Stages 2–3 pyrite and Stage 3 barite-chalcopyrite were measured via *in-situ* SHRIMP and *ex-situ* conventional mass spectrometry methods. The $\delta^{18}\text{O}_{\text{VSMOW}}$ values of quartz at E1 North and E1 South fall in a narrow range from +12.7 to +14.8‰, while magnetite values are characterised by a much broader range of 0 to +8‰; such a range may be the result of partial isotopic reequilibrium. The $\delta^{34}\text{S}_{\text{CDT}}$ values from E1 North, the largest orebody by total contained Cu-Au, range from –5‰ to +3‰ for chalcopyrite, +1 to +8‰ for pyrite, and +7 to +21‰ for barite. E1 South and East are characterised by $\delta^{34}\text{S}$ values nearly 10‰ higher

than E1 North for all three minerals. Despite such variation, calculated barite-chalcopyrite equilibrium temperatures range from 230 to 330°C in all three deposits, though equilibrium was only approached in fine-grained alteration samples that probably formed over timescales greater than 10 Kyr. Estimated $\delta^{34}\text{S}$ of the bulk fluid ($\delta^{34}\text{S}_{\Sigma\text{S}}$) at E1 North is +4 to +5‰, whereas at E1 South it is much higher at +16‰. The $\delta^{34}\text{S}_{\Sigma\text{S}}$ value of E1 South is similar to measured $\delta^{34}\text{S}$ values of Corella marble carbonate-associated-sulfate (+12‰). The $\delta^{34}\text{S}$ values of the minerals and bulk fluid constrain f_{O_2} and pH conditions to a narrow range near the barite stability boundary. The shift in bulk fluid $\delta^{34}\text{S}$ from E1 North to E1 South is most likely explained by the addition of sulfur from a second source.

The pre-ore fluid composition and oxygen isotope signature are most consistent with a magmatic-hydrothermal fluid. The bulk $\delta^{34}\text{S}$ signature of the ore-stage fluid at E1 North is consistent with that of magmatic-hydrothermal deposits. The magma was probably an evolved, alkaline, oxidized, and Cu-Au-F-U-REE-bearing granite, and is speculated to be related to the Williams-Naraku Batholith. The higher bulk $\delta^{34}\text{S}$ value of E1 South is interpreted to represent mixing of the magmatic fluid with a shallower fluid that equilibrated isotopically with Corella Formation sulfate. The steeply-plunging folds and shear zones hosting the E1 Group orebodies may have served as conduits for such an external fluid to interact with the Corella.

Precipitation of chalcopyrite was probably caused by salinity decrease brought upon by mixing of the magmatic fluid with fluids in equilibrium with Corella Formation marble. CO_2 is not present in any FIA in E1 Group samples analysed in this study, suggesting that much of the CO_3^{2-} may have been derived locally from the calcareous host rocks. The paucity of CO_2 may explain the absence of ore brecciation in contrast to the adjacent Ernest Henry IOCG breccia system.

Introduction

The fluid and metal sources of iron oxide-Cu-Au (IOCG) deposits (e.g. Hitzman et al., 1992) have been investigated mainly through a combination of fluid inclusions, stable isotopes of oxygen, hydrogen and sulfur, and noble gas and halogen abundances.

Proposed fluid and metal sources for IOCGs are exclusively magmatic (e.g. Pollard, 2000), exclusively non-magmatic (i.e. metamorphic or evaporitic; Barton and Johnson,

1996; Barton and Johnson, 2004; Kendrick et al., 2006), and finally a hybrid mixing of both styles (Barton and Johnson, 2004; Kendrick et al., 2007; Hunt et al., 2007). These proposed fluid and metal sources appear to vary substantially between individual IOCG deposits, even within the same district (e.g. Fisher and Kendrick, 2008; Oliver et al., 2008). Thus, a detailed fluid characterisation of individual deposits is necessary to develop models of IOCG genesis. This chapter aims to characterise the fluid evolution of the E1 Group in order to improve the understanding of the IOCG genetic model. Here, fundamental fluid inclusion and oxygen and sulfur stable isotope evidence are presented, and possible fluid and metal source(s) of the E1 Group are discussed.

In the Cloncurry District, much of the previous work on IOCG fluids has been focused on quartz-hosted fluid inclusion and oxygen and sulfur stable isotope studies of these systems. Though these data alone may be equivocal, when combined they can provide significant insight into the origin and evolution of mineralising fluids. They may also be supplemented by studies on the abundances and ratios of noble gases and halogens, which have provided further constraint on the origins of fluids responsible for regional Na-Ca alteration and mineralisation at Mount Isa and Ernest Henry (Kendrick et al., 2006; 2007; 2008; 2011).

Fluid inclusion microthermometry and chemical analyses require a detailed petrographic and paragenetic understanding in order to draw meaningful geological conclusions. Consequently, an objective of this study is to delineate the fundamental petrographic relationships of fluid inclusions in paragenetically-constrained pre-ore and syn-ore samples, followed by fundamental microthermometric characterisation of the fluid inclusions.

Sulfur isotope studies of hydrothermal ore deposits necessitate both sulfide and sulfate mineral data in order to unequivocally interpret the origin of the source sulfur reservoir(s) (e.g. Ohmoto, 1972; Ohmoto and Lasaga, 1982). Without cogenetic sulfate data, the possible range of $\delta^{34}\text{S}_{\Sigma\text{S}}$ values that can be constrained by the measured $\delta^{34}\text{S}_{\text{sulfide}}$ values is broad because of possible variations in temperature, pH and f_{O_2} .

Previous sulfur isotopic studies on IOCGs in the Cloncurry District have focused mainly on sulfides, and are therefore limited in the constraints they place on the isotopic values and origin of total sulfur, $\delta^{34}\text{S}_{\Sigma\text{S}}$. This chapter presents cogenetic sulfide-sulfate

data that enable calculation of $\delta^{34}\text{S}_{\Sigma\text{S}}$. The sulfate isotopic data are presented in conjunction with detailed fluid inclusion studies of barite. The stable isotope and fluid inclusion characteristics of the E1 Group are compared to other IOCG deposits in the Cloncurry District. The results of this study provide insight into the fluid evolution of the E1 Group, and establish the geological context for further studies such as fluid inclusion-hosted noble gas and halogen characteristics.

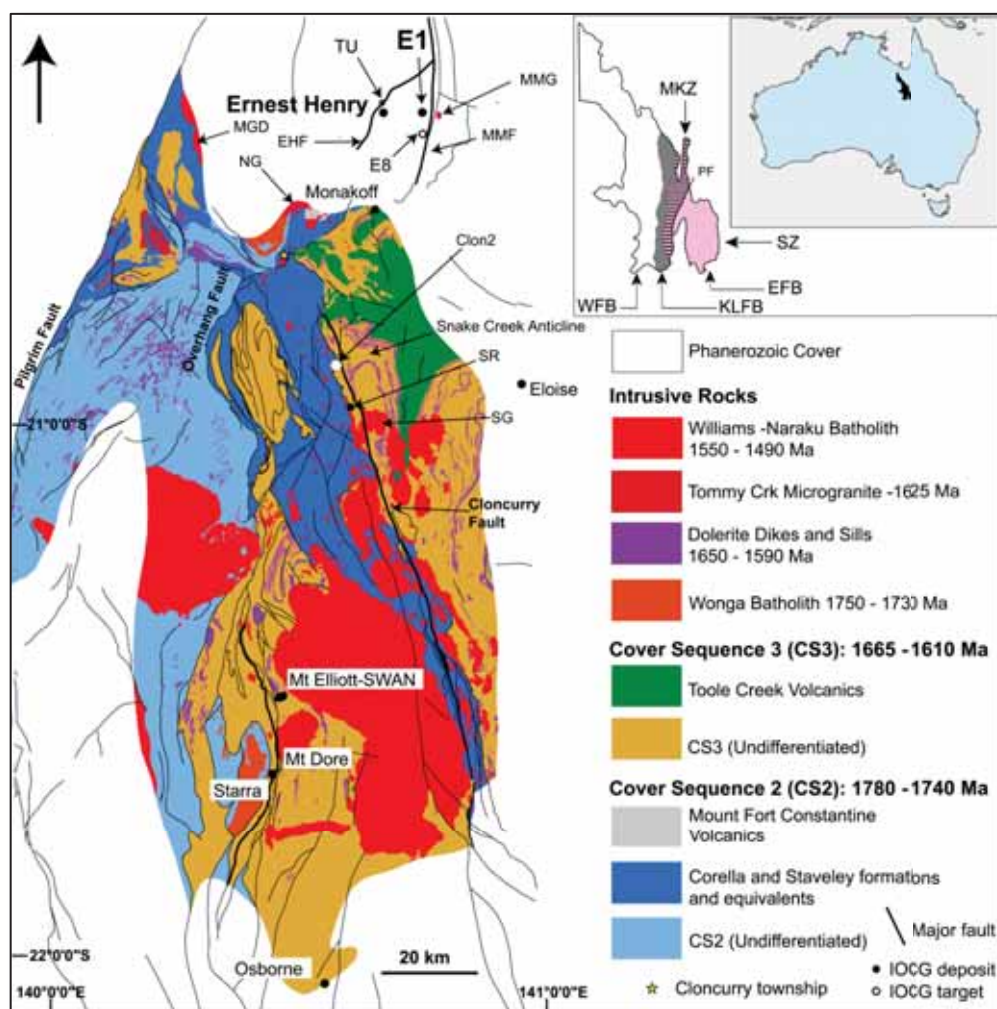


Figure 4.1: Exposed geology and structures of the Eastern Fold Belt east of the Pilgrim Fault (the Selwyn Zone). The inset shows the major belts of the Mount Isa Inlier. The Mary Kathleen Domain is the hashed line portion of the Eastern Fold Belt west of the Pilgrim Fault. Geology polygons and structure polylines modified from the Geological Survey of Queensland (2011). Structures below cover were interpreted by the authors of the report from geophysical datasets. “Clon2” is the CAS sample. EFB, Eastern Fold Belt; MKZ, Mary Kathleen Zone; SZ, Selwyn Zone; KLFB, Kalkadoon-Leichhardt Fold Belt; WFB, Western Fold Belt; MMG, Mount Margaret Granite; MMF, Mount Margaret Fault; EHF, Ernest Henry Fault; MGD, Mavis Granodiorite; NG, Naraku Granite; SR, Suicide Ridge; SG, Saxby Granite; TU, Third Umpire target.

Cloncurry District Geology and Fluid Characteristics

The E1 Group of IOCG deposits is located 40 km northeast of the town of Cloncurry in the Selwyn Zone of the Eastern Fold Belt of the Proterozoic Mount Isa Inlier of northwest Queensland (Fig. 4.1). The Mount Isa Inlier is subdivided into the Western Fold Belt, Kalkadoon-Leichhardt Belt, and Eastern Fold Belt tectonic domains (Blake, 1987). The Eastern Fold Belt is further subdivided into the Mary Kathleen Zone west of the Pilgrim Fault, and the Selwyn Zone east of the fault (Fig. 4.1). Ore deposit styles vary greatly between belts; the Western Fold Belt is dominated by Mount Isa-style Cu and Pb-Zn deposits, while the Eastern Fold Belt and Kalkadoon-Leichhardt Belt host varying styles of Cu-Au and Pb-Zn-Ag mineralisation, of which many are grouped into the IOCG classification (Williams et al., 2005; Groves et al., 2010).

Cover sequence deposition and early intrusions

The sedimentary and volcanic country rocks of the Eastern Fold Belt were laid down between 1875 and 1610 Ma in an intracratonic rift setting (Blake, 1987 and references therein; O’dea et al., 1997). They overlie ~1900 Ma basement rocks related to the Barramundi Orogen and are grouped into three major unconformable cover sequences (Blake and Stewart, 1992).

Cover Sequence 1 includes the 1870–1840 Ma Leichhardt (mafic) Volcanics and the Kalkadoon and Ewen granites, which are assumed to be their source magmas (Wyborn and Page, 1983). The Argylla Formation, Marraba (mafic) Volcanics, Mitakoodi Quartzite, Overhang Jaspilite, Corella/Doherty Formation and Mount Fort Constantine (intermediate) Volcanics of Cover Sequence 2 were then deposited between 1780 and 1740 Ma. The sedimentary rocks in the sequence were composed mainly of mudstones, sandstones, carbonate rocks, shales and evaporite rocks. Granites of the ~1740 Ma Wonga Batholith were intruded mostly in the western portion of the Eastern Fold Belt (Wyborn et al., 1988). Cover Sequence 3 was then deposited between 1690 and 1650 Ma; it includes turbidites of the Llewellyn Creek Formation, shales and sandstones of the Mount Norna Quartzite, and basalts and black shales of the Toole Creek Volcanics (Foster and Austin, 2008; Rubenach et al., 2008). The Staveley Formation has been considered by some to be part of Cover Sequence 3 (Foster and Austin, 2008), but may be as old as ~1740–1720 Ma and correlate with the Corella Formation (Betts et al., 2011; Carson et al., 2011).

Isan Orogeny: deformation and metamorphism

Deformational events in post-Barramundian rocks in the Eastern Fold Belt are related mostly to the 1650–1500 Ma Isan Orogeny (Blake et al., 1990; Rubenach et al., 2008). The deformation and metamorphic history of this orogeny is complex, but most workers (e.g. Adshead-Bell, 1998; Rubenach and Lewthwaite, 2002; Giles et al., 2006; O’dea et al., 2006; Rubenach et al., 2008; Abu Sharib and Bell, 2011) agree that at least four major contractional events occurred. The D₁ event (1630–1600 Ma) formed poorly-preserved east-west trending, steep, folds (Rubenach et al., 2008). The dominant north-south-trending, steep, folds and fabric ubiquitous in the Eastern Fold Belt formed in D₂ (1600–1580) at amphibolite facies peak metamorphic conditions (Page and Sun, 1998; Giles and Nutman, 2002; Rubenach et al., 2008). This was followed by the D₃ event (~1550 Ma; Page and Sun, 1998; Rubenach et al., 2008; Duncan et al., 2011), which generated steep north-northwest-trending folds and crenulation of S₂ (Rubenach et al., 2008). Steep, northeast-trending folds associated with additional crenulation of S₂ fabric are a late D₄ event that lasted from around 1530 to 1500 Ma (Davis et al., 2001; Rubenach et al., 2008).

Late intrusions, sodic-calcic metasomatism and IOCG mineralisation

After D₂ peak metamorphism in the Isan Orogeny, voluminous A-type granitoids of the Williams-Naraku Batholith (1550–1490 Ma) were intruded across the Eastern Fold Belt (Fig. 4.1; Page and Sun, 1998). The Mount Margaret Granite, 2 km east of the E1 Group, is the nearest Williams-Naraku Batholith outcrop to the deposit and intruded at 1530 Ma (Fig. 4.1; Page and Sun, 1998). No other outcrops of Williams-Naraku Batholith granites occur near Ernest Henry or E1; the next closest other granite pluton, the ~1505 Ma Malakoff Granite (Page and Sun, 1998) crops out 20 km southwest.

During the 1600–1500 Ma period, many regional sodic (albite ± scapolite) and sodic-calcic (albite ± actinolite ± scapolite ± diopside ± titanite) alteration and brecciation events also took place throughout the Eastern Fold Belt (Rubenach, 2013 and references therein). Major examples of extensive alteration include those coincident with the Osborne and Starra deposits (1600–1580 Ma, Gauthier et al., 2001; Duncan et al., 2011), Knobby Quarry albitite (1555 ± 9 Ma, Oliver et al., 2004), Suicide Ridge (1530–1525 Ma, Bertelli and Baker, 2010; Rubenach et al., 2008) and Ernest Henry (1529 ± 11/-8 Ma; Mark et al., 2006b). Regionally, sodic-calcic alteration is mostly barren, but some is associated with some IOCG orebodies and may be genetically related (e.g.

Ernest Henry; Mark et al., 2006b; Rusk et al., 2010; Osborne; Fisher and Kendrick, 2008; Mount Elliott; Wang and Williams, 2001; E1 Group; Chapter 2).

IOCG ores in the Cloncurry District formed between 1600 and 1490 Ma (Duncan et al., 2011). Temporally, the IOCG deposits can be grouped into those that formed prior to the 1550–1490 Ma Williams-Naraku Batholith (early or pre-Williams-Naraku Batholith), and those that formed during intrusion (late or syn-Williams-Naraku Batholith). The pre-Williams-Naraku Batholith IOCG deposits are Osborne and Starra, while the syn-Williams-Naraku Batholith deposits are the E1 Group, Ernest Henry, Monakoff, Mount Elliott-SWAN and Eloise (Chapter 2; Duncan et al., 2011 and references therein).

Fluid characteristics and genetic Models

Fluid inclusions and stable isotopes of ore deposits and barren alterations in the Cloncurry District, and in other IOCG districts in general, encompass a significant range of characteristics that are not easily reconciled by derivation from a single fluid source. Some existing fluid inclusion and stable isotope data and fluid source genetic models for the district are summarised below.

Fluid inclusions

Much of the work on IOCG fluid inclusions has been summarised in Pollard (2000), Williams and Skirrow (2000), and Hunt et al. (2007). The halogen and noble gas compositions of fluid inclusions in the Cloncurry District have been studied by Kendrick et al (2006; 2007; and 2008), as well as by Fisher and Kendrick (2008) and Baker et al. (2008). The characteristics of fluid inclusions in Cloncurry District IOCGs are shown in Table 4.6. Most of these fluid inclusions appear to be similar between all IOCG districts (Pollard, 2000; Hunt et al., 2007). Almost all fluid inclusion studies focus on quartz, as it appears to preserve more inclusions than other phases (e.g. Baker, 1996). Typical IOCG fluid inclusions hosted in pre-ore and ore-stage quartz are characterised by high- to hypersalinity (>30 wt% NaCl), with multiple daughter phases including halite, sylvite, magnetite, sulfides, and various Fe-Mn-salts, in association with CO₂-rich fluid inclusions (e.g. Adshead, 1995; Baker, 1998; Fisher and Kendrick, 2008; Kendrick et al., 2007; Hunt et al., 2007; Baker et al., 2008). At Ernest Henry, these ultra-saline (up to 70 wt% NaCl_{eq}) fluid inclusions are characterised by molar ⁴⁰Ar/³⁶Ar values ranging from about 29,000 to <2,500, Br/Cl values of 2×10⁻³ to

0.4×10^{-3} and I/Cl values of 11×10^{-6} to 1×10^{-6} (Kendrick et al., 2007); these ranges are considered by those authors to represent two distinct compositional endmembers. Osborne ore-stage fluids are variably saline (<12 – 65 wt% NaCl_{eq}), and some are CO₂-rich (Fisher and Kendrick, 2008). In contrast to Ernest Henry, their molar $^{40}\text{Ar}/^{36}\text{Ar}$ values are $<2,000$, though their Br/Cl (0.3 – 3.8×10^{-3}) and I/Cl (2.4 – 7×10^{-6}) values are similarly highly variable (Fisher and Kendrick, 2008).

In some cases, ore-stage and late-stage fluids are characterised by low to moderate salinities (Baker, 1998; Xu, 2000; Fisher and Kendrick, 2008); low-salinity and CO₂-rich fluid inclusions at Ernest Henry have molar $^{40}\text{Ar}/^{36}\text{Ar}$ values less than 2,500. In contrast, Xu (2000) documented late incursion of low to high-salinity H₂O–NaCl–CaCl₂ fluids in multiple IOCG deposits in the region, and in many cases observed an apparent salinity increase through time. Regional, barren, sodic-calcic (Na–Ca) and magnetite (e.g. Lightning Creek) alteration zones are generally characterised by similar, low- to high-salinity and CO₂-rich, early and late fluid inclusion populations (Blake et al., 1997; Perring et al., 2001); their molar $^{40}\text{Ar}/^{36}\text{Ar}$ (2,700 to 25,000), Br/Cl (0.3 – 4×10^{-3}) and I/Cl (0.2 – 35×10^{-6}) values also vary widely (Kendrick et al., 2008).

Oxygen and sulfur isotopes

Numerous studies have been published on oxygen and sulfur isotopes in IOCG deposits; Davidson and Dixon (1992), Mark et al. (2000), Marschik and Fontboté (2001), and Hunt et al. (2007) provide summaries on much of the data. Table 4.6 summarises sulfur isotope data for deposits in the Cloncurry District. Oxygen isotopes from quartz, magnetite, and carbonate have been analysed in Adshead (1995), Twyerould (1997), Little (1999), Mark et al. (2000), Perring et al. (2001), Baker et al. (2001), Marshall et al. (2006) and Hunt et al. (2007). Calculated equilibrium temperatures for quartz - magnetite assemblages in Cloncurry IOCGs, which typically pre-date mineralisation, are mostly higher than 400°C, and fluid $\delta^{18}\text{O}_{\text{VSMOW}}$ values derived from the same assemblages generally fall in a narrow range of +7‰ to +10‰ (Hunt et al., 2007). However, late-stage hematite and carbonate assemblages are characterised by a much broader range of $\delta^{18}\text{O}_{\text{fluid}}$ values (–5‰ to +15‰; Mark et al., 2006a; Hunt et al., 2007). Chalcopyrite and pyrite $\delta_{34}\text{S}$ values typically cluster near 0‰, and range from –2‰ to +5‰ (Table 4.6). Sulfate minerals (barite or anhydrite), which have not been significantly studied in the district, are significantly heavier due to the tendency of ^{34}S

to become enriched in more oxidized sulfur species (Seal, 2000); they range from +5‰ to +15‰ (Table 4.6; Davidson and Dixon, 1992; Oreskes and Einaudi, 1992; Twyerould, 1997; Andrew et al., 2001; Hunt et al., 2007).

Genetic models

Genetic models (i.e. hydrothermal fluid and metal sources and traps) for IOCG deposits remain the subject of debate in the Cloncurry District and world-wide. Although magmatic-hydrothermal fluid $\pm$ metal involvement has been proposed in many IOCGs (e.g. Pollard, 2000; Barton and Johnson, 2000; Sillitoe, 2003; Pollard, 2006; Knipping et al., 2015), fluid inclusion, stable isotope and halogen and noble gas data are in some cases equivocal, and most deposits have not been spatially linked to a causative intrusion. Consequently, non-magmatic and magmatic-non-magmatic hybrid mixing systems have been invoked to explain the genesis of many IOCG ores (Fig. 4.2; Barton and Johnson, 2000; Haynes, 2000; Mark et al., 2000; Mathur et al., 2002; Chiaradia et al., 2006; Hunt et al., 2007; Groves et al., 2010; Marschik and Kendrick, 2015). Some models suggest a common source for the fluids and metals, but the two may be distinct in some deposits.

In most magmatic-hydrothermal models, intrusions provide the dominant source of fluids and metals (Fig. 4.2A), although external fluids may provide sulfur and some metals (Pollard, 2006). The combination of hypersaline fluid inclusions and low $\delta^{34}\text{S}_{\text{sulfide}}$ and narrow range of $\delta^{18}\text{O}_{\text{water}}$ values described above have been interpreted as evidence for magmatic fluid and sulfur components (Hunt et al., 2007). Although the $\delta^{34}\text{S}_{\text{sulfide}}$ values alone are equivocal, the higher $^{40}\text{Ar}/^{36}\text{Ar}$ and I/Cl values for Ernest Henry described above add further evidence to a significant magmatic component in some IOCGs (Kendrick et al., 2007). Regional faults, commonly associated with IOCGs, may allow vertical and/or lateral movement of fluids kilometers away from source intrusions, concealing their association with the resulting deposit (Sillitoe, 2003). An example of the magmatic-hydrothermal fluid-dominated model in the Cloncurry District is the Lightning Creek magnetite prospect (> 2 Gt Fe; Perring et al., 2001), which is interpreted as a magmatic-hydrothermal precursor to IOCG ore (Perring et al., 2001).

Alternatively, non-magmatic fluid sources, such as basinal/connate waters and resultant halite-dissolution brines (Kendrick et al., 2007), bittern brines (Hammerli et al., 2014;

Marschik and Kendrick, 2015), or metamorphic fluids (i.e. fluids released during metamorphic dewatering reactions; Barton and Johnson, 2004; Duncan et al., 2011), may have been dominant in some IOCGs (Fig. 4.2B–C). The hypersaline fluids and metals could be derived from connate fluids in basin evaporite rocks like the Corella/Doherty Formations, and possibly also in mafic volcanic rocks such as the Toole Creek Volcanics. These basinal fluids may be convected through regional faults or shear zones by magmatic heat (Barton and Johnson, 1996, 2000, 2004), or expelled during metamorphism (Williams, 1994). In both cases, the fluids leach metals from the country rocks, though the magmas may also contribute metals (Barton and Johnson, 2004). As an example, the low $^{40}\text{Ar}/^{36}\text{Ar}$ and I/Cl values described above at the pre-Williams-Naraku Batholith Osborne deposit are considered evidence for substantial involvement of metamorphic brines, derived from metamorphosed evaporite-containing sedimentary rocks, in this deposit (Fisher and Kendrick, 2008). A similar source is interpreted for the Starra deposit, based on geochronological evidence placing it prior to the Williams-Naraku Batholith (Duncan et al., 2011); Cu and Au were probably derived from alteration of mafic country rocks by these fluids (Oliver et al., 2008).

Many authors (Mark et al., 2000; Barton and Johnson 2000, 2004; Williams et al., 2005; Hunt et al., 2007; Groves et al., 2010) argue that most IOCGs form from a combination of the aforementioned fluid types (Fig. 4.2A). Interaction between magmatic-hydrothermal and shallower fluids could be facilitated by the first- and second-order structures typically associated with IOCG deposits. Hybrid mixing models have been proposed for major IOCGs such as the Olympic Dam deposit in South Australia, (Haynes et al., 1995; Reynolds, 2000), and for deposits in the Cloncurry District that formed coevally with regional magmas, such as Ernest Henry (Twyerould, 1997; Mark et al., 2006b; Kendrick et al., 2007), Mount Elliott (Wang and Williams, 2001), Monakoff (Williams et al., 2015) and Eloise (Baker et al., 2001). At Ernest Henry, a broad range of oxygen and sulfur isotopes (Twyerould, 1997; Mark et al., 2006a) and mixed $^{40}\text{Ar}/^{36}\text{Ar}$ and halogen ratios (Kendrick et al., 2007) indicate that magmatic and metamorphic or halite-dissolution fluids were involved in ore formation.

Mixing of the fluids described above is the preferred driver of ore precipitation in most deposits (e.g. Haynes et al., 1995; Chiaradia et al., 2006; Kendrick et al., 2007; Williams et al., 2015). Meteoric or near-surface-derived waters may also be involved in mixing. Such mixing, in addition to wall-rock interactions, can lead to temperature and

salinity decreases, redox changes or sulfidation to destabilize metal complexes. In magmatic fluid-dominated systems, unmixing of brines and CO₂ has also been proposed to deposit ores (Pollard, 2006). This study will demonstrate that the E1 Group is an example of a hybrid, mixed magmatic-non-magmatic, IOCG deposit.

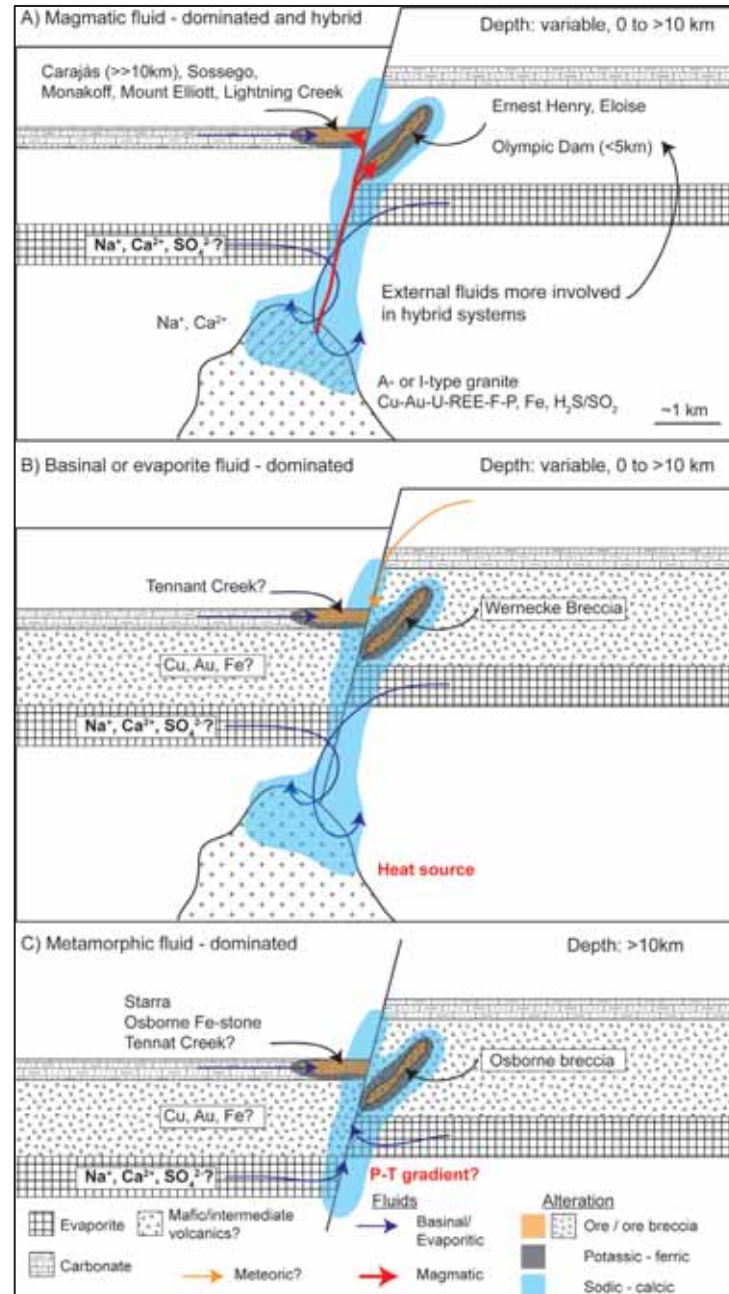


Figure 4.2: Idealized schematic diagrams of the three major IOCG fluid source models, based partly on Barton and Johnson (2004). A) Magmatic fluid-dominated and hybrid, in which magmatic fluids supply most of the metals and fluids, including Na and Ca. Some connate or surface fluid interaction may be necessary to account for metasomatism of the intrusion itself, and these are much more prevalent in hybrid systems. B) Basinal or evaporite fluid-dominated, in which magmas provide heat source to drive convection of connate basinal brines; near-surface evaporite fluids may also migrate down deep structures. Metals are mostly sourced from leaching of the country rocks (especially mafic volcanics). C) Metamorphic fluid-dominated, where fluids are presumably expelled from hydrous minerals during metamorphism. Temperature-pressure gradients may act as a fluid circulation mechanism. For each scenario, formation depth ranges are indicated.

E1 Group Geology, Structures and Paragenesis

The E1 Group of Cu-Au deposits – E1 North, East, and South – is located in the northeast Cloncurry District of the Eastern Fold Belt, 8 km east of the Ernest Henry IOCG deposit (Fig. 4.1). E1 East lies 700 m northeast of E1 North, and E1 South is 1 km southeast. The closest other target is E8, 2 km south of E1 South (Fig. 4.3). The E1 Group is hosted within Corella Formation metasedimentary rocks intercalated with intermediate Mount Fort Constantine metavolcanic rocks, both of Cover Sequence 2 (Chapter 2). The host rocks do not crop out and are unconformably covered by 30–50 m of Mesozoic sedimentary rocks. The metasedimentary rocks comprise marble, psammite, and carbonaceous metasiltstone and pelite (Fig. 4.4A–C). The metavolcanic rocks are basaltic meta-andesite to meta-andesite with variable porphyritic, amygdaloidal and massive textures, and metavolcanic breccia and metatuff (Fig. 4.4D–E). This metavolcano-sedimentary rock package is intruded by diorite (Fig. 4.4F), which is probably a part of the Ernest Henry Diorite suite (~1650 Ma; Page and Sun 1998). Clasts of the diorite are present in albite-hematite-K-feldspar-biotite-altered, discordant, breccia (Fig. 4.4G–I), that cuts across the system (Fig. 4.4I). The discordant breccia is intruded by dolerite dykes of unknown age (Fig. 4.4J). E1 Group ores are hosted mainly in the metasedimentary rocks (excluding the carbonaceous pelite), but strongly-sheared metavolcanic rocks are also mineralised in the E1 North Shear zone.

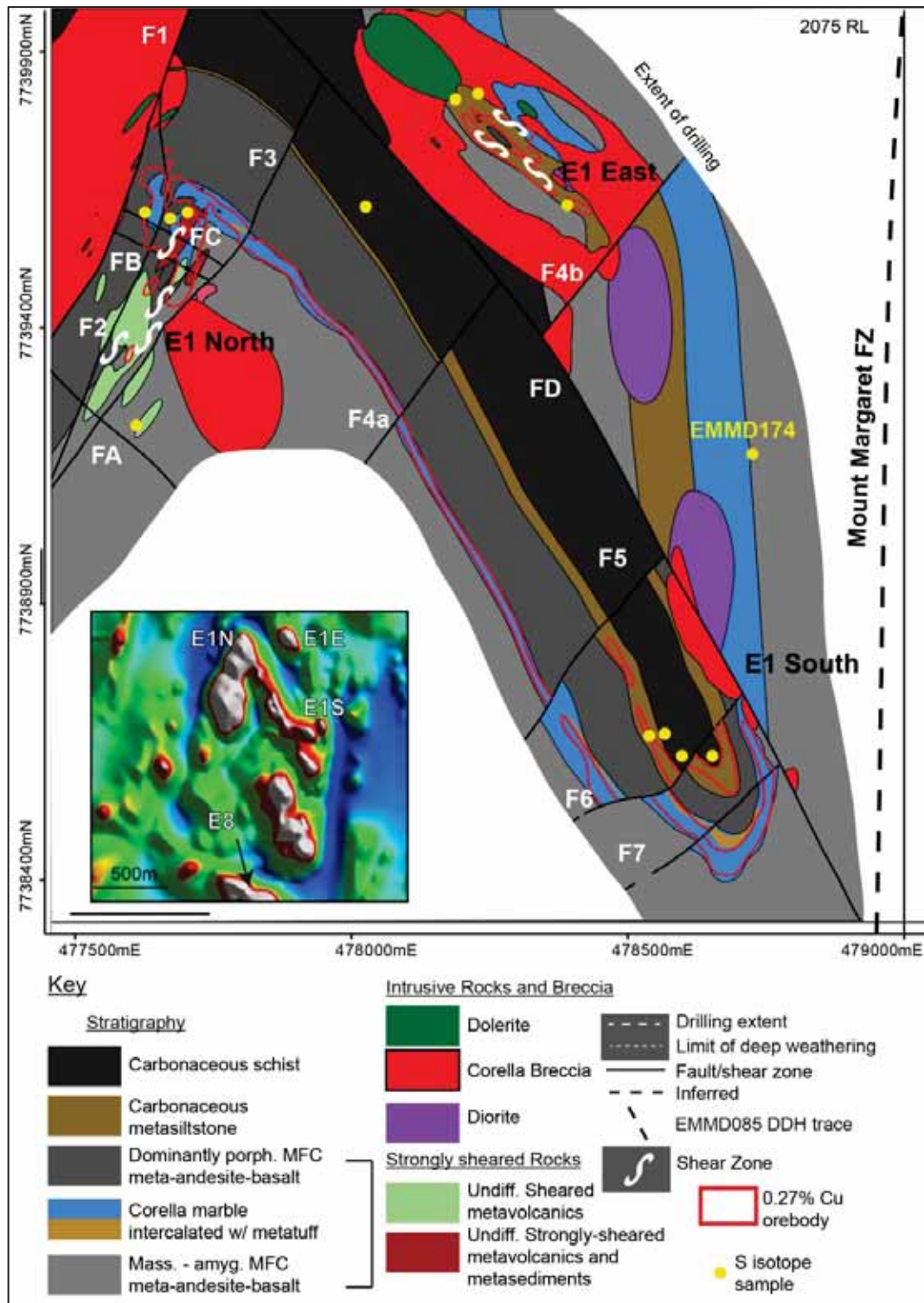


Figure 4.3: Geological map of the E1 Group at 2075 m RL / 75 m ASL, with isotope/fluid inclusion sample locations marked. Modified after Chapter 2. The inset is from Chapter 3 (Fig. 3.9) and shows the location of the E8 target. GDA 94 projection. RL, relative level mine datum; ASL, above sea level.

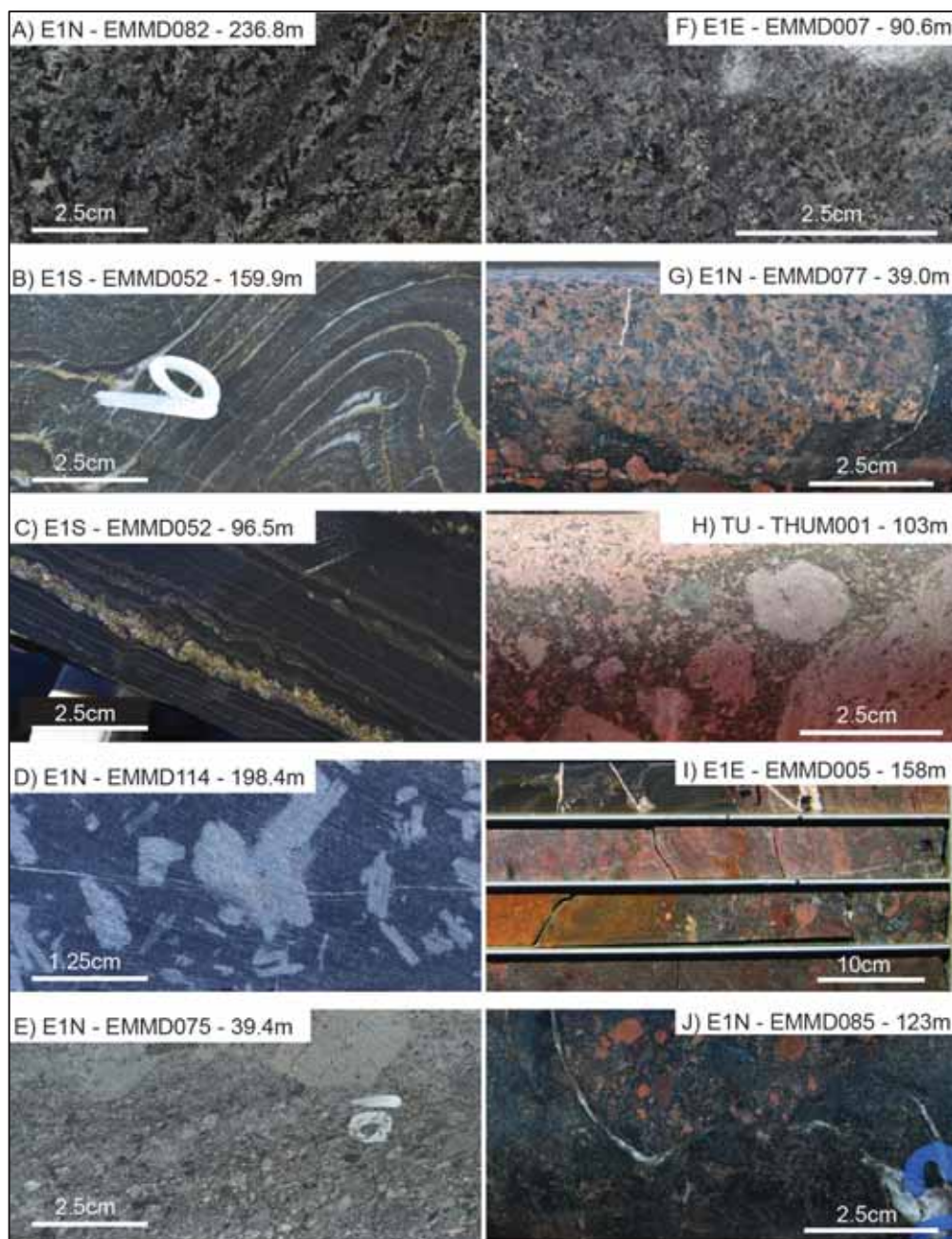


Figure 4.4: Drill core photographs of E1 Group host rocks. A) Porphyroblastic marble with disseminated magnetite and sulfide alteration. Porphyroblasts are chlorite after actinolite. B) Carbonaceous metasilstone with pyrite-carbonate-quartz alteration and veining. Note dilational fold microreefs infilled with carbonate and quartz. C) Carbonaceous schist/phyllite with similar pyrite-carbonate-quartz alteration. D) Representative plagioclase-phyric meta-andesite in metavolcanic rocks intercalated with Corella marble. Note slight albite(-hematite) alteration of phenocrysts. E) Metatuff. F) Diorite inferred to be from the Ernest Henry Diorite suite. G) Diorite clast in discordant breccia. H) Discordant breccia from Third Umpire prospect north of Ernest Henry. The matrix is composed mainly of albite, amphibole and pyroxene. (I) Strongly albite(-hematite)-K-feldspar-biotite-chlorite-carbonate-altered discordant contact of metasilstone (upper right part of core tray) with discordant breccia at E1 East. (J) Dolerite with discordant breccia xenoliths. E1N, E1 North; E1E, E1 East; E1S, E1 South. Act, actinolite; Cal, calcite; Py, pyrite; Qz, quartz; Bt, biotite; Chl, chlorite; Ab, albite; K-spar, K-feldspar; Px, pyroxene; Dol, dolerite.

The structures and deformation history of the E1 Group are described in detail in Chapter 3. The E1 North, South and East orebodies are hosted in a series of northwest - plunging regional D₂ folds: the E1 North Antiform, the E1 South Synform, and the E1 East Antiform, respectively (Fig. 4.3). These folds are related to smaller-scale F₂ folds, and the dominant S₂ foliation, observed in drill core (Chapter 3). The folds are cut by several northeast-southwest-trending and northwest-southeast-trending faults at E1 North (Faults 1–3 and B–D, Fig. 4.3). The faults bound intense shear zones trending northeast, collectively referred to as the E1 North Shear Zone. The shear zones are coincident with mineralisation and magnetite-apatite alteration along strike (Chapter 2; Chapter 3). Early movement on the faults was related to development of the E1 North Shear Zone in local D₃ / regional D₄ (Chapter 3). Faults 4–7 offset mineralisation, and are local D₄ / regional D₅ structures; Faults 1–3 were reactivated as oblique reverse faults during this event (Chapter 3). The Mount Margaret Fault Zone lies east of the deposit (Fig. 4.3); it is a long-lived structure that was probably active during deposition of the host rocks, and subsequently reactivated during local/regional D₂, local D₃ and later events (Chapter 3).

Mineralisation and alteration in the E1 Group are characterised by layer-controlled replacement bodies in the metasedimentary rocks, coupled with volumetrically minor veins (Chapter 2). Alteration in the E1 Group is complex, and is grouped into three main paragenetic stages, with the second, pre-ore, stage comprising three substages (Fig. 4.5). The stages are: 1) early sodic-(-calcic), 2a) precursor ferric/ferrous-potassic-silicic, 2b) intermediate sodic (-Ti), 2c) early carbonate (-Fe-Mg) flooding and mineralisation, and 3) main Cu-Au-carbonate(-Fe-Mn)- barite-fluorite-U-REE mineralisation (Chapter 2).

	Stage 1 Early Na-Ca	Stage 2a Fe-K-P	Stage 2b Na-Ti	Stage 2c CO ₃ flood	Stage 3 Late Min.	
Albite	██████████		-----			
Amphibole	██████████					
K-feldspar		██████████				
K(-Ba)-feldspar		-----				
Quartz	██████████	██████████		-----		
Ba-silicate		-----				
Biotite		██████████		----- Mg-Fe-rich	Fe-Mn-rich	
Carbonate				██████████	██████████	
Apatite		██████████				
Barite					██████████	
Chlorite				██████████	██████████	
Epidote					-----	
Fluorite			?		██████████	
Arsenopyrite		-----	-----			
Chalcopyrite				----- ?	██████████	
Bi-Au-sulfosalt*				██████████		
Electrum*						
Pyrite				██████████		
Pyrrhotite		-----	-----			
Hematite	██████████		?			
Magnetite		██████████	-----	██████████		
Bastnäsite						
Monazite						
U-silicate (tr)						
Uraninite (tr)						
Ilmenite		----- ?	-----			
Rutile		-----	-----			
Sericite	-----				██████████	
Titanite	██████████			----- ?		
Sphalerite				----- ?	-----	
Equivalent Ernest Henry Stage (Mark et al., 2006)	Na-Ca Cycle 1 Stage 1 Albite, amph., titanite	Stage 2 K-Fe Biotite, magnetite, K-feldspar	Na-Ca Cycle 2 Stage 2 Albite	Stage 3 Mineralization		
Equivalent Monakoff Stage (Williams et al., 2014)	Stage 1 Ca Garnet, biotite	Stage 2 K-Fe Magnetite, biotite, pyrrhotite		Stage 3 Main ore Fluorite, barite, calcite (-Mn), chalcopyrite, galena., sphalerite., U-REE	Stage 4 Late ore Alloclasite, Au-pyrite, Arsenopyrite	

Figure 4.5: E1 Group paragenetic sequence from Chapter 2, with equivalent Ernest Henry and Monakoff stages as reported by Mark et al. (2006b) and Williams et al. (2015), respectively. Bar thickness corresponds to relative abundance. Dashed line indicates uncertain timing. *Indicates phases identified in Williams et al. (2015).

Fluid Inclusion and Stable Isotope Systematics

Determination of fluid inclusion origin

Fluid inclusions in E1 Group samples were grouped into fluid inclusion assemblages (FIA) based on their origin: primary or secondary. Criteria described in Roedder (1984) and Van den Kerkhof and Hein (2001) were used to interpret the origin of the fluid inclusions. Namely, fluid inclusions were interpreted to be primary if they were: isolated or occurred in non-linear clusters, relatively large with respect to their host mineral, and not in trails except those parallel to mineral growth zones (i.e. ‘pseusecondary’). Although not necessarily diagnostic, negative crystal shape was considered as additional evidence for a primary origin (Roedder, 1979). Fluid inclusions not characterised by these features were assumed to be secondary in origin.

Calculation of system physiochemical parameters

The fluid inclusion and stable isotope data presented are used to constrain physiochemical parameters such as pressure and temperature conditions of ore precipitation, values of bulk $\delta^{34}\text{S}$ ($\delta^{34}\text{S}_{\Sigma\text{S}}$) or $\delta^{18}\text{O}_{\text{water}}$, salinity, pH and f_{O_2} . All oxygen isotope ratios are reported as $\delta^{18}\text{O}$ values (‰) normalized to the Vienna Standard Mean Ocean Water (VSMOW), and all sulfur isotope ratios are reported as $\delta^{34}\text{S}$ (‰) normalized to Canyon Diablo Troilite (CDT).

Temperature

Isotope-pair geothermometry relies on the assumptions that the mineral pairs of interest formed under equilibrium conditions at the same time, and that neither mineral has been subjected to later partial or total isotopic reequilibrium (Ohmoto and Rye, 1979; Seal, 2006). Theoretical aspects of isotope geothermometry are presented for oxygen in Clayton and Epstein (1961), and for sulfur in Sakai (1968), Ohmoto (1972). The temperature equations used for quartz-magnetite and barite-chalcopyrite temperature calculations are shown in Table 4.1.

Table 4.1: Summary of Equations used for isotope-pair thermometry

Equation ^{1, 3}	Temperature Range (°C)	Δ range (‰) ²	Reference
Oxygen			
(1) $1000 \ln \alpha_{\text{quartz-H}_2\text{O}} = 2.05 \times 10^6 T^{-2} - 1.14$	500–800	<10	Matsuhisa et al. (1979)
(2) $1000 \ln \alpha_{\text{quartz-H}_2\text{O}} = 3.306 \times 10^6 T^{-2} - 2.71$	180–550	>9.5	Ligang et al. (1989)
(3) $1000 \ln \alpha_{\text{magnetite-H}_2\text{O}} = -0.426 \times 10^{18} T^{-6} + 3.302 \times 10^{12} T^{-4} - 8.984 \times 10^6 T^{-2}$	300–800	all	Cole et al. (2004)
Sulfur			
(4) $1000 \ln \alpha_{\text{SO}_4 - \text{H}_2\text{S}} = 6.463 \times 10^6 T^{-2} + 0.56$	200–400	14.5 - 29	Ohmoto and Lasaga (1982)
(5) $1000 \ln \alpha_{\text{barite - H}_2\text{S}} = 7.95 \times 10^6 T^{-2}$	>400	>14.5	Ohmoto and Rye (1979)
(6) $1000 \ln \alpha_{\text{chalcopyrite - H}_2\text{S}} = 0.05 \times 10^6 T^{-2}$	0–1000	all	Li and Liu (2006)
(7) $1000 \ln \alpha_{\text{pyrite - H}_2\text{S}} = 0.4 \times 10^6 T^{-2}$	200–700	all ⁴	Ohmoto and Rye (1979)

¹T is in K²difference between $\delta^{18}\text{O}_{\text{quartz}}$ and $\delta^{18}\text{O}_{\text{magnetite}}$, or $\delta^{34}\text{S}_{\text{barite}}$ and $\delta^{34}\text{S}_{\text{chalcopyrite}}$ ³fractionation between SO_4 and barite is negligible (Sakai, 1968)⁴one barite-py sample was analysed

Pressure

Based on the assumption that the homogenisation temperature of a fluid inclusion represents its minimum trapping temperature, the trapping pressure of the inclusion can be estimated if the true trapping or formation temperatures of the host mineral are known. Pressure estimates for Stage 3 barite-chalcopyrite formation are estimated from the calculated barite-chalcopyrite formation temperatures and ice melting and homogenisation temperatures from barite primary inclusions using an Excel spreadsheet from Steele-MacInnis et al. (2012).

Fluid $\delta^{18}\text{O}$

The value of fluid $\delta^{18}\text{O}_{\text{VSMOW}}$ can be derived from temperature estimates calculated using values for $\Delta_{\text{quartz-magnetite}}$ mineral pairs that were in isotopic equilibrium. To estimate the $\delta^{18}\text{O}$ composition of the Stage 2a fluid, calculated quartz-magnetite

temperatures were substituted into equations (1) and (2) (Table 4.1) to derive the 1000 $\ln \alpha_{\text{quartz-H}_2\text{O}}$ of the fluid and its $\delta^{18}\text{O}$ composition.

System total sulfur

Estimating the bulk $\delta^{34}\text{S}$ of an aqueous system ($\delta^{34}\text{S}_{\Sigma\text{S}}$) is more complex than oxygen because of the numerous aqueous sulfur species and minerals typically present in hydrothermal systems (Sakai, 1968). Sakai (1968), Ohmoto (1972), and Ohmoto and Lasaga (1982) demonstrated that, when in chemical and isotopic equilibrium, fractionation between sulfur isotopes in various aqueous sulfur species and precipitated minerals is dependent on a combination of temperature, pH, f_{O_2} , and the bulk fluid $\delta^{34}\text{S}$ ($\delta^{34}\text{S}_{\Sigma\text{S}}$).

To determine $\delta^{34}\text{S}_{\Sigma\text{S}}$, the following assumptions must be valid: (1) $\delta^{34}\text{S}_{\Sigma\text{S}}$ must be constant throughout the precipitation process, with deviations only due to fractionation between SO_4^{2-} and H_2S , and (2) the mole ratio of $\text{SO}_4^{2-}/\text{H}_2\text{S}$ must not change significantly (Field and Gustafson, 1976; Seal, 2006). In order to satisfy assumption (1), the sulfur reservoir of the system must be, for practical purposes, unlimited in order to prevent Rayleigh fractionation. These assumptions appear to be generally valid for many porphyry systems dominated by oxidized magmatic-hydrothermal fluids, in which the dominant sulfur species is SO_2 (Seal, 2006). In such systems, SO_2 undergoes disproportionation (hydrolysis) into SO_4 and H_2S according to the reaction:



With these assumptions in mind, $\delta^{34}\text{S}_{\Sigma\text{S}}$ can be regressed using two types of plots of mineral $\delta^{34}\text{S}$: a Δ - δ diagram (e.g. Fig. 4.17; Field and Gustafson, 1976), and a δ - δ diagram (e.g. Fig. 4.18; Gregory and Criss, 1986; Criss et al., 1987; Fifarek and Rye, 2005). Both diagrams also provide estimations of mole fractions of SO_4^{2-} and H_2S in the fluid phase, and provide constraints in the pH and f_{O_2} conditions of the system.

When coupled with mineral assemblage observations, pH and f_{O_2} can validate $\delta^{34}\text{S}_{\Sigma\text{S}}$ estimations. The utility and caveats of these methods are described in Field and Gustafson (1976), Rye (2005) and Seal (2006).

Sampling

Individual sample descriptions for fluid inclusion and oxygen and sulfur isotope samples are detailed in Appendix G (the same samples were used for both studies). Sulfur isotope sample locations are shown in Figure 4.3.

Fluid inclusion samples

For fluid inclusion studies, two drill core samples each were selected of pre-ore, Stage 2a quartz (Fig. 4.5) and syn-ore, Stage 3 barite (Fig. 4.5). Several quartz vein samples were collected from other areas of E1 North and E1 East, but almost every sample lacked fluid inclusions large enough to make useful observations. Ongoing deformation during mineralisation (Chapter 3) probably partially recrystallized much of the Stage 2a quartz in the system. One sample from Stage 2a (Figs. 4.6A; 4.8A) was collected from 326.83 m in drill hole EMMD022 (sample EMMD022-326.83m), and is characterised by massive, moderately-crystalline (0.5–1 mm) quartz associated with euhedral, 0.5–2 mm magnetite; visually, it is only weakly mineralised. The drillhole transects the E1 North Shear Zone on the west limb of the E1 North Antiform (Fig. 4.3). At the drill core scale, the quartz and magnetite are probably infill in a vein which has been partly obscured by alteration selvages of magnetite. This sample is outside of the main E1 North orebody, but contains some late irregular veinlets and alterations of carbonate and chalcopyrite that overprint the magnetite and quartz. Most of the protolith textures near the sample have been destroyed by extensive deformation and metasomatism, but sporadic amygdules indicate that much of the drillhole is composed of sheared Mount Fort Constantine intermediate-mafic meta-andesite-basalt.

Undulose extinction and irregular boundaries in some quartz crystals (Figs. 4.8C; 4.9D) indicate that some quartz has been subjected to a moderate degree of microstructural deformation (e.g. White, 1973). The euhedral nature of the magnetite suggests it was originally intergrown with the quartz. Cathodoluminescence imaging of the quartz (Fig. 4.9E) yields no obvious difference between the quartz interstitial to magnetite, and the veinlets within it. It is thus likely that the quartz veinlets represent local reprecipitation of quartz removed via pressure dissolution during deformation. Stage 2 magnetite-quartz-biotite is syn-local D₃ /regional D₄ (Chapter 3); it is not clear if the deformation in the quartz is related to local D₃ or a later event. Partial recrystallization and

deformation of the quartz formed secondary inclusions near the crystal boundaries (Fig. 4.9D), but isolated primary fluid inclusions are preserved near the centers of crystals.

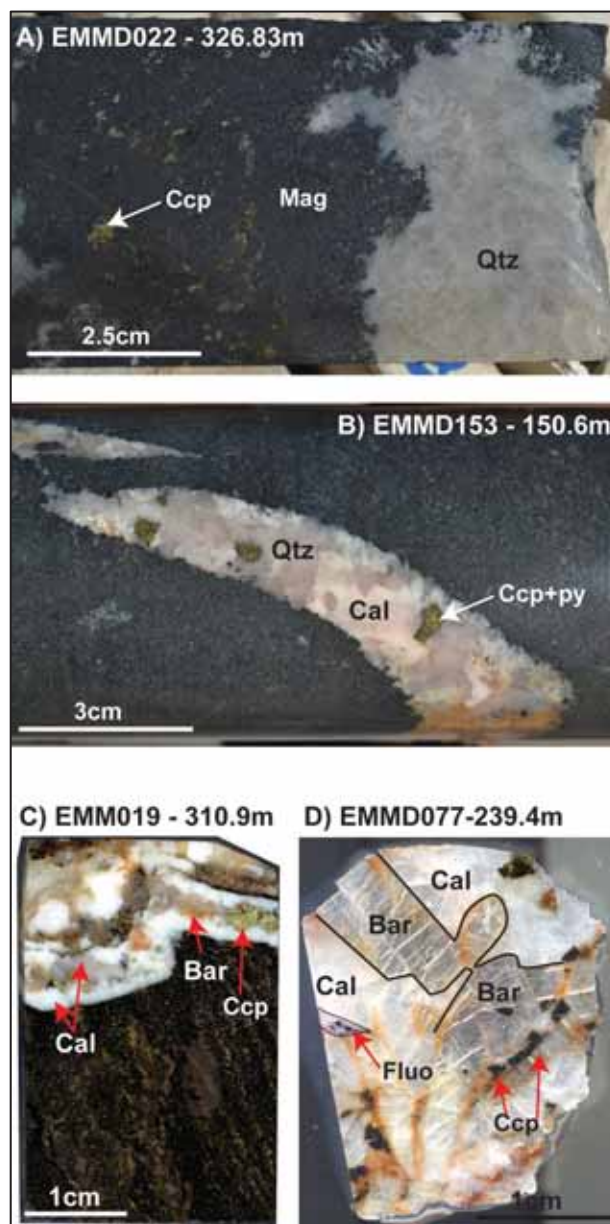


Figure 4.6: Fluid inclusion samples. A) Stage 2a quartz and magnetite, with minor Stage 3 chalcopyrite and calcite overprints. Collected from drillhole EMMD022-326.83 m. B) Stage 2a quartz vein with later Stage 2c calcite and Stage 3 chalcopyrite infill. Collected from drillhole EMMD153-150.6m. C) Stage 3 barite-chalcopyrite vein with late calcite substage (white mineral) that has re-opened the vein around the edges. EMM019-310.9m. D) Sample EMMD077-239.4m from E1 North, which is composed of a Stage 3 vein with early barite-chalcopyrite and late sub-stage calcite and fluorite infill.

Another Stage 2a quartz sample (EMMD153-150.6m; Figs. 4.6B; 4.9A) was taken from the east limb of the E1 North Antiform and within the orebody. It is clearly vein-hosted, and is characterised by large (up to 1 cm), euhedral quartz with little or no deformation. The sample lacks magnetite, but examples of vein-hosted Stage 2a magnetite are shown

in Figures 4.7G, I, J, L and Figure 4.8B; these magnetite-bearing quartz veins were not selected as they lacked sufficiently-large fluid inclusions. The vein in sample EMMD153-150.6m cuts across a deformed metatuff lens that is altered by magnetite, sericite, and carbonate. The metatuff lens is intercalated with Corella Formation marble. The calcite, pyrite and chalcopyrite, related to Stage 2c, precipitated after the quartz. In thin section the carbonate and sulfides are observed to replace the quartz at crystal edges. The relationship of the quartz and carbonate in this sample is consistent with the observation that carbonate and chalcopyrite of Stage 2c or later always overprint or fill the interstices of existing quartz crystals (Chapter 2); therefore, the carbonate in this sample is likely to be related to Stage 2c (Fig. 4.5).

A Stage 3 sample (EMMD077-239.4m; Figs. 4.6D; 4.9C) was collected from the west limb of the E1 North Antiform and within the E1 North orebody, and comprises vein-hosted, euhedral (~0.5–1 cm), barite associated with carbonate, chalcopyrite, and fluorite. The vein cuts across strongly sheared and metasomatized rock altered mostly to magnetite, barite, fluorite, and chalcopyrite. The protolith was either a volcanoclastic or calcareous sedimentary rock. The order of precipitation is barite → calcite ± fluorite. Chalcopyrite inclusions (< 5 µm) are present within the barite which suggests the two minerals are cogenetic rather than sequential.

Another Stage 3 sample (EMM019-310.9m; Fig. 4.6C; 4.9F) comes from drillhole EMM019 and intersects the Corella Formation marble horizon near the hinge of the E1 South Synform. The marble is strongly magnetite-chalcopyrite-pyrite-biotite-altered. The sample is vein-hosted and is characterised by a complex paragenesis with multiple stages of vein opening; the early vein was infilled mainly by barite and chalcopyrite, and was re-opened along the edges and filled in with late, white, calcite (Fig. 4.6C). The barite sample was collected from the vein at 310.9 m depth (EMM019-310.9m), and an additional calcite sample was taken from the same vein at 311.1 m (EMM019-311.1m; Fig. 4.9B).

Stable isotope samples

In order to adequately characterise the oxygen and sulfur isotope signatures of differing styles of E1 Group ores, samples were collected from both fine-crystalline Stage 2a quartz-magnetite and Stage 3 barite-chalcopyrite alteration, as well as from temporally-

equivalent veins. Figure 4.8 displays representative examples of the microtextures of quartz-magnetite and barite-chalcopyrite samples analysed via SHRIMP.

Oxygen isotope samples

Quartz-magnetite samples are characterised by fine- to medium-crystalline infill of vesicles in metavolcanic rocks and veins in both metavolcanic rocks and marble (Figs. 4.7G–H; 4.8A–C), and include sample EMMD022-326.83m described in the previous section. Quartz and magnetite are interpreted to have originally formed at the same time, based on intergrowth of the two minerals and the presence of magnetite inclusions in quartz (Figs. 4.6A; 4.8A–C).

Barite-chalcopyrite and pyrite samples

Five fine-crystalline chalcopyrite $\pm$ barite samples were collected from laminated, strongly magnetite-barite-fluorite-sulfide altered, carbonate-rich rocks in E1 North and South (Figs. 4.7A–D; 4.8D–E). The same samples also host laminae-parallel microveins (Figs. 4.7B; 4.8D; maximum width $\sim 500\ \mu\text{m}$) containing barite and chalcopyrite. In addition to the fine-grained samples, three vein-hosted barite-chalcopyrite-pyrite samples were analysed for isotope pairs, including the previously-described fluid inclusion samples EMM019-310.9m and EMM019-311.1m. Barite-chalcopyrite co-genesis in E1 samples is interpreted from intergrowth textures (Figs. 2.11T, Chapter 2; 4.8D–E), as well as from the presence of chalcopyrite inclusions in barite veins.

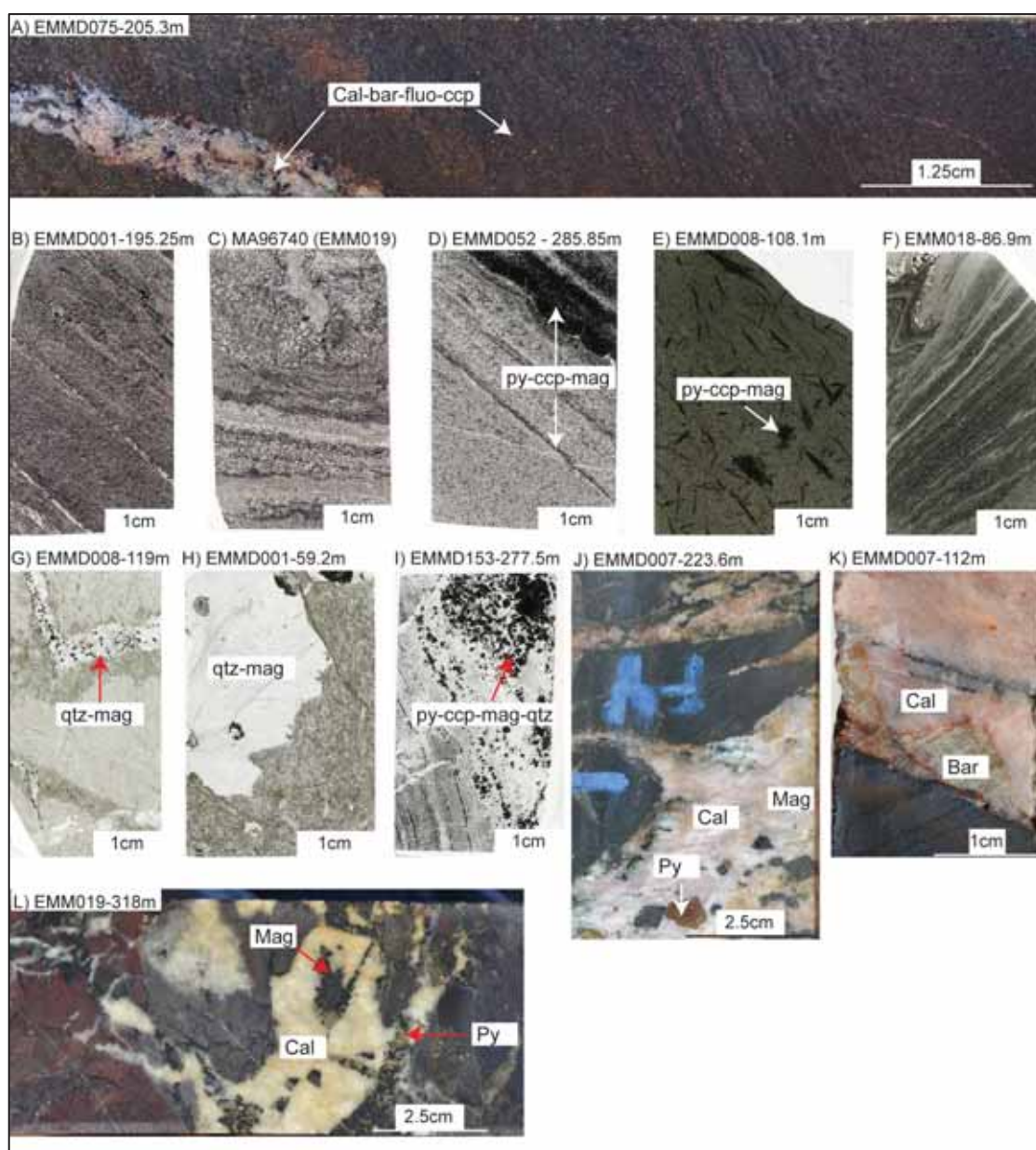


Figure 4.7: Representative photos of oxygen and sulfur isotope samples. A) Stage 3 carbonate-fluorite-barite-sulfide vein cutting metasedimentary rock completely altered by the same assemblage, and magnetite. The groundmass in the sample was also mapped by MLA (see Figure 2.9A). B) Layered rock (metasedimentary?) completely altered by magnetite-barite-fluorite-chalcopryrite-pyrite. C) Marble partly altered by magnetite, barite, fluorite, chalcopryrite. D) Marble with alternating pyrite-chalcopryrite-rich and -poor layers. Arrows point to analysis points. E) Porphyroblastic metasedimentary rock (marble?). Groundmass rich in biotite and chlorite; porphyroblasts may have been actinolite but now replaced by magnetite, pyrite and chalcopryrite. F) Carbonaceous schist (meta-black shale) with disseminated and blebby pyrite. G) deformed Stage 2a quartz-magnetite vein in meta-andesite. H) Stage 2a quartz (-magnetite)-infilled amydules in meta-andesite. I) Thin section from core shown in Figure 2.11P. Stage 2c magnetite (-quartz) and pyrite with Stage 3 chalcopryrite; infill? in siliceous marble. J) Stage 2c calcite-magnetite-pyrite vein cutting meta-andesite, overprinted by Stage 3? calcite. K) Stage 3 barite (and late substage) calcite vein cutting meta-andesite. L) Stage 2c calcite-magnetite-pyrite vein and breccia in meta-andesite cutting Stage 1 or 2b red alteration.

Twelve samples containing pyrite were also collected. Petrographic textures (Fig. 4.8D–H) suggest that the fine-crystalline (< 1 mm) pyrite alteration typically overprints or is ambiguous in relation to magnetite, and is sometimes overprinted by chalcopyrite (Fig. 4.8F), indicating that it is related to Stages 2c and 3. Two Stage 3 vein-hosted pyrite samples were also measured. Disseminated, very fine-crystalline (< 100 µm) and amorphous pyrite hosted in carbonaceous schist was also measured (sample EMM018-89.6m; Figs. 4.7F; 4.8H). The fine grain size and lack of obvious morphologic indicators (e.g. framboydial texture) make it difficult to assess whether this pyrite is primary, diagenetic and metamorphosed, or hydrothermal in nature. In addition to the disseminated pyrite, one sample (EMMD167-105.9m, E1 North) of vein-hosted pyrite cutting carbonaceous schist was analysed. The pyrite is associated with quartz and carbonate and is probably paragenetically late.

The rocks that host the fine-grained alteration and vein-hosted barite-chalcopyrite samples are generally interpreted to be marbles and calcareous metasiltsstones (Chapter 2), but the degree of metasomatism has inhibited clear protolith identification based on mineralogy. The lamination in the E1 North samples is likely to be a fabric after bedding, as the samples are located in the E1 North Shear Zone (Fig. 4.3). For example, sample EMMD085-310.5m (see MLA map in Fig. 2.9E) is characterised by deformed laminae, and probably represents a shear foliation. The laminations in E1 South samples are probably bedding, or bedding-parallel shears. Most of the pyrite and chalcopyrite-bearing and barite-poor samples are from meta-andesites and carbonaceous metasiltsstones.

In order to characterise the sulfur isotope signatures distal to mineralisation, two samples were analysed from drillhole EMMD174, which is located between the E1 East and E1 South orebodies (Fig. 4.3). Sample EMMD174-92.3m is composed of lightly-altered, pink, Corella Formation marble with substantial biotite shear foliation and minor, disseminated, pyrite and magnetite. Sample EMMD174-117.7m was collected from a hornblende amphibolite and contains minor disseminated pyrite and chalcopyrite. One sample was also collected from the E8 target (Fig. 4.3), located 2 km south of the E1 Group; the sample is from amygdaloidal basaltic meta-andesite. The E8 target is characterised by the same paragenetic sequence, and is probably part of the same hydrothermal system (Chapter 2).

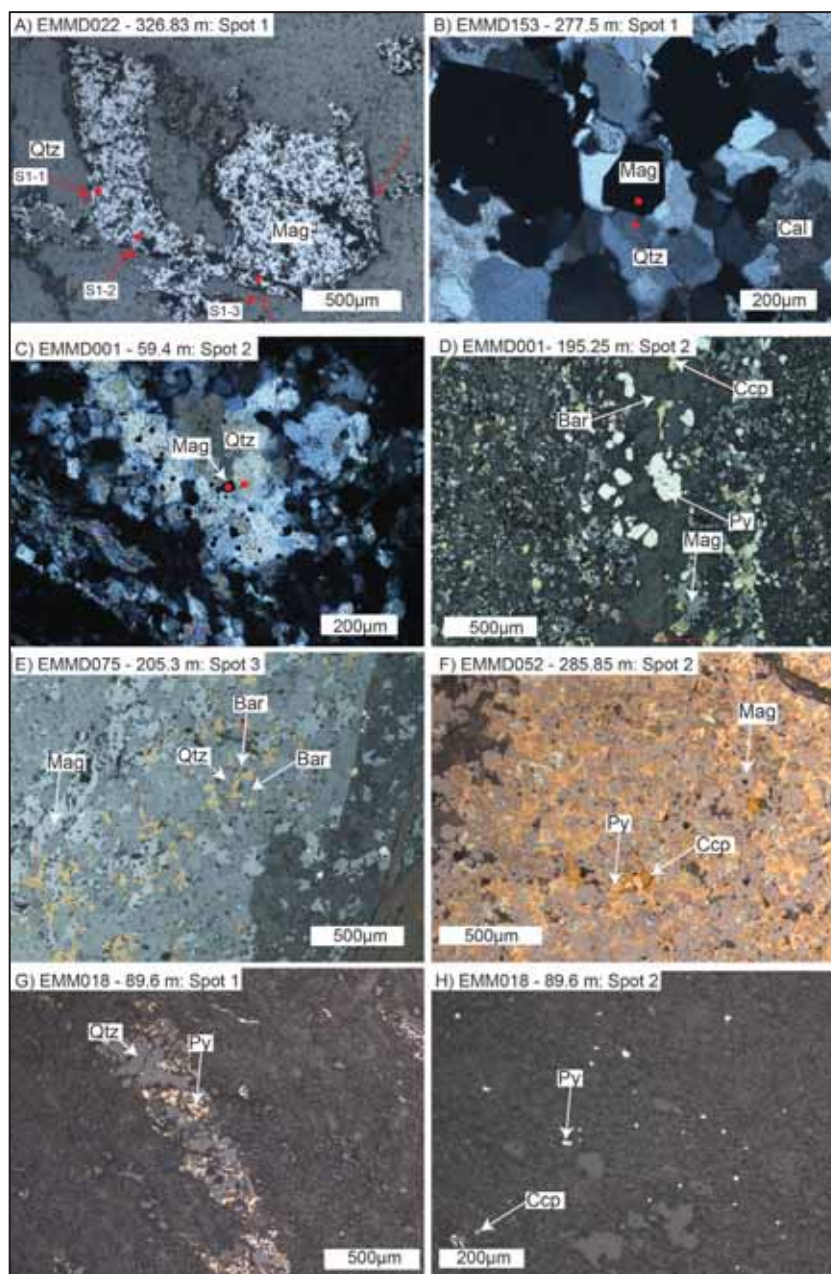


Figure 4.8: Representative photomicrographs of fine-grained samples analysed via *in-situ* SHRIMP. A) Stage 2a coarse-grained (>1mm) quartz-magnetite from the core shown in Fig. 4.6A; reflected light. Points correspond to the values reported in Table 4.3. B) Stage 2a quartz-magnetite vein overprinted by Stage 3 calcite; cross-nicols. C) Small amygdule with deformed Stage 2a quartz-magnetite infill in thin section from Fig. 4.7H; cross-nicols. D) Barite-chalcopyrite -pyrite microveinlet in the sample shown in Fig. 4.7B; reflected light. E) Reflected light view of groundmass from the sample in Fig. 4.7A. F) Reflected light view of the pyrite-chalcopyrite-magnetite-rich layer in the upper-right of the sample in Fig. 4.7D. G) Reflected light view of blebby infill? quartz-pyrite in the carbonaceous schist sample in Fig. 4.7F. H) Disseminated pyrite and chalcopyrite in the same sample. Red dots are analytical spots. Analytical spot size ~20–30 µm.

Along with sulfur isotope analyses of the mineralised E1 Group samples, two whole-rock specimens of unmineralised Corella Formation marble were sampled in an attempt to characterise the isotope signature of carbonate-associated sulfur (CAS; Kaplan et al., 1963) in the calcareous Corella Formation host rocks of the E1 Group. Carbonate

associated sulfate isotope analysis has been widely applied to ancient carbonates (e.g., Ueda et al., 1987; Gellatly and Lyons, 1996) and modern settings (Burdett et al., 1989). These samples were collected in the Snake Creek Anticline area south of Cloncurry ('Clon02' in Fig. 4.1) and away from any significant known Cu-Au deposits. The samples are characterised by relict interlaying of siliclastic-calcareous sedimentary rocks. The siliclastic layers have been boudinaged and albitised, and much of the original marble carbonate has recrystallized in boudin necks. The samples are composed of about 30–40% calcite, 30% quartz and/or albite, and 10–20% biotite, and contain minor scapolite, garnet and magnetite. The albite and magnetite are likely to be metasomatic. This style of deformation and mineralogy is typical of Corella Formation marbles throughout the Eastern Fold Belt (e.g. Marshall et al., 2006; Marshall and Oliver, 2008). No sulfide minerals are observed, i.e. sulfur measured in the analysis is probably hosted within carbonate and is not associated with metasomatism.

Analytical Methods

Fluid inclusions

Samples for making fluid inclusion thick sections were cut off from thin section sample blocks and mounted onto glass slides using beeswax. Next, the offcuts were ground and doubly-polished to sections between 200–300 μm in thickness. After polishing, the sample was removed from the glass plate and the beeswax was removed by melting the sample to $\sim 50^\circ\text{C}$. Most samples contain several different minerals of varying hardness including quartz, calcite, pyrite, chalcopyrite, barite, fluorite and chlorite, which hindered the grinding-polishing process and necessitated thicker sections to prevent sample destruction. For this reason the carbonate in most samples was not translucent enough for optical petrography and a separate sample from EMM019-310.9m was made to analyse carbonate related to the ore-stage. The thick sections were then split into chips $< 5\text{ mm}$ in size in order to fit in the heating-freezing stage.

Fluid inclusion studies were conducted on a Linkam heating-freezing stage (MDS600), which is attached to an Olympus BX52 microscope with 40x and 50x long working distance objectives. Schematic maps (Fig. 4.9) of the analysed inclusions were made before analysis. Each inclusion was sketched to record potential expansion or leaking, or phase changes (e.g., nucleation of solid phases) due to heating and/or freezing experiments. Low-temperature phase changes were measured prior to homogenisation

to maximize the number of analyses prior to potential decrepitation or expansion of fluid inclusions during heating. Low-temperature calibration of the heating-freezing stage was done by using a fluid inclusion standard (supplied by FluidInc) containing mixed H₂O-CO₂ inclusions and measuring the melting temperature of CO₂ (−56.6°C). Positive or negative deviations of this melting temperature, caused by instrument drift, were factored into observed melting temperatures in this study. These deviations are ±0.3°C, but are consistent throughout a given day; calibration is done daily. Observational error for final ice melting measurements is about ±0.5°C.

Calibration for heating runs is carried out weekly using the critical temperature of vapour-into-liquid homogenisation (T_{hl-v}) of H₂O (374°C); precision for these runs is typically ±4°C. This is comparable to observational error of T_{hl-v} in the samples, which is about 5°C because the vapour bubble shrinks beyond visual recognition immediately prior to homogenisation. To observe melting phase changes, the samples were cooled to below −100°C and subsequently heated to room temperature. Melting temperatures were measured using a heating rate of 2°C/min. Homogenisation temperatures were determined with a heating rate of 5°C/min. To ensure the reliability of homogenisation into the liquid phase, samples were heated until the vapour bubble was no longer visible, and then immediately cooled by ~20°C to test for delayed bubble reappearance. Composition and density for H₂O-NaCl and H₂O-NaCl-CaCl₂ fluid inclusions were calculated from numerical models by Steele-MacInnis et al. (2011, 2012) using their Excel spreadsheets. Microthermometry data are presented in Appendix F and histograms are displayed in Figure 4.11.

Stable isotopes

Values of $\delta^{18}\text{O}$ were measured from quartz-magnetite, and $\delta^{34}\text{S}$ from barite-chalcopyrite and pyrite (Figs. 4.6–4.8). The abundance of fine-crystalline alteration, with most barite, chalcopyrite, quartz and magnetite crystals smaller than 100 μm , and the relative paucity of veins in the deposit, necessitated *in-situ* analysis of most samples using Sensitive High Resolution Ion Microprobe (SHRIMP) instruments at the Australian National University. The procedures for SHRIMP $\delta^{18}\text{O}$ analysis are detailed in Ickert et al. (2008) and for $\delta^{34}\text{S}$ in Eldridge et al. (1987). The measured values of $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ of the internal laboratory standards, and their error, for each run are available in Appendix G. The following standards were used: UWQ-1 quartz ($\delta^{18}\text{O}_{\text{VSMOW}} =$

+12.3‰; Kelly et al., 2007); 5830 magnetite ($\delta^{18}\text{O}_{\text{VSMOW}} = +4.5\text{‰}$; Huberty et al., 2010); Norilsk chalcopyrite (+8.0‰; Crowe and Vaughan, 1996); Ba2 (+57.0‰) and Ba4 (+3.5‰) barites of Eldridge et al. (1987); and Ruttan pyrite (+1.2‰; Crowe and Vaughan, 1996). Analytical errors for $\delta^{18}\text{O}$ values are about $\pm 0.6\text{‰}$ for quartz and $\pm 1.2\text{‰}$ (App. G). Analytical errors on $\delta^{34}\text{S}$ values are generally ± 0.3 to $\pm 0.5\text{‰}$ for all sulfur minerals (App. G). In order to assess potential variation within the fine-grained samples, as well as zonation within larger vein-hosted minerals, numerous spots were analysed in each sample. The total numbers of analysed spots are 64 for chalcopyrite, 42 for pyrite, 40 for barite, and 9 for both quartz and magnetite.

In addition to SHRIMP, three sample each of vein-hosted quartz, magnetite, chalcopyrite, pyrite and barite were analysed using conventional *ex-situ* mass spectrometry (MS). The quartz and magnetite vein and vesicle infill samples were prepared using the BrF_5 technique (Clayton and Mayeda, 1963) and analysed *ex-situ* on a Finnigan MAT 252 IRMS at the US Geological Survey. The sulfur samples were analysed *ex-situ* via conventional Isotope Ratio Mass Spectrometry (IRMS) at the Stable Isotope Geochemistry Laboratory at the University of Queensland. The vein samples were crushed and sonic-washed, and grains of barite, chalcopyrite and pyrite were hand-picked for bulk analysis. Standards used by UQ are NBS127 (BaSO_4 ; $\delta^{34}\text{S}_{\text{CDT}} = +20.3\text{‰}$), IAEA S-1 ($\delta^{34}\text{S}_{\text{CDT}} = -0.3\text{‰}$), and IAEA S-3 ($\delta^{34}\text{S}_{\text{CDT}} = +32.3\text{‰}$). Analytical errors for *ex-situ* analyses of quartz, magnetite and sulfur minerals are in the same range as the SHRIMP errors described above (App. G). This method was used to analyse sulfur isotope pairs for barite and chalcopyrite in sample EMMD077-239.4m, which was also studied for barite fluid inclusions.

The whole-rock Corella carbonate associated sulfate (CAS) samples were processed and analysed at the University of Tasmania. CAS extraction techniques have been refined over the last two decades (see Wotte et al. 2012 and references therein) but, essentially, all use HCl to dissolve carefully washed and cleaned sedimentary (or metasedimentary) carbonate rocks. This releases lattice-bound and micro-inclusion sulfate from carbonate minerals in the rock. BaCl_2 is added to the resultant solution to precipitate BaSO_4 which is filtered from solution and analysed by conventional stable isotope mass spectrometric methods.

The Corella Formation marble samples were processed to extract (CAS) following the CAS procedure of Wotte et al., 2012. Cleaned pieces of core (~250g each) were crushed in a Mn-steel jaw crusher, then milled in a Cr-steel ring mill. Weighed amounts of powder (~200g) were washed multiple times with a 10% NaCl solution to remove any sulfate that was loosely-bound. The wash solutions were filtered, and aqueous BaCl₂ was added to them; any BaSO₄ precipitate was retained for isotopic analysis. When the wash solutions ceased to precipitate BaSO₄, the sample powders were reacted with several hundred millilitres of ~25% HCl and stirred regularly for 24 hours. If required, additional acid was added until the reaction stopped. The liquid from this step was also filtered and BaCl₂ solution was added to precipitate BaSO₄ for isotopic analysis. Undigested powder was dried and weighed in order to calculate how much carbonate was in the original sample and how much CAS was in the carbonate (Appendix G).

The five BaSO₄ filtrates (three washes and two acid digestions) were then analysed in duplicate using an IsoPrime100 mass spectrometer and Vario Pyro cube combustion system in the Central Science Laboratory at the University of Tasmania.

Reproducibility, based on duplicates, is around 0.2 to 0.3‰, and the results used here are likely to be in error by $\pm 0.5\text{‰}$ (App. G).

Results

Fluid inclusions

Five fluid inclusion assemblages (FIA) were observed in E1 North and South samples (Table 4.2). Stage 2a quartz hosts two major FIAs: FIA-1A primary fluid inclusions and FIA-1B secondary inclusions. Stage 3 barite hosts three major FIAs: FIA-2A primary, FIA-2B secondary (event 1), and FIA-2C secondary (event 2). Stage 3 calcite hosts a FIA similar to FIA-2B, which is referred to as FIA-2D. The characteristics of each assemblage are presented below, and summarised in Table 4.2.

Stage 2a quartz

Pre-ore, Stage 2a quartz associated with ferric/ferrous-potassic alteration hosts two FIAs. The first FIA (FIA-1A), is a population of liquid-vapour-multisolid inclusions (Figs. 4.9A; 4.10A–B). In sample EMMD153-150.6m, these inclusions are typically at least 15 μm in diameter, irregular to rectangular in shape, and occur either isolated or in clusters (Fig. 4.9A). The fluid inclusions contain halite crystals that range in size relative to the host inclusion from 10% of the cross-sectional area up to over 90% (Figs.

4.9A; 4.10A). The same fluid inclusions are also observed in sample EMMD022-326.83m, but here they are isolated only and are generally smaller ($< 10 \mu\text{m}$ in size). Freezing-melting profiles, conducted on a couple of inclusions with halite crystals $< 10\%$ of the size of the inclusion, yielded initial melting temperatures between -23° and -20°C , indicating a system dominated by H_2O - NaCl . Almost all the inclusions decrepitated between 400° and 450°C , and none homogenised below this temperature range.

Table 4.2: Summary of E1 Group FIAs

FIA	Stage	Mineral	Origin	Phases	System	Salinity (wt% NaCl)	ρ_{bulk} (g/cm ³)	T_{h} (°C)	Comments
1A	2a	quartz	primary	S + L + V	H_2O - NaCl	>50	-	-	Heterogenously trapped
1B	Post-2a	quartz	secondary	L $\pm$ V	-	-	-	-	too small to observe
2A	3	barite	primary	L + V	H_2O - NaCl	0 - 15	0.933	$160^\circ - 180^\circ$	-
2B	Late 3	barite	secondary	L + V	H_2O - CaCl_2 - NaCl	2.5–8; 9.5–18.5 CaCl_2	-	-	-
2C	Post-3?	barite	secondary	L + V	-	-	-	-	too small to observe
2D	Late 3	calcite	primary	L + V	H_2O - CaCl_2 - NaCl	2.9 – 6.5; 9.5 – 16.3 CaCl_2	-	-	-

The isolated to clustered distribution of FIA 1A in Stage 2a quartz suggests that this is a primary assemblage. The large variation in relative halite crystal size in these inclusions is indicative of heterogeneous trapping of a halite-saturated fluid during crystal growth (e.g. Van den Kerkhof and Hein, 2001). Such a process is in particular evidenced by fluid inclusions that are almost entirely occupied by halite (Fig. 4.10A–B). The possibility of heterogeneous trapping precludes the application of microthermometry for constraining the chemistry and trapping conditions of the quartz-forming fluids (Roedder, 1979).

The second FIA in quartz (FIA-1B) is a population of smaller, two-phase liquid-vapour inclusions. These rounded fluid inclusions form trails (Fig. 4.9A) in both quartz samples but are too small ($< 5 \mu\text{m}$) to observe phase changes and infer composition. In sample EMMD022-326.83m, this FIA is typically represented by fluid inclusions that are most abundant around the recrystallized edges of quartz crystals (Fig. 4.9D). They form, on the other hand, more linear trails in sample EMMD153-150.6m (Fig. 4.9A).

Fluid inclusion assemblage 1B is considered to be secondary in origin, based on the small size of the inclusions relative to 1A, and their distribution in trails and along crystal deformation boundaries (Fig. 4.9A, D).

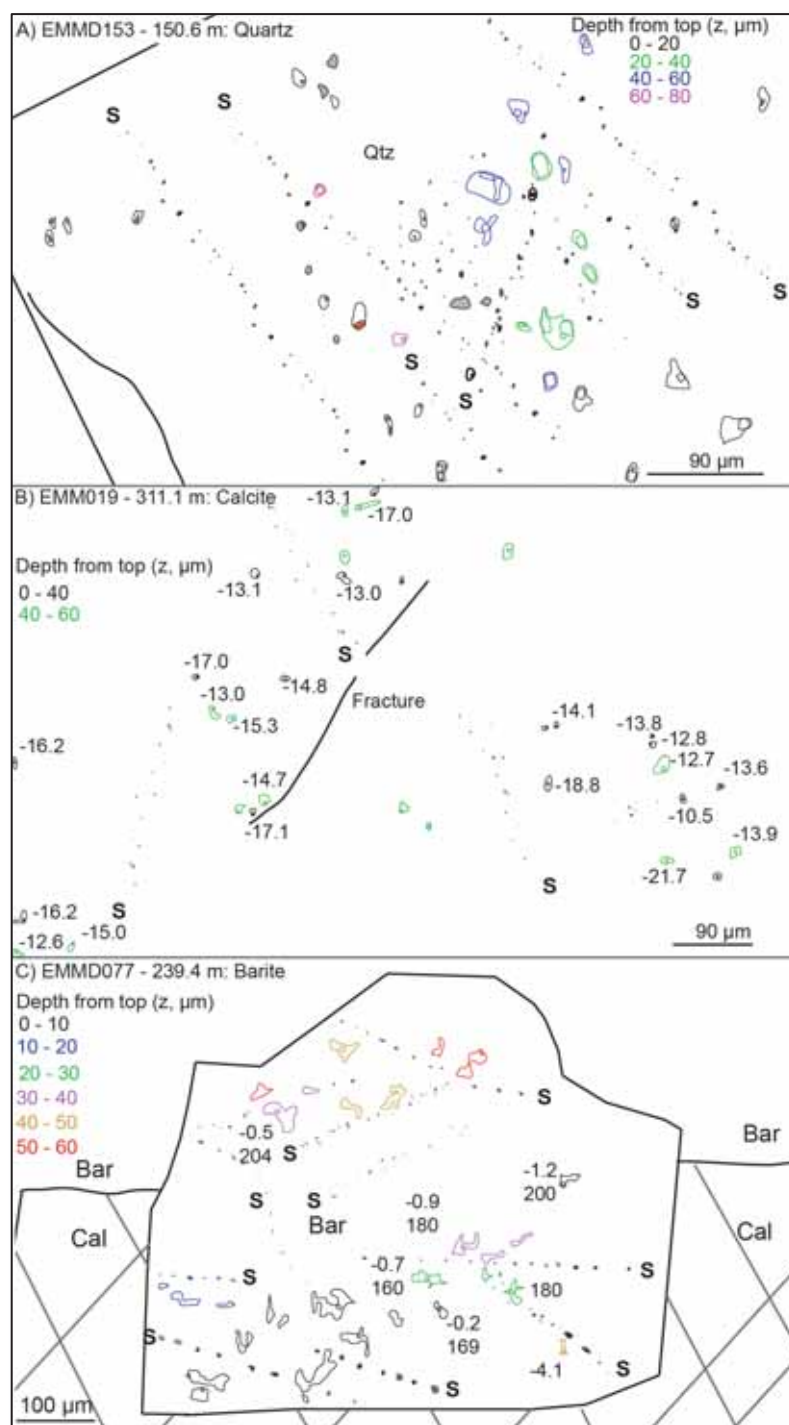


Figure 4.9: Schematic maps of E1 Group FIAs. A) FIA-1A in Stage 2a quartz. B) FIA-2D in Stage 3 calcite. C) FIA-2A and FIA-2B (secondary trails) in Stage 3 barite. Continued on the next page.

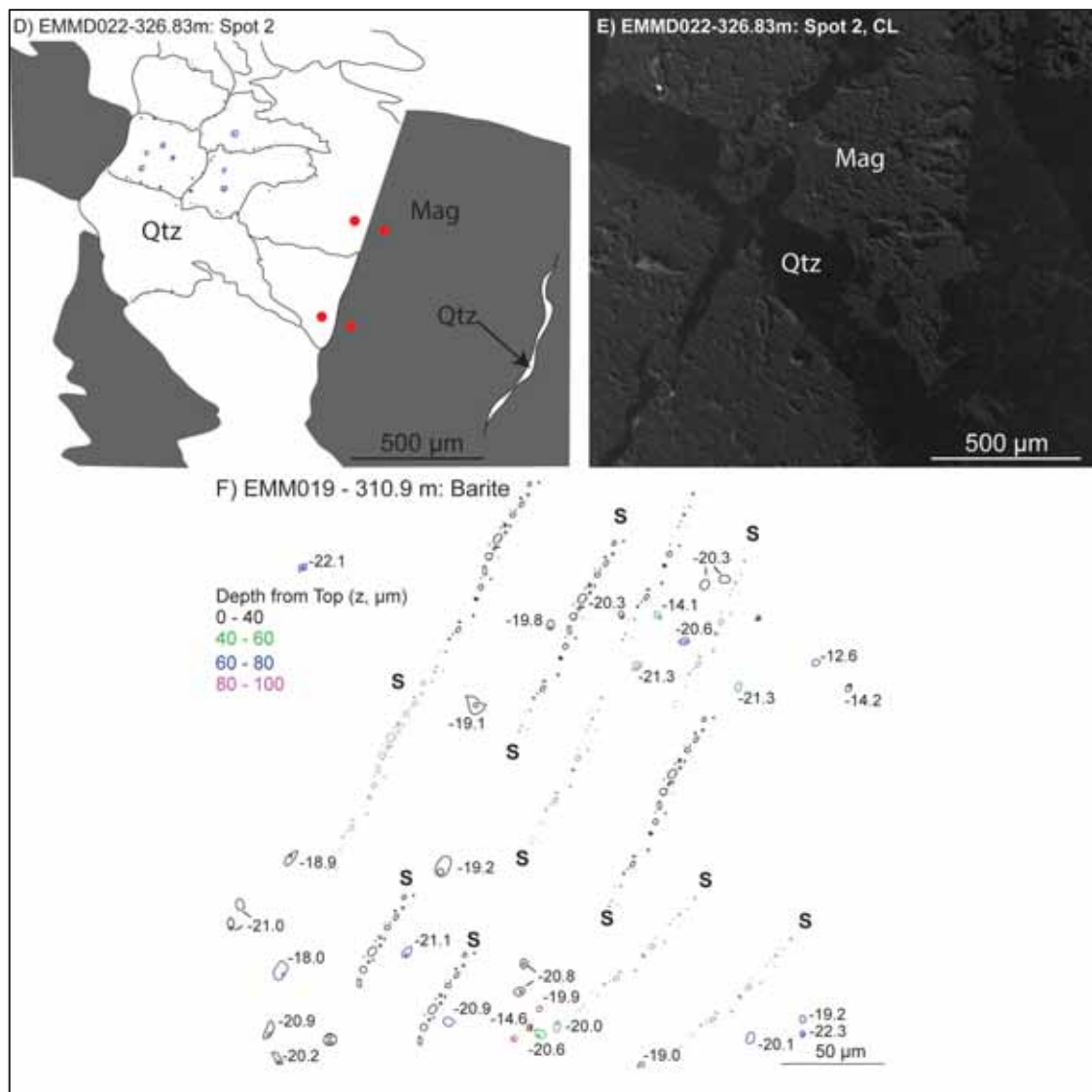


Figure 4.9 (cont.): D) Cartoon showing textural relationship of FIA-1A and FIA-1B in light- to moderately-deformed quartz in sample EMMD022-326.83. The FIA-1A inclusions are only preserved near the centers of the crystals, while FIA-1B inclusions are prevalent near the recrystallized boundaries. Black dots indicate approximate, representative locations of *in-situ* SHRIMP isotope analyses. E) CL image near the area shown in (D); the quartz is notably dark. Note only one generation of quartz is visible. F) Schematic map of the FIA-2B inclusions in barite; secondary trails are interpreted to be FIA-2C. Colours indicate the depth range of the inclusion within the sample. S, secondary; Qtz, quartz; Mag, magnetite; Bar, barite; Cal, calcite.

Stage 3 barite and calcite

Stage 3 barite hosts three FIAs. The oldest FIA (2A) includes two phase liquid-vapour fluid inclusions (Figs. 4.9C; 4.10C), which only occur in sample EMMD077-239.4m from E1 North. Table 4.2 presents summary qualitative and microthermometric data for this assemblage. The fluid inclusions are generally large (up to 70 μm) in diameter along the longest axis and characterised by irregular forms with many internal $\sim 90^\circ$ corners (Figs. 4.9C; 4.10C). They typically form in clusters and the edges of some of the fluid inclusions are subparallel to the barite crystal face (Fig. 4.9C).

Almost all of the inclusions are characterised by a degree of fill (DF; relative volume fraction of liquid phase, Shepherd et al., 1985) of 0.9 or higher; those with a DF of 0.7 to 0.9 probably leaked (App. F). The vapour bubbles in some of the inclusions are metastable, as they did not appear until after multiple cycles of freezing and heating.

Stage 3 barite FIA 2A is interpreted to be primary, based on the relatively large size (with respect to the host crystal), irregular shape, and isolated to clustered distribution of its inclusions (e.g. Van den Kerkhof and Hein, 2001).

Initial melting occurs between -23 and -21°C , indicating that NaCl is the dominant salt (Fig. 4.11C). Final ice melting occurs between -10.0 and 0.0°C (Fig. 4.11D). Some of the larger inclusions showed evidence of leakage after freezing (increase in vapour bubble size), which is probably caused by an increase of the fluid inclusion volume because of ice expansion (Roedder, 1962). The final ice melting temperatures yields a salinity range of 0 to 14 wt% NaCl. Upon heating, the homogenisation into the liquid phase occurred between 160° and 247°C ($n = 30$), though a single inclusion homogenised at 148°C (Fig. 4.11B).

The ten inclusions that homogenised within the range of 160 – 190°C (Fig. 4.11B) are most likely representative of the true minimum trapping temperature of the population. Another 19 fluid inclusions that homogenised above 195°C are interpreted to have experienced some degree of leakage, though some have similar degrees of filling to the intact inclusions.

Fluid inclusions of the second FIA (2B) in Stage 3 barite are composed of a two-phase, liquid-vapour inclusions that are generally rounded and range in size from about 5 – $15\ \mu\text{m}$ in diameter (Figs. 4.9C, F; 4.10D). In sample EMMD077-239.4m they form secondary trails across the barite crystal in various directions. The well-rounded shape and relatively small size of these inclusions makes them distinct from FIA-2A fluid inclusions. Figure 4.10E shows a rare example of a very irregularly-shaped FIA-2B fluid inclusion that is much larger than the other fluid inclusions in the associated trail. It appears to have originally been a FIA-2A fluid inclusion that has been refilled during the formation of FIA-2B. FIA-2B inclusions are characterised by a DF of 0.9 or higher, and inclusions with lower DF were ignored.

During freezing, yellow-brown, granular antarcticite (e.g. Goldstein and Reynolds, 1994) forms in the FIA-2B fluid inclusions (Fig. 4.10D). Initial melting is observed between -65 and -50°C , which indicates that the aqueous fluid is dominated by CaCl_2 and NaCl . Fine-crystalline aggregates of yellow-white hydrohalite are observed to melt between -35 and -29°C (Fig. 4.11C), but because of the small crystal and inclusion size, these measurements are probably at least $\pm 5^{\circ}\text{C}$ in error. Final ice melting occurs at temperatures between -19 and -9.1°C in the E1 North sample, and at temperatures between -23.7 and -10.5°C in the E1 South sample (Fig. 4.11D). These temperatures correspond to salinity range: 1.1–8.0 wt% NaCl and 2.1–18.4 wt% CaCl_2 , respectively (Figs. 4.11E–F; 4.12). FIA-2B inclusions in the E1 South sample (EMM019-310.9m) cluster in the more CaCl_2 -rich end of this range and contain nearly 5 wt% more CaCl_2 .

FIA-2C inclusions are small ($<5\text{ }\mu\text{m}$), two-phase, liquid-vapour inclusions, and are only clearly observed in sample EMMD077-239.4m, though they may also be present in samples from EMM019 in E1 South. They form linear trails that cut across both FIA-2A and 2B inclusions, and are therefore interpreted to be secondary inclusions. Phase changes in these inclusions were not studied as they are too small to observe. FIA-2B and 2C-FIAs are the only inclusions identified in Stage 3 barite in sample EMM019-310.9m from E1 South. Most 2B inclusions in this sample form secondary trails, though some are isolated.

FIA-2D fluid inclusions are hosted in Stage 3 calcite in sample EMM19-311.1m (Fig. 4.9B), and are virtually identical to the FIA-2B in terms of shape and composition (Fig. 4.11). FIA-2D inclusions, however, are significantly smaller ($5\text{--}10\text{ }\mu\text{m}$). Like the FIA-2B inclusions, they contain granular antarcticite and undergo eutectic melting between -65 and -50°C . Their hydrohalite melting temperatures range from -36° to -29°C , and their final ice melting temperatures range from -21.7° to -10.5°C (Figure 4.11E–F). These melting temperatures correspond to a salinity range of 2.9–6.5 wt% NaCl and 9.5–16.3 wt% CaCl_2 (Figs. 4.11E–F; 4.12).

In contrast to FIA-2B, FIA-2D inclusions are characterised by an isolated distribution and are interpreted to be primary in origin. Given the sequential vein paragenesis of barite $\rightarrow$ calcite, it is possible that FIA 2B formed in the barite as a secondary generation while FIA 2D was being trapped in the calcite during its growth.

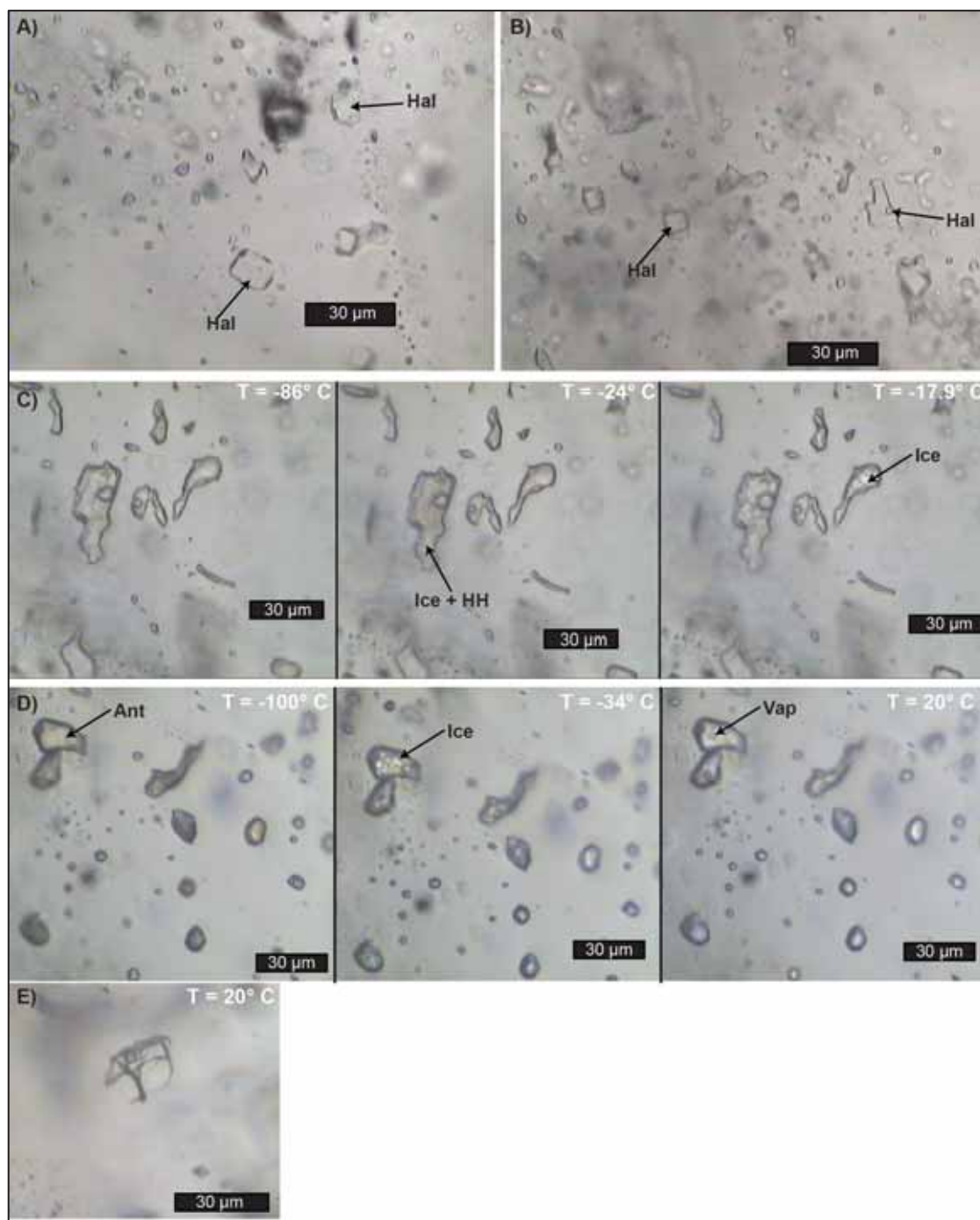


Figure 4.10: FIA photomicrographs. A-B) FIA-1A inclusions in quartz. Note the large halite crystals occupying almost the entire inclusion in some instances. C) Freezing-heating profile of FIA-2A inclusions (H₂O-NaCl). Hydrohalite melts first, leaving behind ice crystals. Grainy yellowish material in center image is hydrohalite. D) Freezing-heating profile of FIA-2B and 2D (not shown) inclusions (H₂O-CaCl₂-NaCl). Brown material present at freezing is antarcticite. Hydrohalite melts ~ -35 to -30° C, leaving ice behind. E) Irregularly-shaped inclusion with FIA-2B composition, interpreted to have originally been a FIA-2A inclusion later refilled by 2B.

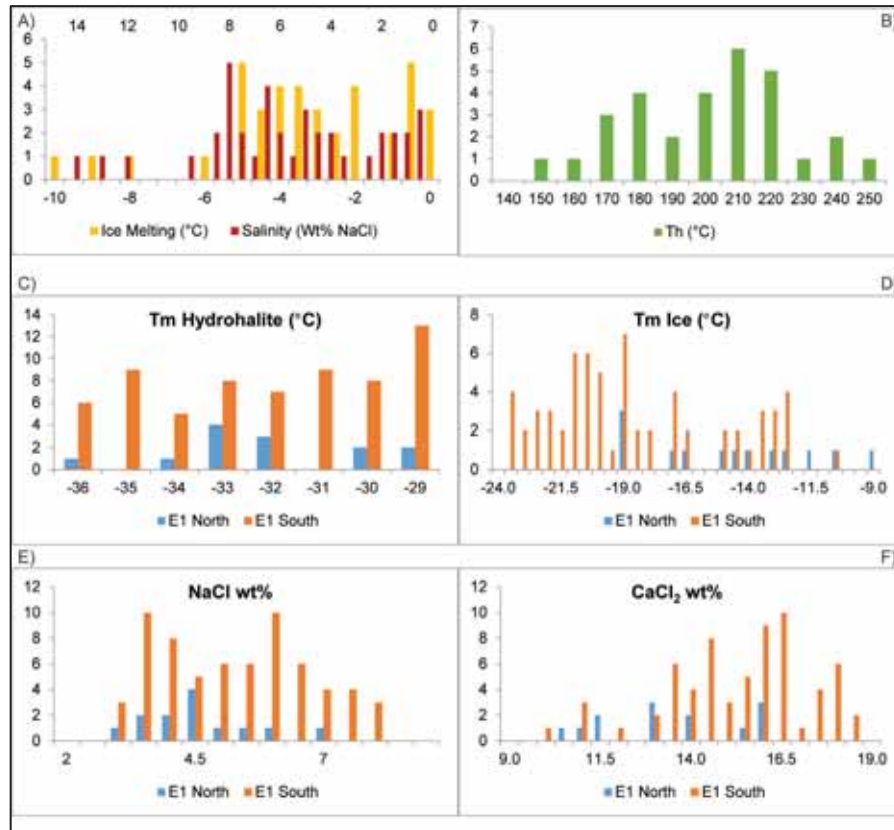


Figure 4.11: Microthermometry histograms. A) FIA-2A final melting temperatures and calculated salinities. B) FIA-2A homogenisation temperatures. C) FIA-2B and 2D hydrohalite melting temperatures. D) FIA-2B and 2D ice melting temperatures. E) FIA-2B and 2D calculated NaCl salinity. F) FIA-2B and 2D calculated CaCl₂ salinities.

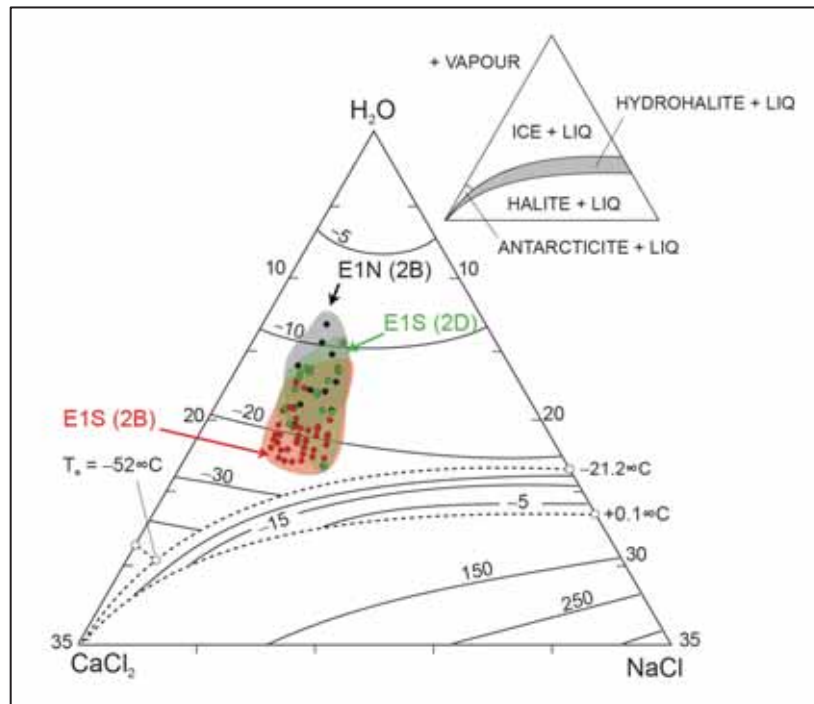


Figure 4.12: H₂O-CaCl₂-NaCl ternary plot of FIA-2B (barite-hosted) and FIA-2D (calcite-hosted) FIAs. Compositions calculated using the model from Steele-MacInnis et al. (2011).

Stable isotopes
Oxygen

Table 4.3 presents SHRIMP and IRMS $\delta^{18}\text{O}_{\text{VSMOW}}$ data and statistics for all quartz and magnetite samples, and histograms are shown in Figure 4.13. Quartz $\delta^{18}\text{O}$ values fall in a narrow range from +12.7 to +14.8‰ (mean = $+13.6 \pm 0.7\text{‰}$), with the exception of sample EMMD142-117.5m, which is significantly higher at +17.1‰. Sample EMM019-318m (+14.8‰) from E1 South is within error of the highest E1 North values of +14.3‰. Magnetite $\delta^{18}\text{O}$ values are lower and vary widely from 0 to +8‰ (mean = $+3.3 \pm 2.5\text{‰}$). Variation within samples and within individual grains (e.g. Fig. 4.8A) is also high, especially in EMMD022-326.83m, which has a minimum of +1.1‰ and maximum value of +8‰ (Table 4.3). A single E1 South analysis from sample EMM019-318m has a $\delta^{18}\text{O}$ of 5.0‰, which overlaps with E1 North.

Sulfur

Histograms of $\delta^{34}\text{S}_{\text{CDT}}$ of all samples are shown in Figure 4.14; the tabulated raw data are available in Appendix G. Summarised statistics are presented in Table 4.4. In general, there is substantial variation in $\delta^{34}\text{S}$ values in all minerals between each orebody; the values at E1 East and South are consistently higher than those from E1 North and E8. Intra-grain $\delta^{34}\text{S}$ values are consistent in all sulfur minerals analysed (App. G). Stage 3 chalcopyrite $\delta^{34}\text{S}$ values at E1 North, in both alteration and vein samples, range from -5.8 to +2.7‰ (mean = $-0.7 \pm 2.0\text{‰}$). However, sample EMMD153-277.5m has a much more enriched $\delta^{34}\text{S}$ value of +13.9‰. Pre-Stage 3 pyrite $\delta^{34}\text{S}$ values from E1 North are mostly higher and range from +1.2 to +7.7‰ (mean = $+4.4 \pm 3.5\text{‰}$). The higher values are found in samples of vein-hosted pyrite cutting carbonaceous schist. Like chalcopyrite, the $\delta^{34}\text{S}$ value of pyrite (+14.5‰) in EMMD153-277.5m is much higher than the other E1 North values. The $\delta^{34}\text{S}$ values of Stage 3 barite in fine-crystalline alteration and microvein samples at E1 North are much higher than chalcopyrite and pyrite, and have a range of +15.9 to +21.2‰ (mean = $+18.9 \pm 1.9\text{‰}$). The two vein-hosted Stage 3 barite samples, EMMD077-239.4m and EMMD055-155.35m, are characterised by significantly lower $\delta^{34}\text{S}$ values of +6.7‰ and +11.5‰.

Table 4.3: $\delta^{18}\text{O}$ Results

Site	Drillhole - depth	Paragenetic Stage	Description and protolith	Spot	$\delta^{18}\text{O}_{\text{qtz}}$ (‰)	Error (‰; 95% CI)	$\delta^{18}\text{O}_{\text{mag}}$ (‰)	Error (‰; 95% CI)	Calculated Temperature (°C)	Error (°C)	Calculated $\delta^{18}\text{O}_{\text{fluid}}$
E1 North	EMMD153 - 277.5m	2a	Stage 2a mag-qtz veining with Stage 2c calcite and Stage 3 py-ccp overprint and alteration of siliceous marble	S1-1	14.3	0.5	0.7	1.2	376	69	9.2
				S2-1	13.5	0.5	1.7	1.2	447	82	9.8
				Mean	13.9	-	1.2	-	-	-	-
				S2-1	13.4	0.6	2.9	1.2	506	92	10.7
	EMMD001 - 59.2m	2a	Dissem. mag-qtz alteration and infill of amyg. meta-andesite	S3-1	12.9	0.5	3.4	1.2	558	102	10.8
				S3-2	13.4	0.6	0.0	1.2	386	71	8.4
				Mean	13.2	-	2.1	-	-	-	-
				S1-1	13.6	0.6	5.3	1.2	625	146	-
	EMMD022 - 326.83m	2a	Massive, polycrystalline qtz associated with euhedral magnetite	S1-2	13.2	0.6	6.1	1.2	703	175	-
				S1-3	13.2	0.5	8.0	1.2	855	260	-
				S2-2	12.7	0.6	1.1	1.2	457	84	9.2
				Mean	13.2	-	5.1	-	-	-	-
				Ex - situ							
	EMMD153 - 150.6m	2a	Stage 2a quartz vein with later Stage 2c infill cutting volcanoclastic breccia	WM	14.6	0.2	-	-	-	-	-
	EMMD142 - 117.5m	2a	Qtz infill of amygdule in meta-andesite, overprinted by calcite	WM	17.1	0.2	-	-	-	-	-
E1 South	EMM019 - 318m	2a	Stage 2a qtz-mag vein with 2c cal-py infill cutting silicified and albitised meta-andesite	WM	14.8	0.2	5.0	1.2	515	93	12.5
E1 East	EMMD007 - 223.6m	2a	Stage 2a qtz-mag vein with 2c cal-py infill cutting silicified and albitised meta-andesite	WM	-	-	2.3	1.2	-	-	-
Statistics											
All data normalized to VSMOW				Mean	13.6		3.3		464	85	10
WM = whole mineral				Std Dev	0.7		2.5		68	12	1
All samples				Min	12.7		0.0		376	69	8
				Max	17.1		8.0		855	102	12

CI, confidence interval

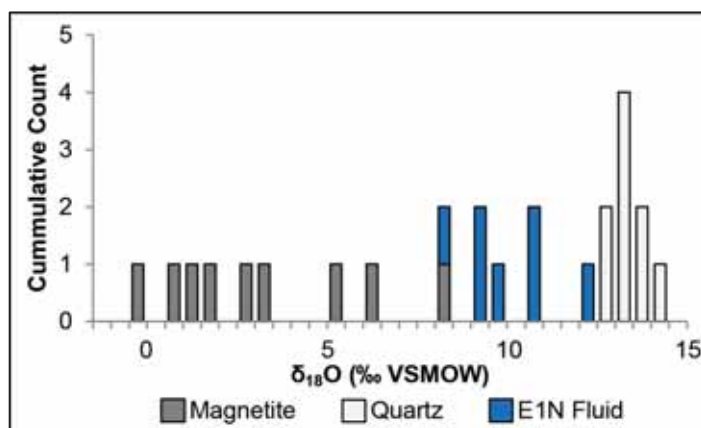


Figure 4.13: $\delta^{18}\text{O}$ histograms of quartz, magnetite, and calculated $\delta^{18}\text{O}$ for the fluid.

E1 South chalcopyrite $\delta^{34}\text{S}$ values are characterised by a much greater range than E1 North values, between +1.7 to +17.3‰, and are much higher at a mean of $+11.1 \pm 3.5\text{‰}$. Most values are above +6.8‰, with two exceptions. A single analysis of disseminated chalcopyrite from sample EMM018-86.9m, hosted in carbonaceous schist, has a $\delta^{34}\text{S}$ of +3.0‰ and one analysis in EMMD052-285.85m with $\delta^{34}\text{S} = +1.7\text{‰}$. Vein-hosted chalcopyrite $\delta^{34}\text{S}$ (mean = +12.1‰) is similar with that of chalcopyrite alteration in laminated marbles, which falls between +7.8‰ and +11.7‰. Pyrite values are even more spread out and range between +2.0‰ and 20.1‰ (mean = $9.9 \pm 7.6\text{‰}$). In general, pyrite values from E1 South are similar to chalcopyrite values in the same sample, except in sample EMM019-202.1m, where the pyrite is enriched by about 2‰. Pyrite in sample EMMD052-285.85m also displays variability with a minimum $\delta^{34}\text{S}$ of +8.5‰ in the sulfide-rich layer (Figs. 4.7D; 4.8F, Spot 2) to +12.6‰ in a less altered layer. Paragenetically-later chalcopyrite in the less-altered layer of this sample averages $+11.7 \pm 0.4\text{‰}$, which is similar to the pyrite in the same layer. The aforementioned anomalous chalcopyrite $\delta^{34}\text{S}$ value of +1.7‰ from this sample is from the same layer as the enriched pyrite. Pyrite from sample EMM019-86.9m has a mean $\delta^{34}\text{S}$ value of +2.2‰, which is similar to the low chalcopyrite value (+3.0‰) in this sample, and about 3‰ less than pyrite associated with the same lithology analysed near E1 North in sample EMMD167-105.9m. These values are noticeably much lower than $\delta^{34}\text{S}$ values for pyrite (mean = +19.2) and chalcopyrite (mean = +17.1) in sample EMM019-202.1m, which was collected from a similar carbonaceous metasilstone that grades into the schist. Barite $\delta^{34}\text{S}$ values from laminated marbles (+26.6 to +29.5‰) in E1 South are higher

than those in E1 North laminated rocks, but despite this vein-hosted barite $\delta^{34}\text{S}$ values at E1 South are lower (+19.1 to +21.2‰) than those from alteration barite.

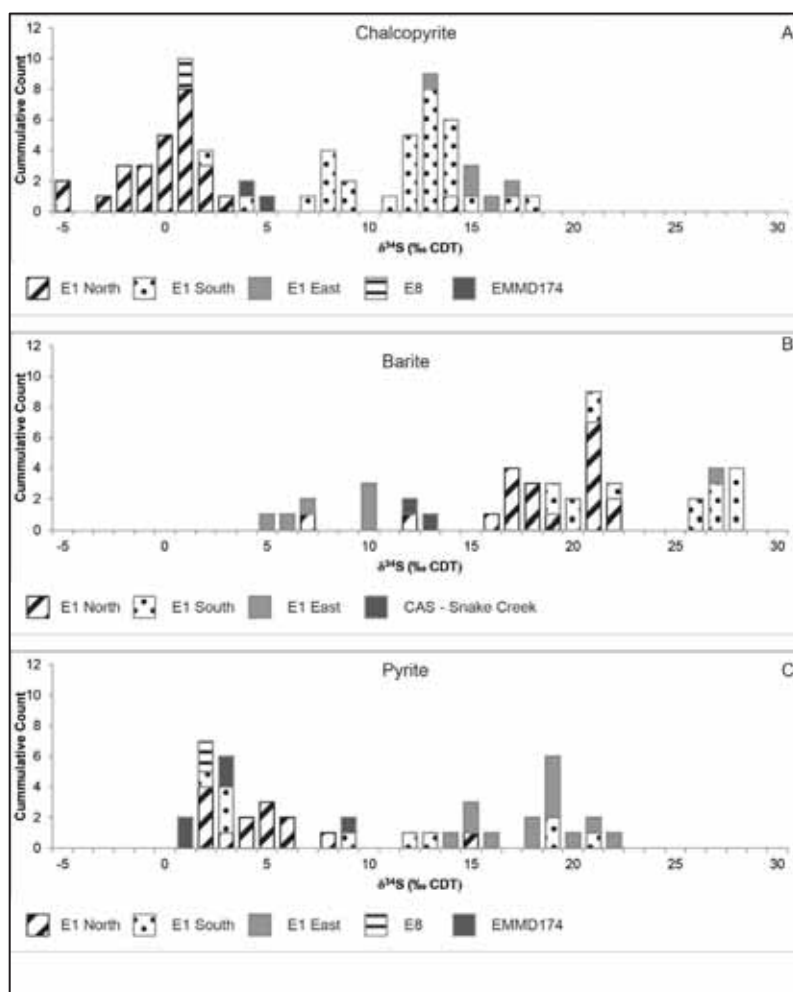


Figure 4.14: $\delta^{34}\text{S}$ histograms for all locations. A) Chalcopyrite. B) Barite. C) Pyrite.

The $\delta^{34}\text{S}$ values of E1 East chalcopyrite range from +12.5 to +16.9‰ (mean = +14.7 ± 1.6), and are the highest of the three orebodies. Although this range overlaps with E1 South, it is narrower and the $\delta^{34}\text{S}$ values of vein-hosted chalcopyrite (mean = +16.0 ± 1.3‰) are similar to alteration chalcopyrite (+12.5 to +14.7‰). Pyrite $\delta^{34}\text{S}$ values are also higher than in the other orebodies and fall between +13.4‰ and +21.4‰ (mean = +17.6 ± 2.4). Like E1 North, pyrite $\delta^{34}\text{S}$ values are mostly enriched relative to chalcopyrite values in the same sample. The highest value of +21.4‰ comes from vein-hosted pyrite cutting a meta-andesite (EMMD007-223.6m). Barite $\delta^{34}\text{S}$ values in E1 East were measured in three vein-hosted samples, and range from +5.6‰ to +26.5‰. The latter sample (EMMD008-114.45m) is similar to most E1 North and South barite

values, but the other is much lower than barites in these two orebodies, except for sample EMMD077-239.4m from E1 North.

Values of $\delta^{34}\text{S}$ from drill hole EMMD174 (samples EMMD174-117.7m and EMMD174-92.3m), which is poorly mineralised, average at +3.0‰ and +4.0‰ for pyrite and chalcopyrite, respectively. This drill hole is located between the E1 East and E1 South orebodies, and transects less-altered marble along strike from the E1 East orebody. Values of $\delta^{34}\text{S}$ from chalcopyrite in sample EMMD226-130.4m, hosted in meta-andesite and located at the E8 target, average +0.7‰ while pyrite $\delta^{34}\text{S}$ has a value of +1.6‰. The $\delta^{34}\text{S}$ values of sulfides from these two drillholes are similar to E1 North. The two bulk-rock samples of Corella Formation marble CAS, collected from the Snake Creek Area, have $\delta^{34}\text{S}$ values of +11.6‰ and +12.5‰. These values overlap with analytical error ($\pm 0.5\text{‰}$). The values are similar to chalcopyrite and pyrite $\delta^{34}\text{S}$ values in marble-hosted samples from E1 South, but are distinct from values of $\delta^{34}\text{S}$ in poorly-mineralised marble in drill hole EMMD174.

Table 4.4: $\delta^{34}\text{S}$ Statistics

	$\delta^{34}\text{S}_{\text{CDT}} (\text{‰})$			
	Chalcopyrite	Pyrite	Barite	
E1 North				
Mean	-0.1	4.4	17.9	
Standard Deviation (σ_1)	3.5	3.5	3.6	
Minimum	-5.8	1.2	6.7	
Maximum	13.9	14.5	21.2	
Excluding EMMD153-277.5			Excluding Veins	
Maximum	2.7	7.7	Minimum (excl. veins)	15.9
Mean	-0.7	3.6	Mean (excl. veins)	18.9
Standard Deviation (σ_1)	2.1	1.9	Standard Deviation (σ_1)	1.9
E1 East				
Mean	14.7	17.6	10.3	
Standard Deviation (σ_1)	1.6	2.4	7.5	
Minimum	12.5	13.4	4.5	
Maximum	16.9	21.4	26.5	
E1 South				
Mean	11.1	9.9	24.3	
Standard Deviation (σ_1)	3.5	7.6	3.9	
Minimum	1.7	2.0	18.2	
Maximum	17.3	20.1	29.7	
Mean excl EMM018-86.9	11.4	-	-	
Minimum	1.7	-	-	
Standard Deviation (σ_1)	3.2	-	-	
EMMD174				
Mean	4.0	3.0	-	
Standard Deviation (σ_1)	-	3.1	-	
Minimum	-	0.5	-	
Maximum	-	8.2	-	
E8				
Mean	0.69	1.57	-	
Total				
<i>n (in-situ)</i>	63	41	40	
<i>n (ex-situ)</i>	3	3	3	

Physiochemical Characteristics

The fluid inclusion and isotope data can be used to estimate some of the physiochemical characteristics of the fluids, including temperature and salinity of both pre-ore and mineralising fluids, $\delta^{18}\text{O}_{\text{fluid}}$ of the pre-ore fluid, and $\delta^{34}\text{S}_{\Sigma\text{S}}$, oxygen fugacity and pH of the mineralising fluid. In previous sections, the fluid inclusion and stable isotope aspects were reported separately; here they are combined.

Temperature

Stage 2a quartz-magnetite

Calculated quartz-magnetite equilibrium temperatures vary considerably between the three samples, from 354° to 915°C, and also within individual samples. This variation is mostly the result of the wide range of magnetite $\delta^{18}\text{O}$ values, as quartz $\delta^{18}\text{O}$ values are more consistent. The $\delta^{18}\text{O}$ values of three pairs resulted in temperatures above 600°C, including the 915°C maximum; the validity of these temperatures is discussed below. The other seven analyses fall within the range of 354° to 535°C (mean = $442 \pm 90^\circ\text{C}$), and represent reasonable isotopic equilibrium temperatures based on the mineral assemblage. The high mean error is caused by the relatively high analytical errors of the magnetite oxygen isotope analysis. Uncertainties in the empirical constants of equations 1–2 are only ~0.1%. Sample EMM019-318m from E1 South has a calculated temperature of 515°C, which is comparable to E1 North.

Stage 3 barite-chalcopryrite

E1 North ore formation temperatures, calculated from measurements in laminated ore samples, range from 233° to 343°C, with a mean temperature of 300°C and an average analytical error of $\pm 12^\circ\text{C}$ (Table 4.5; Fig. 4.15). Despite the variation in $\delta^{34}\text{S}$ of chalcopryrite and barite between E1 North and South, the $\delta^{34}\text{S}$ values of both minerals are proportionately higher at E1 South and result in comparable $\Delta_{\text{sulfate-sulfide}}$ values between 18‰ and 23‰. This corresponds to calculated temperatures of about 320°C, which are similar to values from E1 North (Fig. 4.15). The only apparent valid E1 East temperature calculation is from pyrite-chalcopryrite and is 290°C (Fig. 4.15). Variation within individual samples ranges from 10° to 40°C (Table 4.5), which cannot be explained by error alone and is probably not reasonable over sub-cm distances. Such variation suggests local disequilibrium or partial isotopic reequilibrium of chalcopryrite $\delta^{34}\text{S}$ values (e.g. Seal, 2006). Alternatively, the variation may represent multiple fluid pulses over short time periods, rather than continuous alteration. The highest temperature estimates, $> \sim 340^\circ\text{C}$, are over 20°C higher than other spot analyses in individual samples and probably also represent isotopic reequilibrium in chalcopryrite.

Table 4.5: Calculated Barite-Chalcopyrite Equilibrium Temperatures

Sample	Spot	Δ sulfate-sulfide	Calculated Temperature (°C)	Error ($\pm$ °C)
E1 North	S1-1.1	17.5	341	15
	S1-1.2	20.5	294	12
EMMD075 - 205.3	S1-2.1	20.9	288	11
	S2-1.1	20.3	297	12
	S2-2.1	20.9	288	12
	S2-3.1	20.0	301	13
	S2-4.1	19.7	305	13
	Mean	20.0	302	13
	Standard Deviation (σ_1)	1.2	18	1
	S1-1.1	19.6	308	12
	S1-1.2	19.3	312	13
	S1-2.1	17.3	347	15
EMMD001-195.25	S3-1.1	18.8	320	13
	S3-1.2	17.9	334	15
	Mean	18.6	324	14
	Standard Deviation (σ_1)	1.0	16	1
	S1-6a	22.9	262	10
	S1-9a	25.6	233	9
	S1-7a	21.2	284	11
	S1-10a	22.4	269	10
	Mean	23.0	262	10
	Standard Deviation (σ_1)	1.8	21	1
EMMD077-239.4	Mean*	4.0	1137	+166/-123
EMMD055-14	Mean*	10.3	605	+37/-32
	Mean	20.3	300	12
Summary	Minimum T		233	
	Maximum T		347	
MA96740 (EMM019 - UD)	S1-1.1	19.1	315	14
	S1-1.2	18.7	322	13
	S2-1.1	17.8	338	14
	S2-1.2	18.8	319	14
	S2-1.3	18.9	317	14
	S3-1.1	19.4	311	13
	S3-1.2	19.6	307	12
	Mean	18.9	318	13
	Standard Deviation (σ_1)	0.6	10	1
	S1-2.1	4.7	1022	+125/-97
EMM019-311.1	S1-2.1	4.2	1103	+154/-115
	S1-2.3	7.2	780	+65/-54
	S1-1a	6.8	807	+70/-58
EMM019-310.9	S1-3a	8.4	700	+50/-43
	S3-2	18.1	332	12
EMMD052 - 285.85	S3-3	17.7	339	13
	Mean	18.9	322	13
Summary	Minimum T		307	
	Maximum T		339	
EMMD008-114.15	Mean*	11.85**	546	+29/-26
	Py-ccp	1.1***	290	+270/-130

ex-situ* samplescombination of mean *ex-situ* and *in-situ* values***mean *in-situ* py and ccp values

red temperatures are likely to be erroneous (see text)

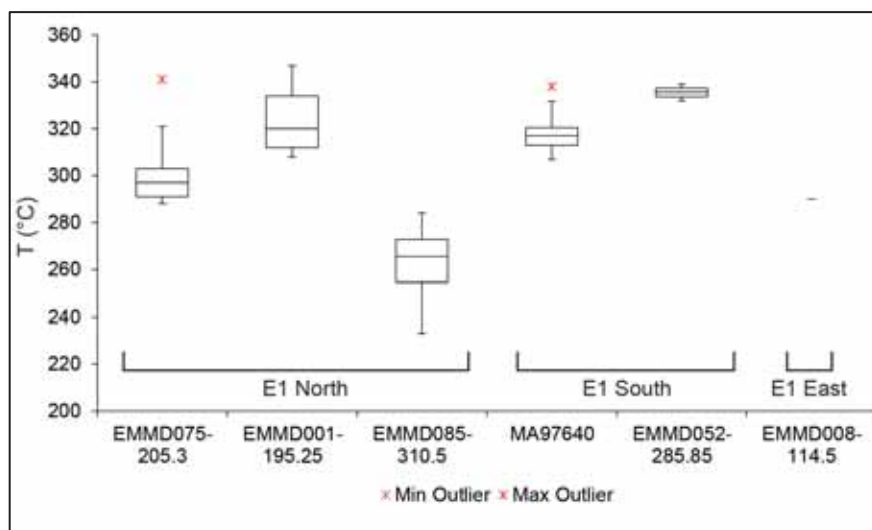


Figure 4.15: Tukey box plots (Tukey, 1977) of calculated barite-chalcopyrite equilibrium temperatures.

No previous ore formation temperature estimates have been made for this deposit. These temperatures are consistent with pyrite-chalcopyrite isotopic temperatures of 200–400°C calculated for the nearby Ernest Henry deposit (Twyerould, 1997), as well as most porphyry systems (Seal et al., 2006 and references therein). Low $\Delta_{\text{barite-chalcopyrite}}$ values, however, were found for all vein-hosted specimens in all three systems, which resulted in calculated temperatures between 600° and 1100°C, and with much greater errors ($> \pm 50^\circ\text{C}$). The lowest temperature of a vein-hosted barite-chalcopyrite mineral pair comes from sample (EMMD008-114.15m) from E1 East, calculated at 546 $\pm 29/-26^\circ\text{C}$ (Table 4.5). Even the lowest vein temperatures are much greater than those calculated from alteration samples, suggesting that the barite and chalcopyrite in the veins did not approach isotopic equilibrium. In contrast, the calculated pyrite-chalcopyrite equilibrium temperature for the same sample is 290°C, which falls in the range of the alteration samples and suggests that the sulfides did approach equilibrium. As previously described in Chapter 3, the veins represent tension structures related to regional D₄ shearing and extension. It is likely that both types of samples formed during shearing related to D₄, but the veins formed relatively quickly with respect to the laminated ores, which in contrast formed slowly enough for replacement reactions to approach equilibrium. Although Ohmoto and Lasaga (1982) demonstrate that sulfide-sulfate equilibrium below 350°C is rare in many systems, their data indicate that equilibrium can be reached in less than 5 years at 250°C in systems with a pH range of 4–7, or in 10⁵ years at a pH of 9. This is not unreasonable when considering that

timescales involved in ductile shearing and carbonate replacement are likely to be much greater than 10^3 years (Skinner, 1997).

Stage 3 trapping pressure estimates

The calculated isotopic temperatures of Stage 3 barite-chalcopyrite are compatible with the barite fluid inclusion data. The fluid inclusions that homogenised above 200°C were likely disturbed, while those that homogenised between 148° to 190°C likely represent true minimum trapping temperatures. The isotopic equilibrium temperature could not be determined for the vein-hosted sample EMMD077-239.4m, which was studied for FIA-2A inclusions, because equilibrium was not attained between the barite and chalcopyrite in this sample. However, calculated temperatures for two nearby samples, EMMD001-195.25m and EMMD075-205.3m, were within 20°C of one another, suggesting that temperature variations within the center of the E1 North orebody were minor. The variation is not much higher than the mean analytical error ($\pm 12^{\circ}\text{C}$); therefore, the mean temperature of these two samples ($\sim 315^{\circ}\text{C}$) is considered a reasonable approximation for the true trapping temperature in the vicinity of EMMD077-239.4m. The calculated trapping pressures for 2A FIAs range from 2200 to 3300 (± 500) bar (Fig. 4.16), which correspond to an approximate depth range of 8–12 km (assuming a density of 2.7 g/cm^3). This depth range is comparable to estimates of ore formation from 6–10 km at Ernest Henry, made by Kendrick et al. (2007) based on fluid inclusion halogen ratios. This depth range is compatible with the brittle-ductile strain patterns discussed in Chapter 2.

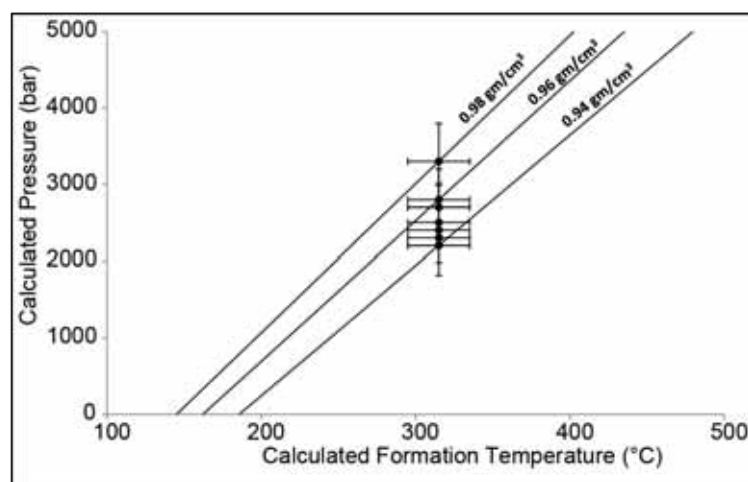


Figure 4.16: P-T diagram of calculated isochores and resultant true trapping pressures and errors for FIA-2A barite inclusions, based on a calculated isotopic true temperature of 315°C (see text). Isochores calculated using Hokieflincs (Steele-MacInnis et al., 2012).

$\delta^{18}\text{O}_{\text{fluid}}$ and total sulfur ($\delta^{34}\text{S}_{\Sigma\text{S}}$)

Calculation of mineral equilibrium temperatures enables derivation of the isotopic composition of the mineral-forming fluids. When combined with fluid inclusion observations, the data can provide insight into the source(s) of the hydrothermal fluids.

Stage 2a Fluids

Fluid $\delta^{18}\text{O}$ values are displayed in Table 4.3 and Fig. 4.13, and form a narrow range of +8.4 to +10.9‰ (mean = +9.7‰, $1\sigma = 1.0$). The erroneously-high temperature estimates were excluded from this calculation. Analytical error in the raw mineral $\delta^{18}\text{O}$ values results in fluid compositions that are $\pm 1.5\text{‰}$ in error.

Stage 3 Fluids

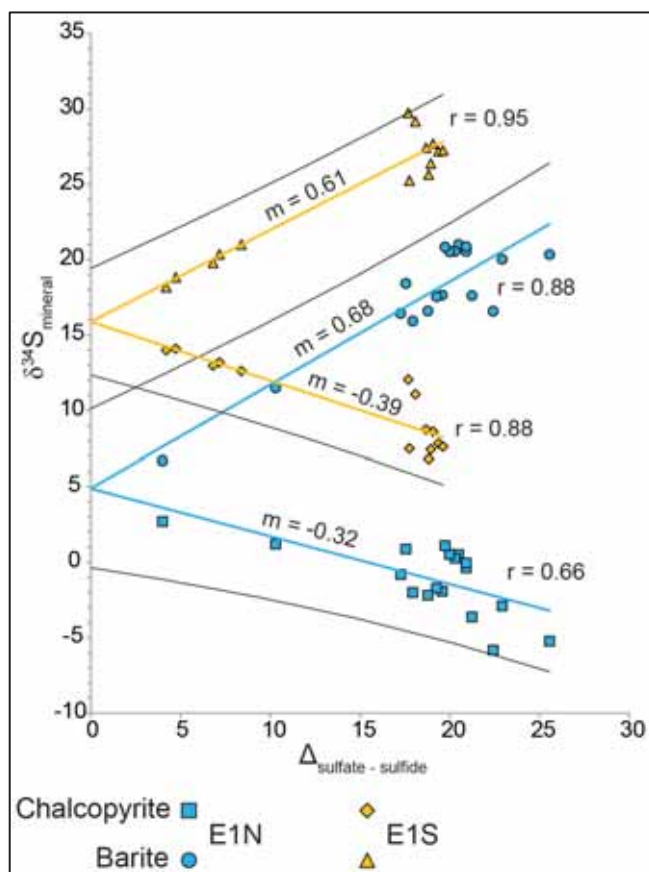


Figure 4.17: $\delta^{34}\text{S}_{\Sigma\text{S}}$ plots for E1 North and South using the Δ - δ plot of Field and Gustafson (1976). Black lines are 95% regression confidence intervals.

The Δ - δ diagram (Fig. 4.17) demonstrates that the bulk fluid $\delta^{34}\text{S}$ of E1 north is $+4.9 \pm 5.3\text{‰}$ (95% confidence interval). The higher $\delta^{34}\text{S}$ values of E1 South samples prevent them from being regressed in the same trend as E1 North samples; the E1 South vein-

hosted and alteration-hosted samples form linear trends that converge at $+15.9 \pm 3.6\text{‰}$ (95% confidence). Although the aforementioned r values indicate reasonable correlations between the sulfide and sulfate minerals, it is visually evident that some of the analyses are not linear. Following Figure 3 of Field and Gustafson (1976), the slopes of the E1 North chalcopyrite ($m = -0.32$) and barite ($m = 0.68$) trends suggest a $\text{SO}_4^{2-} / \text{H}_2\text{S}$ mole ratio of about 35:65. E1 South, on the other hand, is characterised by slightly shallower barite ($m = 0.61$) and slightly steeper chalcopyrite ($m = 0.39$) slopes, which indicate a more sulfate-rich fluid with around 30:70 ratio.

Regressions on a δ - δ diagram for E1 North and South are shown in Figure 4.18. With the exception of analyses from sample EMMD075-205.3m, the E1 North samples form a linear trend ($r = 0.82$) that intersects the tie line at $+4.2 \pm 3.7\text{‰}$. This is compatible with the intercept of the Δ - δ diagram. The non-linearity of analyses from sample EMMD075-205.3m is much more apparent on the δ - δ plot than on the Δ - δ diagram. Although it does not fall along the trend of the other E1 North analyses, the calculated mean barite-chalcopyrite equilibrium temperature for the sample is 302°C , which is similar to others from E1 North and South.

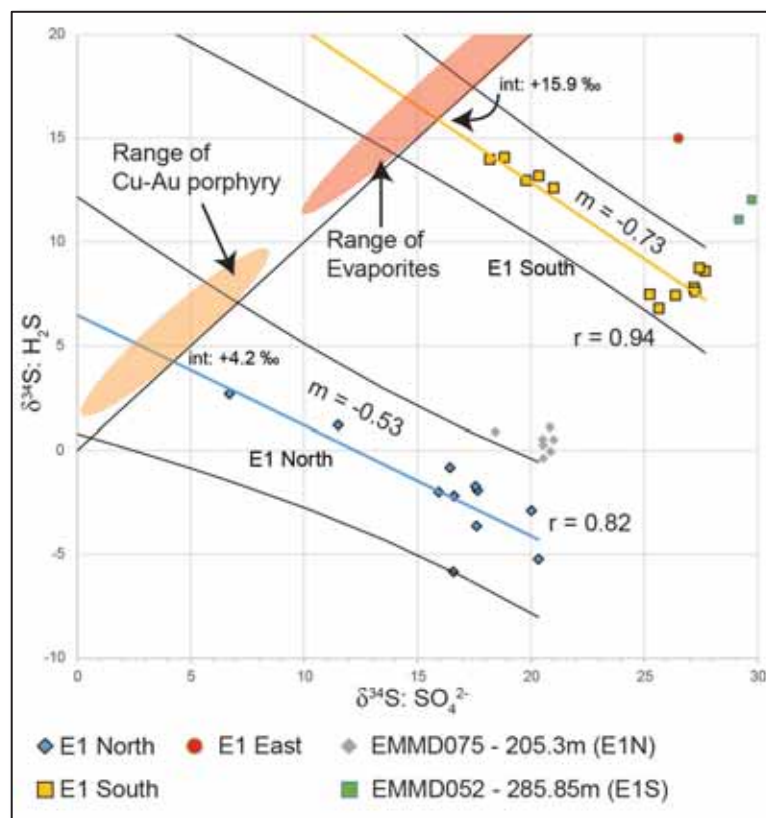


Figure 4.18: $\delta^{34}\text{S}_{\text{SS}}$ plots for E1 North and South using the δ - δ plot of Rye (2005).

The inclusion of EMMD075-205.3m in the $\Delta\delta$ plot (Fig. 4.17) partly accounts for the high error range of the E1 North $\delta^{34}\text{S}_{\Sigma\text{S}}$. Excluding this sample in the $\delta\text{-}\delta$ plot (Fig. 4.18) yields a more narrow range of +0.5‰ to +7.0‰ for the bulk fluid $\delta^{34}\text{S}$. E1 South analyses from drill hole EMM019 form a very linear trend ($r = 0.94$) that results in a bulk fluid $\delta^{34}\text{S}$ value of $+15.9 \pm 1.7\text{‰}$. It is clear, however, that individual analyses from sample MA96740 form a positive-sloping trend. When the individual analyses are averaged they form a linear trend with the vein-hosted samples. The slope of the E1 North trend is -0.53 , which is halfway between -1 and 0 and suggests overall a low $\text{SO}_4^{2-} / \text{H}_2\text{S}$ mole ratio, comparable to the 35:65 estimate from the $\Delta\delta$ plot. The E1 South slope is steeper at -0.73 , which indicates relative sulfate enrichment which is in agreement with the $\Delta\delta$ plot. Molar $\text{SO}_4^{2-} / \text{H}_2\text{S}$ ratios of samples EMMD075-205.3m and EMMD085-310.5m, calculated from MLA analyses in Chapter 2, are 0.88 (~90:10) and 0.50 (50:50), respectively. While the latter is comparable to the slope-based estimates, the former is significantly higher. The implications of variable $\text{SO}_4^{2-} / \text{H}_2\text{S}$ ratios are discussed below.

Oxygen fugacity and fluid pH during Stage 3

Based on the calculated pH- f_{O_2} diagrams of Ohmoto (1972; Figs. 5–7), the high $\delta^{34}\text{S}$ values of E1 Group alteration barite (+15 to +29‰) and lower values of chalcopyrite (-5 to +7‰) plot in a narrow f_{O_2} range at 250°C shown in Figure 4.19A. Chalcopyrite stability at this temperature, taken from Crerar and Barnes (1976), constrains these parameters to a narrow range of 6.0–7.5 for pH and -37 to -38 for $\log_{10} f_{\text{O}_2}$. At 350°C (Fig. 4.19B), the E1 Group data are consistent with predicted equilibrium $\delta^{34}\text{S}$ values of chalcopyrite and barite only when potential differences in $\delta^{34}\text{S}_{\Sigma\text{S}}$, as well as thermodynamic uncertainties in pH and $\log_{10} f_{\text{O}_2}$ (± 0.5 for both), are taken into account. Indeed, the high $\delta^{34}\text{S}$ values of barite in E1 South at temperatures $\gg 300^\circ\text{C}$ are only compatible with a bulk fluid $\delta^{34}\text{S}$ much higher than 0‰, as the data plot below the barite stability field if bulk fluid $\delta^{34}\text{S}$ is close to 0‰. However, as previously mentioned, temperature estimates in E1 Group samples $> 340^\circ\text{C}$ are probably the result of partial chalcopyrite reequilibrium.

It is important to note that coefficients for Equations 4 and 5 in this study are different from those used in the thermodynamic calculations in Ohmoto (1972), which result in

additional $\delta^{34}\text{S}$ contour errors of up to 2‰. Regardless, the pH and f_{O_2} ranges are near the barite-sulfide stability boundary, which is consistent with the observed mineral assemblage of barite-chalcopyrite-pyrite-carbonate. The plots in Ohmoto (1972) assume a $\delta^{34}\text{S}_{\Sigma\text{S}}$ of 0‰, but the narrow range of barite $\delta^{34}\text{S}$ between +29.8 and 0‰ suggests that minor deviations in bulk fluid $\delta^{34}\text{S}$ from 0‰ would not greatly affect the pH- f_{O_2} range at 250°C. The lower $\delta^{34}\text{S}$ values (< +10‰) of vein-hosted barite suggest highly-oxidizing conditions during vein formation. The implications of the variation between E1 North and E1 South mineral $\delta^{34}\text{S}$ values on these parameters are discussed below.

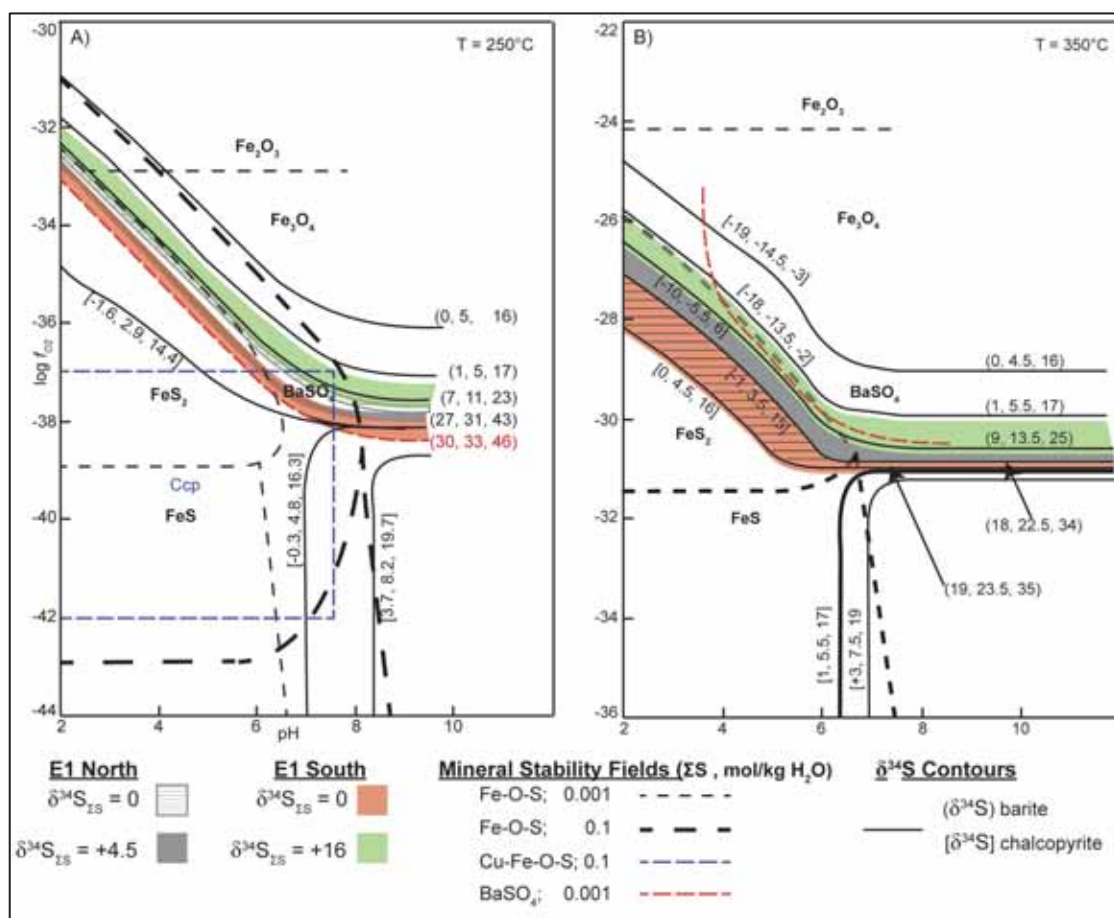


Figure 4.19: E1 Group Stage 3 pH- f_{O_2} ranges defined by the measured $\delta^{34}\text{S}$ values of barite and chalcopyrite, using the thermodynamically-modeled diagrams of Ohmoto (1972) at 250°C (A) and 350°C (B). Solid black lines are isotope contours, with barite $\delta^{34}\text{S}$ values in round brackets and equilibrium $\delta^{34}\text{S}$ chalcopyrite values in square brackets. The left-most values assume $\delta^{34}\text{S}_{\Sigma\text{S}} = 0$ ‰. Center values assume $\delta^{34}\text{S}_{\Sigma\text{S}} = +4.5$ ‰, while right-most values assume $\delta^{34}\text{S}_{\Sigma\text{S}} = +16$ ‰. Contour values at 350°C are derived from equilibrium fractionation factors between H_2S and chalcopyrite or sulfate from Ohmoto (1972). Dashed lines are mineral stability boundaries. Chalcopyrite stability field at 250°C is from Crerar and Barnes (1976).

Discussion

Validating assumptions of isotopic equilibrium

The oxygen and sulfur temperature data and $\delta^{34}\text{S}_{\Sigma\text{S}}$ and f_{O_2} - pH diagrams provide a means to assess whether or not isotopic equilibrium was reached in some or all of the quartz-magnetite and barite-chalcopyrite samples. The Stage 2a temperatures in excess of 600°C are not likely to be reasonable equilibrium temperatures, given the paucity of high-temperature mineral assemblages. Additionally, temperatures below 400°C may represent post-Stage 2c remobilization or renewed magnetite alteration. The analyses in the range of 400° to ~550°C are more likely true equilibrium temperatures based on mineral assemblage. Given the spread of magnetite $\delta^{18}\text{O}_{\text{VSMOW}}$ values of around 8‰ in sample EMMD022-326.83m, the erroneously high calculated temperatures (> 600°C) resulting from the higher magnetite $\delta^{18}\text{O}$ values may be caused by late isotopic reequilibrium of the magnetite under different conditions. Alternatively, the magnetite and quartz may not have reached equilibrium in some instances. Despite the evidence of penetrative strain in the quartz, the consistent isotopic signature across samples suggests that deformation did not have a significant effect on quartz oxygen isotope values.

Temperature calculations from barite-chalcopyrite pairs in vein-hosted samples in E1 North and South yielded unrealistically high temperatures, indicating that the minerals were either formed sequentially, formed at the same time but in isotopic disequilibrium, or disturbed after deposition. The vein-hosted samples, however, form linear trends on the $\Delta\delta$ and $\delta\delta$ diagrams with the alteration-hosted samples including E1 North chalcopyrite ($r = 0.66$; Fig. 4.17), E1 North barite ($r = 0.88$), E1 South chalcopyrite ($r = 0.88$), and E1 South barite ($r = 0.95$). The regressions are statistically significant ($p = 0.000$) at the 95% confidence interval.

Shelton and Rye (1982) documented the same phenomenon in the Mines Gaspé porphyry deposit, in which samples with erroneous temperatures formed linear trends on a $\Delta\delta$ diagram. They proposed a process of systematic disequilibrium between SO_4^{2-} and H_2S , which resulted in low, but covarying, $\Delta_{\text{sulfate-sulfide}}$ values for pyrite-anhydrite and chalcopyrite-anhydrite pairs during precipitation. Most of their pyrite-chalcopyrite pairs did approach equilibrium, so the apparent disequilibrium between SO_4^{2-} and H_2S was interpreted to be a result of lower equilibration rates between sulfates and sulfides (e.g. Ohmoto, 1972). The $\Delta\delta$ plots of E1 North and South (Fig. 4.17) suggest that this

process also took place in vein-hosted barite-chalcopyrite samples in the E1 Group, and that the vein-hosted barite and chalcopyrite were in cogenetic disequilibrium.

Although calculated temperatures are consistent at E1 North and South, non-linearity in some samples may suggest local isotopic reequilibrium or fluctuations in $\text{SO}_4^{2-} / \text{H}_2\text{S}$ within the deposit. This is particularly evident in the δ - δ plot, in which sample EMMD075-205.3m does not fall on the main E1 North trend (Fig. 4.18). Despite this, the calculated temperatures for this sample ($\sim 290^\circ$ to 305°C) are comparable to the other E1 North analyses. Such temperature similarity, coupled with the clustering of individual analyses, suggests that re-equilibration is not the cause of the high barite $\delta^{34}\text{S}$ values. Instead, either a local heterogeneity in the $\text{SO}_4^{2-} / \text{H}_2\text{S}$ mole ratio is proposed to explain the discrepancy. Alternatively, temporal variation within samples (i.e. cyclic fluid input at sub-cm scales) may be a factor, especially when considering the timescales involved in ductile deformation and host rock replacement.

Such discrepancies are also present in the E1 South sample from drillhole EMM019 (MA96740). Like sample EMMD075-205.3m, temperature calculations from this sample (mean = 315°C) are comparable to others and it appears that barite and chalcopyrite were in equilibrium. On the other hand, the spread of chalcopyrite $\delta^{34}\text{S}$ values suggest that the mineral may have experienced some degree of reequilibrium at sub-mm scales. Sample EMMD052-285.85m is similar to EMMD05-205.3m in that it has an equilibrium temperature (335°C) similar to other samples, but does not fall on the E1 South trend. Again, this is probably due to local variation in $\text{SO}_4^{2-} / \text{H}_2\text{S}$ mole ratio. In conclusion, it appears that the assumption of isotopic equilibrium for temperature calculation is valid for most samples. Despite local variations, the overall $\text{SO}_4^{2-} / \text{H}_2\text{S}$ mole ratio is fairly consistent, and it is clear from both the pH- f_{O_2} and $\delta^{34}\text{S}_{\Sigma\text{S}}$ plots that the sulfur minerals from E1 North originated from distinct $\delta^{34}\text{S}_{\Sigma\text{S}}$ values to those in E1 South.

Fluid sources

Stage 2a

The narrow range of $\delta^{18}\text{O}_{\text{fluid}}$ of +8.4 to +10.9‰ (Fig. 4.13) for pre-ore quartz-magnetite (Stage 2a) is within that of metamorphic waters derived from igneous rocks, sandstones or volcanogenic sedimentary rocks (+3 to +25‰; Fig. 4.20; Taylor, 1974), but also

overlaps with the upper limit of magmatic waters (+5 to +9‰; Fig.4.20); they are much lower than metamorphic waters derived from shales, limestones and cherts (+15 to +35‰; Fig. 4.20). They also overlap slightly with the highest $\delta^{18}\text{O}$ values found in shallow connate brines (up to +9‰; Taylor, 1974). The E1 Group $\delta^{18}\text{O}_{\text{fluid}}$ estimates overlap with those from Ernest Henry, Osborne, Eloise and Mount Elliott (Fig. 4.20), but are slightly higher than Starra (+5 to +8‰).

The halite-rich inclusions from FIA-1A hosted in Stage 2a quartz were heterogeneously trapped from a fluid that was supersaturated in halite. In order for such a supersaturated fluid to exist at the calculated isotopic equilibrium temperature range of 450–550°C, the fluid would have to have a salinity of at least 50 wt% NaCl_{eq} (Sourirajan and Kennedy, 1962). This high salinity fluid could be an early magmatic aqueous fluid (Sillitoe, 2010), or metamorphic water that has dissolved halite in the country rocks, or magmatically-heated bittern brine (e.g. Hardie et al., 1982; Barton and Johnson, 1996; Hammerli et al., 2014).

The Stage 2a $\delta^{18}\text{O}_{\text{fluid}}$ values disprove a metamorphic fluid hypothesis, as the +8 to +11‰ range at the E1 Group is not compatible with the +15 to +35‰ range of metamorphic fluids derived from shales, limestones and cherts (Fig. 4.20) associated with evaporite rocks (i.e. the Corella Formation). In addition, most halite would not be preserved in the Corella Formation host rocks by the time of E1 Group mineralisation in local D₃ / regional D₄ (Tompkins, A., pers. comm.; Hammerli et al., 2014). Involvement of shallow basinal brines waters cannot be excluded based on Stage 2a minimum $\delta^{18}\text{O}_{\text{fluid}}$ values close to +8‰. The maximum values close to +11‰, however, suggest that such a basinal component is minor. Based on the above reasons, a magmatic-hydrothermal fluid is believed to be more likely for Stage 2a.

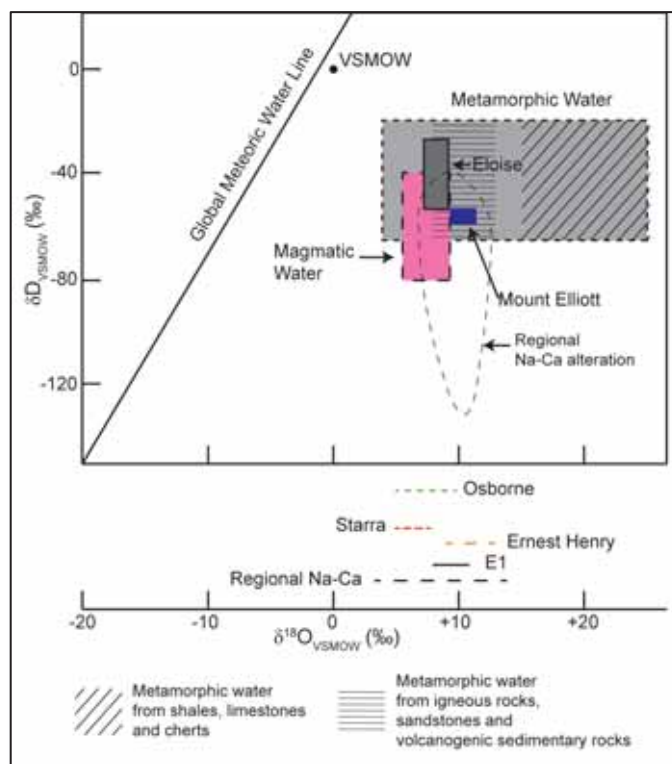


Figure 4.20: $\delta^{18}\text{O}$ and δD fluid composition of Cloncurry IOCG deposits and regional Na-Ca alteration. Dashed lines indicate systems with only $\delta^{18}\text{O}$ constrained (no δD data). Meteoric water line and ranges of magmatic and metamorphic waters are from Taylor (1974). The horizontal hashed area in the metamorphic range corresponds to metamorphosed sandstones and volcanogenic sedimentary rocks, while the diagonal hashed area represents metamorphosed shales, limestones and cherts. Metamorphosed igneous rocks span the entire metamorphic water range. See Table 4.6 for deposit references; regional Na-Ca is from Mark et al. (2006a)

Stage 3

The value of $\delta^{34}\text{S}_{\Sigma\text{S}}$ at E1 North ($\sim +4.5\text{‰}$) is consistent with that of sulfur in magmatic-hydrothermal systems ($+1$ to $+8\text{‰}$; Seal, 2006 and references therein), but is noticeably higher than juvenile magmatic sulfur (0‰). This may be due to assimilation of sedimentary country rocks into the source magma. Given the late 1456 ± 44 Ma age of syn-ore monazite presented in Chapter 2, it is possible that this magma would be associated with the Williams-Naraku Batholith. This is compatible with the interpretations of magmatic involvement by other workers at the nearby Ernest Henry (Kendrick et al., 2007) and Monakoff (Williams et al., 2015) deposits. The low salinity of Stage 3 FIA-2A inclusions may be compatible with late-stage magmatic-hydrothermal fluids (Sillitoe, 2010), but may also have formed by dilution with a less saline, external, fluid. The E1 North bulk $\delta^{34}\text{S}_{\Sigma\text{S}}$ value is distinct from the high $\delta^{34}\text{S}_{\Sigma\text{S}}$ value of E1 South ($+15.9\text{‰}$), which is more consistent with sulfur derived from, or equilibrated with, an evaporitic source. Such a source is also consistent with Ernest

Henry, which appears to have received input of nearer-surface halite dissolution brines along with the magmatic fluid (Kendrick et al. 2007). Williams et al. (2015) interpreted a distinct, reduced, fluid at Monakoff, but suggested it could represent either the evolution of the magmatic fluid, or input of an external fluid. The reduced fluid may be related to the local Cover Sequence 3 host rocks (metabasalt, gabbro, and schist) that are not present at the E1 Group or Ernest Henry.

A two-fluid mixing model

Both the $\Delta\delta$ and $\delta\delta$ diagrams yield similar values of $\delta^{34}\text{S}_{\Sigma\text{S}}$ for the individual systems (E1 North: +4 to +5‰; E1 South +15.9‰. The spread of over 10‰ between these orebodies, coupled with the decrease in salinity between stages 2a and 3, are not easily reconciled by a single fluid, or by mixing of magmatic and non-magmatic brines. Instead, the difference between $\delta^{34}\text{S}_{\Sigma\text{S}}$ in E1 North and E1 South (and presumably between E1 East) may be explained by a two-fluid mixing model that involves a saline magmatic fluid and a low-salinity, shallower, fluid. However, as is discussed below, it is possible that oxidized sulfur was supplied by one or both fluids. The E1 Group can be classified as an example of a hybrid magmatic-non-magmatic IOCG deposit (e.g. Hunt et al., 2007).

In the two-fluid model, the dominant fluid at E1 North, denoted as Fluid 1, is interpreted to be magmatic in origin, based on the combination of low bulk fluid $\delta^{34}\text{S}$ values of +4 to +5‰ of E1 North, the presence of hypersaline FIA-1A inclusions in Stage 2a quartz, and the prevalence of F-rich phases, fluorapatite and fluorite, in the paragenetic sequence (Chapter 2). This magmatic fluid was probably derived from an evolved, alkaline, A-type granite, which can explain the anomalous U-REE concentrations in E1 Group ores (see Chapter 2 and Chapter 3); it is speculated to be related to the Williams-Naraku Batholith. Geochemical data from the Williams-Naraku granites suggests that the magmas were magnetite-bearing and relatively oxidized, and would have presumably carried sulfur as H_2S and SO_2 (Wyborn, 1998). Therefore, as previously described, cooling of the exsolved fluid would result in hydrolysis of SO_2 to H_2S and SO_4^{2-} . The linear trends formed in the $\Delta\delta$ (Fig. 4.17) and $\delta\delta$ (Fig. 4.18) diagrams provide evidence of this process.

The second fluid (Fluid 2) is likely from an external source. The bulk fluid $\delta^{34}\text{S}$ value of +15.9‰ for E1 South is consistent with that of sulfur either derived from, or

equilibrated with, evaporitic Mesoproterozoic sedimentary rocks (Canfield, 2004; Seal, 2006), which have been documented in the Corella Formation and its temporal equivalents throughout the Eastern Fold Belt by earlier workers (Blake and Stewart, 1992). It is also comparable to the $\delta^{34}\text{S}$ of +12‰ measured in this study of carbonate-associated sulfate (CAS) from unmineralised Corella Formation marble. It is proposed that the high bulk fluid $\delta^{34}\text{S}$ values of E1 South can be explained by interaction with Fluid 1, present at E1 North, with a second, oxidized, fluid carrying sulfate derived from, or equilibrated with, the Corella Formation during dissolution and metasomatism of the calcareous and evaporitic protolith. This is consistent with both textural and geochemical evidence presented in Chapter 2 that indicates that much of the E1 Group orebody occurs as carbonate replacement. Measured $\delta^{34}\text{S}$ values of +8.5 to +20.1‰ of pre-ore pyrite at E1 South, which are much heavier than pyrite from E1 North, suggest that this process was continuous through the paragenetic evolution of the system.

The presence of Fluid 2 is further corroborated by FIA-2B inclusions in Stage 3 barite and carbonate. The low-moderate salinity and $\text{CaCl}_2\text{-NaCl-H}_2\text{O}$ composition of these inclusions are consistent with basinal or fluids (Davisson and Criss, 1996; Hardie et al., 2003). The absence of FIA-2A inclusions in the E1 South barite samples and abundance of FIA-2B inclusions is consistent with the isotopic evidence of progressively-increasing dominance of the Corella Formation-derived fluid toward E1 South. Low-salinity, FIA-2A, primary inclusions in E1 North barite probably represent the diluted product of mixing of Fluid 1 with Fluid 2. Furthermore, the higher CaCl_2 content of the E1 South FIA-2B inclusions may be the result of greater basinal fluid component, or an increase in Ca^{2+} caused by extensive dissolution of the host Corella Formation marble.

The signature of Fluid 2 suggests derivation from the Corella Formation itself, but as previously mentioned, this unlikely given the relative timing of ore formation after peak metamorphism. It is probable that most of the connate fluids originally present in the Corella Formation limestones and evaporites were expelled by D4 time. For this reason, it is more likely the isotopic signature of the Corella metasedimentary rocks were imparted into an external fluid that passed through the Corella Formation. Such a fluid may have come from basinal water closer to the surface, but isotopic reequilibrium by the fluid or local host rock interaction precludes anything other than speculation about its original source. Equilibration between the fluid-poor Corella and an external fluid

(presumably CO₂ - poor) may also partly explain the lack of CO₂ present in the mineralising fluid(s).

The addition of SO₄²⁻ from the Corella Formation into mineralising fluid system, would shift the SO₂ disproportionation reaction to the left, forming more SO₂ and simultaneously increasing $\delta^{34}\text{S}_{\text{SO}_2}$ until it has equilibrated with Corella Formation-derived SO₄²⁻. It appears that this process could have happened over a short distance, as one sample from E1 North, EMMD153-277.5m, has much higher $\delta^{34}\text{S}_{\text{sulfide}}$ values (+13 to +14‰) than other E1 North samples (mean = -0.7‰, 1 σ = 2.1). The sample is hosted in less-altered, barite-poor, Corella Formation marble less than 500 m from the heavily barite-fluorite-magnetite-sulfide-altered core of the E1 North orebody. When considering E1 South as a subsystem, it is likely that bulk Fluid 1 $\delta^{34}\text{S}$ was re-equilibrated rapidly as it permeated through the Corella Formation, resulting in a near constant $\delta^{34}\text{S}$. The intensity of metasomatism and shearing at E1 North has made it difficult to map out the full extent of Corella Formation marble horizons. It is likely that the more altered barite-fluorite-rich zone of E1 North was infiltrated by higher volumes of magmatic fluid, therefore limiting the isotopic contribution of Corella metasedimentary rocks. Input of sulfate from the Corella Formation could account for the increase in the SO₄²⁻ / H₂S mole ratio from E1 North to South.

Alternatively, it is possible that only Fluid 1 carried sulfur. The increase in $\delta^{34}\text{S}_{\Sigma\text{S}}$ towards E1 South and E1 East could instead be the result of progressive oxidation by Fluid 2. In this hypothesis, the magmatic fluid would most likely need to be reduced, and the most abundant sulfur species would be H₂S (rather than SO₂). The unidirectional oxidation of H₂S to SO₄²⁻ would cause enrichment of ³⁴S in the H₂S reactant, and ³⁴S depletion in the SO₄²⁻ product. Continued oxidation would follow a Rayleigh distillation model as progressive enrichment of the reactant causes enrichment of SO₄²⁻ (Seal, 2006). The Rayleigh model can be described by the equation:

$$\delta^{34}\text{S}_{\text{fluid}}^{\text{f}} = (\delta^{34}\text{S}_{\text{fluid}}^{\text{i}} + 1000) f^{\alpha-1} - 1000,$$

where α is the fractionation factor between SO₄²⁻ and H₂S, and f is the fraction of the fluid H₂S remaining.

To the author's knowledge, the kinetic or equilibrium fractionation factor for this reaction has not been published. However, assuming it is comparable to the equilibrium fractionation factor of 1.019 for $\text{SO}_4^{2-} \leftrightarrow \text{H}_2\text{S}$ at 300°C (Ohmoto and Lasaga, 1982), then the calculated $\delta^{34}\text{S}_{\text{fluid}}^f$ is comparable with the estimated $\delta^{34}\text{S}_{\text{ES}}$ value from E1 South at values of f between 0.4 and 0.6, and using the E1 North $\delta^{34}\text{S}_{\text{ES}}$ of +4‰ for $\delta^{34}\text{S}_{\text{fluid}}^i$. Thus, the higher bulk fluid $\delta^{34}\text{S}$ values of E1 South are also consistent with such a Rayleigh model. Furthermore, the low values of vein-hosted barite are also compatible with sudden increases in f_{O_2} , and the decrease in $\delta^{34}\text{S}$ from Stage 2 pyrite to Stage 3 chalcopyrite at E1 North is also indicative of increasing oxygen fugacity through time. Again, the high $\delta^{34}\text{S}$ values of sample EMMD153-277.5m would suggest that this process happened rapidly as the magmatic fluid permeated the calcareous rocks at E1 North.

A Rayleigh distillation scenario violates the assumption that $\delta^{34}\text{S}$ for the bulk fluid was constant throughout the mineralising process, which would invalidate the Δ - δ and δ - δ diagrams of E1 South. On the other hand, the rapid increase in the value of $\delta^{34}\text{S}$ in chalcopyrite between the E1 North orebody (mean = -0.7‰) and sample EMMD153-277.5 (+13.9‰) may suggest that the oxidation reaction took place quickly enough to result in a uniform bulk fluid $\delta^{34}\text{S}$ in E1 South. Furthermore, the linearity of these plots and apparent isotopic equilibrium of alteration samples indicates that such a process involved substantial isotopic exchange between the reactant H_2S and product SO_4^{2-} . Ideal Rayleigh models do not permit such exchange, and consequently a batch distillation model shown in the equation below would more accurately describe the process (e.g. Valley, 1986; Zheng, 1990).

$$\delta^{34}\text{S}_{\text{fluid}}^f = \delta^{34}\text{S}_{\text{fluid}}^i - (1 - f) \times 1000 \ln \alpha_{\text{H}_2\text{S}}^{\text{SO}_4^{2-}}$$

This model predicts a $\delta^{34}\text{S}_{\text{fluid}}^f$ value around 2‰ lower than the Rayleigh model for a given f value.

Although the batch distillation model for H_2S oxidation may account for the higher E1 East and E1 South $\delta^{34}\text{S}$ values, it implies that the original magmatic fluid was relatively reduced, which is not consistent with the highly oxidized, U-F-rich geochemistry of Williams-Naraku granites northeast of Cloncurry (Wyborn, 1998). Furthermore, the

+4‰ $\delta^{34}\text{S}$ value of the bulk fluid for E1 North is slightly higher than ideal magmatic sulfur (0‰), which suggests incorporation of sulfur from oxidized sedimentary rocks into the magma. Though there is some evidence of sulfur oxidation, it is not clear that this was the dominant process which resulted in the observed mineral $\delta^{34}\text{S}$ values. Indeed, when adjusting in the pH- f_{O_2} range (Fig. 4.19) for the estimated $\delta^{34}\text{S}_{\Sigma\text{S}}$ values, it suggests that changes in f_{O_2} were in the order of 1–2 log units, except during vein formation. Finally, if such a reduced fluid had passed through the carbonaceous metasilstones of E1 South and E1 East, it seems unlikely that sufficient oxidation would take place to caused mineralisation in these rocks. It is more likely that the explanation for the shift in $\delta^{34}\text{S}$ between E1 North, E1 East, and E1 South is a combination of both scenarios, in which an oxidized, evolved magmatic fluid interacted with a more-oxidized sulfate-bearing fluid that equilibrated with sulfur in the Corella Formation. More data focusing on detailed spatial and lithological isotopic distributions would be necessary to test the validity of the hydrolysis and distillation models.

Precipitation mechanisms

The deposition of ore minerals can be brought upon by changes in temperature, pH, oxygen fugacity, salinity, fluid phase, or a combination thereof, which ultimately shift the stability of the ore components into insoluble regimes. These changes can be caused by fluid upwelling, wall rock interaction, or mixing with one or more other fluids. The sulfur isotope and fluid inclusion data discussed above indicate that ore genesis at the E1 Group involved a substantial component of fluid mixing, which initiated salinity and temperature drop, and possibly an increase in f_{O_2} . Changes in f_{O_2} have a major influence in ore mineralogy in some IOCG deposits, such as Olympic Dam (Oreskes and Einaudi, 1990; Haynes et al., 1995), which is reflected in transitions from magnetite-chalcopyrite zones to hematite-bornite zones (e.g. Fig. 4.19). The sulfur isotope data of E1 Group barite and chalcopyrite, however, fall into a limited range of f_{O_2} conditions, which suggests that these parameters were relatively stable throughout the system, and were not the most important factor in causing chalcopyrite precipitation, despite the possible effect on isotopic shift between E1 North and South. In contrast to chalcopyrite, the observed oxidation shifts of 1–2 log₁₀ units may have played a major role in barite precipitation, especially if pH and f_{O_2} conditions were near the barite stability boundary. Nevertheless, the similar proportions of barite, fluorite, chalcopyrite

and magnetite in both E1 North and South (Fig. 2.20) indicate that oxygen fugacity was not substantially different between the systems.

The exceptions to this are ores hosted in the carbonaceous metasiltstone unit present at E1 South and East. At E1 South, the metasiltstone grades upward to a carbonaceous schist that is unmineralised. The metasiltstone hosts magnetite and chalcopyrite alteration, in addition to pyrrhotite and arsenopyrite, but does not contain any sulfate minerals. This unit clearly acted locally as a reductant to the ore fluids passing through it, but it is not structurally or stratigraphically linked to the marble unit and consequently did not react with those fluids. It is interesting that some of the highest pyrite and chalcopyrite $\delta^{34}\text{S}$ values (+20 and +17‰) measured in the E1 Group are from samples hosted in the carbonaceous metasiltstone. These $\delta^{34}\text{S}$ values overlap with the wide range of sedimentary sulfide from -50 to +40‰ (Seal, 2006 and references therein), and thus the simplest explanation is that these metasomatic sulfide $\delta^{34}\text{S}$ values are inherited locally from the host rock. Alternatively, reduction of a fluid with a high bulk fluid $\delta^{34}\text{S}$ value could explain the high $\delta^{34}\text{S}$ values for pyrite and chalcopyrite in the carbonaceous rocks.

Ohmoto and Lasaga (1982) concluded that in hydrothermal systems below 350°C, temperature changes alone are not a major factor in the deposition of cogenetic sulfide and sulfate minerals, and instead invoke mixing as a significant driver. In a mixing system, dilution of the high-salinity magmatic fluid, Fluid 1, with the relatively less-saline Corella Formation-derived fluid, would result in a substantial salinity decrease that could destabilize the Fe- and Cu chlorine complexes and lead to mineralisation. This is consistent with the observed salinity decrease between Stage 2a quartz-hosted, FIA-1A inclusions, and Stage 3 barite-hosted, FIA-2A inclusions. The fluid mixing model also explains the presence of barite. If the Corella Formation-hosted fluid was more oxidized than the magmatic fluid, some oxidation of H_2S may have occurred. The mixing process was probably not uniform across space and time in the deposit, and may have taken place in multiple cycles. This is evidenced by the fluorite-hosted FIAs identified by Williams et al. (2015), which are probably slightly later than the primary FIAs in barite, and which may represent renewed input of this higher-salinity, magmatic-hydrothermal F-rich, Fluid 1 into the system. This could also explain the observed variability in chalcopyrite $\delta^{34}\text{S}$ values within individual fine-grained, alteration-hosted, samples that results in non-linearity on the bulk fluid $\delta^{34}\text{S}$ diagrams.

Metal sources

Potential metal source(s) for the E1 Group ores can be inferred from a combination of mineralogical, fluid inclusion and stable isotope evidence. The highly F-rich and U-REE anomalous nature of the E1 Group orebody is consistent with a source from an evolved alkaline magma. In addition, the E1 North orebody, which is characterised by a magmatic isotopic signature, contains the most Cu and Au of the three orebodies. For these reasons, Cu, Au, F, P, U, and REE are interpreted to have been derived from an evolved, Williams-Naraku-type, granite. Alternatively, some Fe, Cu, and Au may have been leached from mafic country rocks by the magmatic fluid during earlier Na-Ca alteration (e.g. Oliver et al., 2004; 2008); the only significant mafic rocks around the deposit are metadolerite dykes. As previously discussed, sulfur probably came from both the magma and Corella formation, especially if the latter contained metaevaporite beds. The oxidized nature of the calcareous rocks leaves the magma as the only likely source of reduced sulfur (H_2S), though SO_4^{2-} may have come from both sources.

The main source of Ba^{2+} is not clear, but it was probably not directly from a magma. The presence of Ba-rich K-feldspar in Stage 2a alteration at the E1 Group (Chapter 2), as well as at Ernest Henry (Mark et al., 2006b), may be a result of Ba-leaching from igneous K-feldspar during metasomatism of the Mount Fort Constantine Volcanics. It is speculated that barium produced in Stage 3 may have been sourced from continued alteration of the metavolcanic rocks, as well as from overprinting of Stage 2a K-feldspar. The Ba would have been soluble in the early high-salinity magmatic brine prior to sulfur disproportionation, which could explain its incorporation into Stage 2a K-feldspar. An alternative Ba source may be metaevaporite rocks in the Corella Formation. This possibility is less likely, however, because barite alteration is restricted to within the Cu-Au orebody and is not present in significant amounts in the less-altered marble horizon between E1 North and E1 South. Additionally, Ba in the Corella formation would probably already exist as barite, and would consequently be difficult to remobilize in significant amounts during mineralisation. The relative insolubility of fluorite suggests that Ca and F were carried by separate fluids. When considering the extent of carbonate replacement observed in the E1 Group, it is not unreasonable to conclude that much of the Ca and CO_3^{2-} were probably locally derived from dissolution of Corella Formation marble. This hypothesis does not require a CO_2 -rich fluid, and

could therefore help to reconcile the paucity of CO₂ inclusions in the E1 Group samples studied.

In summary, the $\delta^{18}\text{O}$, $\delta^{34}\text{S}$ and fluid inclusion data from pre-ore and ore-stage minerals indicate that ore was precipitated mainly by salinity decrease, and possibly oxidation, caused by mixing of a high-salinity, oxidized, magmatic fluid (Fluid 1) with a lower-salinity, fluid (Fluid 2) derived from an external source and equilibrated with the local Corella Formation metasedimentary rocks. Such a fluid may have originated from shallower basinal waters, or possibly even meteoric sources (e.g. Kerrich et al., 1984), prior to incorporating Corella Formation sulfur; the external fluid was also oxidized. The magmatic fluid is the proposed source of Cu, Au, H₂S, F, U, REE, and probably SO_4^{2-} , while Fluid 2 probably carried Ca and SO_4^{2-} . The source of barium is ambiguous, but may have been leached from the intermediate-felsic Mount Fort Constantine metavolcanic rocks during early albitisation and potassic metasomatism. This mixing model is combined with the structural aspects from Chapter 3 and presented visually in Figure 5.1.

Implications

IOCG genesis and regional comparisons

The fluid inclusion and isotopic characteristics of pre-ore and ore-stage fluids of the E1 Group are similar to those in other IOCG deposits, but have some differences. The high-salinity, FIA-1A Fluid Inclusion Assemblage observed at the E1 Group is similar to fluid inclusion populations reported in most IOCG deposits (Table 4.6) in the Cloncurry District, and in other districts (Hunt et al., 2007). Such hypersaline waters (> 50 wt% NaCl_{eq}) are probably capable of mobilizing a variety of elements, which can help to explain the broad suite of anomalous elements in IOCG deposits like the E1 Group (Chapter 2). The basinal, NaCl-CaCl₂-rich fluid inclusions described by Xu (2000), and present across the Eastern Fold Belt, are abundant at the E1 Group, and probably represent direct evidence of another fluid which could have caused dilution of the hypersaline magmatic fluid to drive ore precipitation.

Table 4.6: Fluid inclusion and Sulfur Isotope characteristics of Cloncurry District IOCGs

Deposit	Major Assemblage	Stage	Mineral	Fluid inclusion characteristics						Sulfur Isotopes		Temperature estimates (°C)		
				Salinity (wt% NaCl _{eq})	Phases	CO ₂	Major chlorides	Other solids	Th (°C)	Ccp	SO ₄ ²⁻	Temperature (°C)	Method	References
Starra	Mag-qtz	Pre-ore	Qtz ⁶	30–50	L-MS-V; L-V	yes	Na	mag, cal, fpy	345°–615°	-	-	400°–500° ⁶	O - isotopes	Rotherham et al., 1998 ⁶
	Ccp-carb-anh ± bar	Syn-ore	Qtz ⁶	30–40	L-MS-V; L-S-V	no	Na,Mn	bar, anh, fpy	225°–360°	–5 ⁶	+30 bar; +2.3 anh	180°–300° ⁶	O - isotopes	
Osborne	Qtz-fspr	Pre-ore	Qtz ⁷	>40	L-MS-V	yes	Na	NR	>400°	-	-	-	-	Fisher and Kendrick, 2008 ⁷
	Ccp-qtz-mag	Syn-ore	Qtz ⁸	<45	L-MS-V; L-V	yes	Na,K,Ca	syl	250°–500°	–1.1 ⁹	-	300°–400° ⁸	microthermometry	Adshead, 1995 ⁸ ; Davidson and Dixon, 1992 ⁹
Eloise	Hbl-bt-qtz	Pre-ore	Qtz ¹⁰	32–68	L-MS-V	no	Na,K,Fe, Mn	syl, Fe-Mn-Ca-Si-chlorides	270°–540°	-	-	450°–600° ¹⁰	microthermometry	Baker, 1998 ¹⁰
	Ccp-py-po-mag-carb-qtz	Syn-ore	Qtz ¹⁰	30–40	L-MS-V; L-S; L-V	yes			100°–500°	+1.6 ¹¹	-	200°–450° ¹⁰	microthermometry	Baker et al., 2001 ¹¹
Lightning Creek	Ab-mag; Mag-cpx-ab; Cpx-mag-ab	Early	Qtz ¹²	33–50	L-MS-V; L	yes	Na, Fe-Mn, K	cal	> 420°	-	-	> 520°	O - isotopes	Perring et al., 2001 ¹²
Mount Elliott	Dp-sc-ab	Pre-ore	Dp ¹⁶	high	L-MS-V	yes ¹⁷	Na, Fe, K	-	NR	–5.1 ¹⁴	-	350°– 500° ¹⁴ ,	mineral assemblage	Garrett, 1992 ¹⁴ Pollard et al., 1997 ¹⁵ Little, 1997 ¹⁶
	Cal	Post-ore	Cal ¹⁵	11–44; 4–21	L-S-V	no	Na, Ca	-	130°–380° ¹⁵	(syn-ore)	-	-	-	
Ernest Henry	Ccp-mag-carb-qtz-py-fluo-bar-kspr	Syn-ore	Qtz ³	>30 %	L-MS-V; L-V	yes	Na,Ca	NR	250°–600°	+1.1 ¹	+11 ²	200°–400° ¹	S - isotopes	Twyerould, 1997 ¹ ; Andrew et al., 2000 ² ; Kendrick et al., 2007 ³ Williams et al., 2015 ⁴ ; Davidson et al., 2002 ⁵
Monakoff	Ccp-bar-fluo-carb-py	Syn-post-ore	Fluo ⁴	high	L-MS-V; L-V	yes	Na,Ca	NR	>450°	-	+7.1 ²	>400° ⁵	mineral assemblage	
E1 Group	Qtz±mag	Pre-ore	Qtz ¹³	>50	L-S-V	no	Na	NR	NR	-	-	-	-	This study ¹³
	Bar-ccp	Syn-ore	Bar ¹³	0–15	L-V	no	Na	NR	160°–180°	-0.1 to +14.7	+10.3 to +23.3	230°–330°	S - isotopes	
	Cal	Post-ore	Cal ¹³	13–23 NaCl+Ca Cl ₂	L-V	no	Na, Cl	NR	NR	-	-	-	-	
L, liquid; MS, multi-solid; V, vapour; syl, sylvite; anh, anhydrite; mag, magnetite; cal, calcite; bar, barite; fluo, fluorite; dp, diopside; ccp, chalcopyrite; carb, carbonate; kspr, K-feldspar; qtz, quartz; cpx, clinopyroxene; hbl, hornblende; bt, biotite; po, pyrrhotite; ab, albite; py, pyrite; fspr, feldspar; fpy, ferropyrrosmalite; sc, scapolite; NR, not reported.														

The E1 Group is unique among the deposits in the area in that it lacks CO₂ - rich fluid inclusion populations. Given the extensive deformation of Stage 2a quartz, it is possible that these inclusions are simply not well-preserved in the few samples analysed.

Alternatively, the apparent absence of CO₂ may account for the observed textural differences between the E1 Group and Ernest Henry deposits. In Chapter 3, it was proposed that the E1 Group was subjected to less fluid overpressure (that is, the difference between hydrostatic and lithostatic pressure was lower) than Ernest Henry, and as a consequence there was insufficient force to initiate a fluidized brecciation process as described by Oliver et al. (2006) and Bertelli and Baker (2010). Those authors concluded that CO₂ release from Williams-Naraku granites contributed to most of the fluid overpressure at Ernest Henry and regional, unmineralised, breccias. Instead, fluid pressure at the E1 Group was low enough for permeability generated by shearing to accommodate much of the exsolved magmatic fluids. Oliver et al. (2008) suggested that the CO₂ probably originated from mafic magmas in the mantle, which subsequently rose and mixed with Williams-Naraku magmas. It is not clear why CO₂ may have been absent in the case of the E1 Group, but a possible explanation may be simply that the granitic precursor melt did not interact with mafic magmas.

While E1 Group FIAs are mostly comparable to regional IOCG fluid inclusions, the isotopic signatures are substantially different. The $\delta^{34}\text{S}$ values of E1 North chalcopyrite and pyrite are similar to those of Ernest Henry, Starra, Osborne and Eloise (Fig. 4.21). E1 East and South, however, are characterised by much higher values of $\delta^{34}\text{S}$ than any other system in the region. Sulfate data for the region is limited, but E1 Group barite is similar to that in Ernest Henry (Fig. 4.21C). Barite at Starra (+30‰) is characterised by similar $\delta^{34}\text{S}$ values to E1 South barite, but Starra anhydrite values are much lower (+2‰). It is worth noting that Ernest Henry is the only other system with a spread in $\delta^{34}\text{S}$ values (>15‰) comparable to E1 East and South (Fig. 4.21). In that deposit the higher chalcopyrite and pyrite values are below the economic orebody in the footwall (Twyerould, 1997). Some of these higher $\delta^{34}\text{S}$ values are associated with Corella Formation marbles, which compose much of the footwall sequence at Ernest Henry. Despite the spread in $\delta^{34}\text{S}$ values between deposits, ore formation temperature estimates overlap between most of them (Fig. 4.21D).

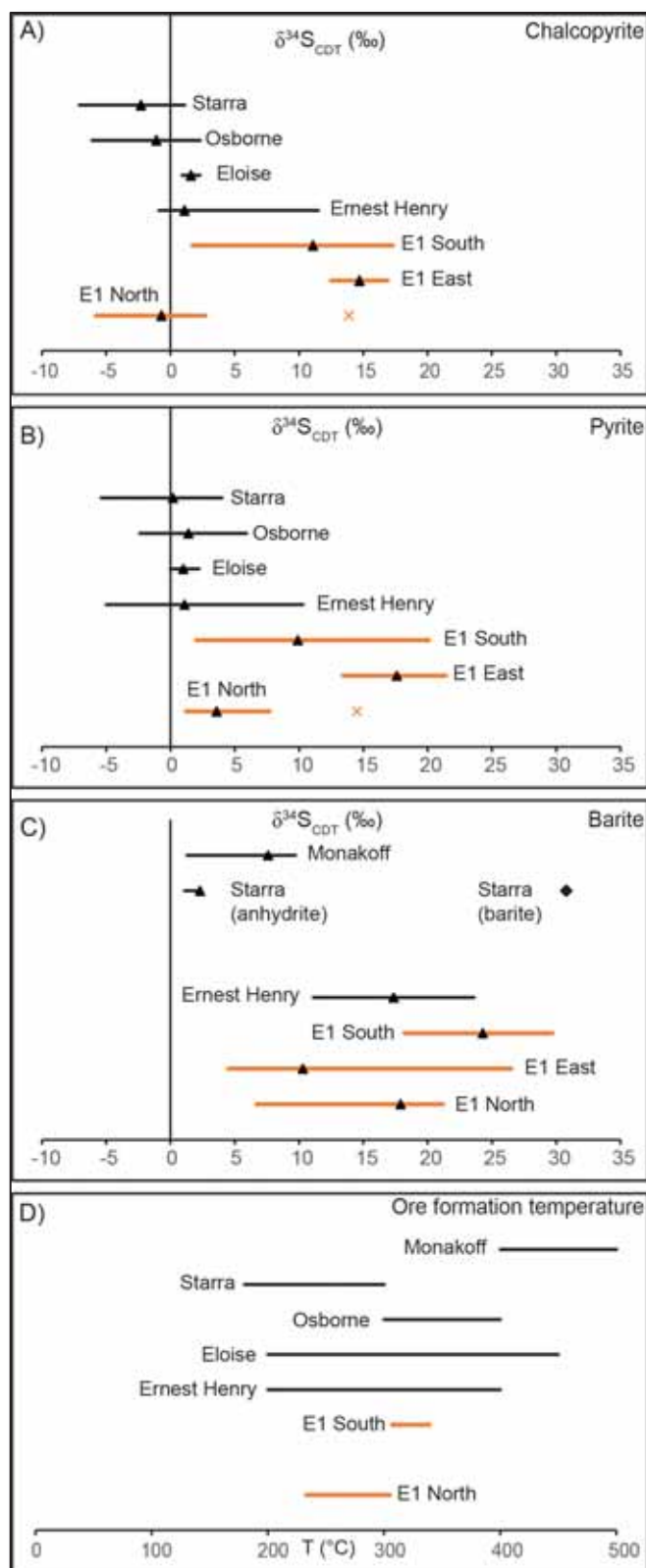


Figure 4.21: Range of $\delta^{34}\text{S}$ chalcopyrite (A), pyrite (B), and barite (C) values for Cloncurry IOCGs. D) Range of estimated ore formation temperatures. See Table 4.6 for references.

The variation in $\delta^{34}\text{S}$ values at the E1 Group and Ernest Henry appear to reflect a substantial amount of wall rock and external fluid interaction. This suggests that the orebodies in some of the other deposits are much closer to their potential source magmas than the E1 South and E1 East ore zones, or that the ore fluids passed through markedly different host rocks prior to deposition, or both. The E1 Group as a whole may represent an oxidized end-member to this process, in which an oxidized magmatic fluid permeated oxidized metasedimentary rocks (e.g. marble). It is proposed that the Eloise Cu-Au deposit may represent another end-member. In contrast to the E1 Group, Eloise contains magnetite but is dominated by pyrrhotite and pyrite, indicating a reducing environment during ore deposition (Baker, 1998; Baker et al., 2001). Eloise is also different in that it is hosted in metasedimentary and mafic rocks of the Soldiers Cap Group of Cover Sequence 3 (Baker, 1998), which include the graphitic pelites and mafic rocks of the Toole Creek Volcanics. Fluids in both deposits, however, are interpreted to be mostly magmatic in origin (Baker et al., 2001). It is possible that a Williams-Naraku-related granite, initially oxidized, passed through these reduced rocks and was altered to a low f_{O_2} state by the time the Eloise ores were precipitated. This is consistent with the interpretation by Baker (1998) that Eloise is a distal magmatic deposit. Thus, Cu-Au mineralisation in the Eastern Fold Belt may represent a continuum of magmatic-hydrothermal systems, in which the oxidation state of the local country rocks plays a major role in ultimately developing either a true IOCG such as the E1 Group, or an iron sulfide-Cu-Au deposit (ISCG) like Eloise.

Global comparisons

The fluid mixing model of the E1 Group is compatible with genetic models of IOCGs in other districts, including the Gawler Craton, Punta del Cobre and Carajás. At the Olympic Dam (Gawler Craton) deposit, McPhie et al. (2011b) linked the high fluorine enrichment in the orebody to a magmatic-hydrothermal fluid derived from coeval, F-rich, granites; this fluid mixed with a shallower (basinal or near-surface) fluid during ore genesis (e.g. Haynes et al., 1995; Reynolds, 2000; McPhie et al., 2011a). Mixing of a deep-seated magmatic fluid with an external fluid has also been proposed for Candelaria, Mantoverde and Sossego (Chapter 1), but there is interpreted variation in the relative ratios of these types of fluids between deposits. For example, Mantoverde (Coastal Cordillera) may have been dominated by non-magmatic fluids (mostly basinal brines) during mineralisation (Benavides et al., 2007), while Sossego (Carajás) and

Candelaria (Coastal Cordillera) were characterised by relatively higher magmatic-hydrothermal input. Indeed, as demonstrated above for the E1 Group, the degree of involvement of magmatic and non-magmatic fluids can vary even within an individual deposit. The fluid evolution of the E1 Group thus provides additional evidence of the hybrid magmatic and non-magmatic fluid source model for IOCG deposits and, when coupled with comparisons to other deposits, suggests that few IOCG systems are exclusively magmatic or non-magmatic.

Exploration

The genetic model of the E1 Group can provide insight into the features of a prospective IOCG system. For example, the combination of fluid inclusion and stable isotope data indicate that ore precipitation was caused primarily by a decrease in salinity, and possibly an increase oxidation state, as the result of mixing between a magmatic fluid and another fluid probably derived from a shallow connate fluid. This is in contrast to unmineralised Fe-oxide-rich systems like Lightning Creek, which were dominated almost entirely by magmatic fluids. In the case of the E1 Group, the mixing process generates the most copper and gold at the intersection of a shear zone with another conduit such as a fold hinge, which enables such shallow fluids to permeate deep enough to interact with a magmatic fluid at depth (>6 km). Fold hinges alone can still focus economic mineralisation. Marbles and metaevaporitic rocks, such as those in the Corella Formation, may have lost most of their original connate waters prior to mineralisation, but can nevertheless impart a distinct $\delta^{34}\text{S}$ signature on the ore assemblage in systems like E1 South. Furthermore, they can act as a chemical trap for ores over distances of at least 1–2 km along strike.

Sulfur isotopes of sulfides and sulfates may serve as potential vectors to the high-grade centers of these mixed magmatic-hydrothermal systems. As an example, the $\delta^{34}\text{S}$ values of chalcopyrite at E1 North (–5.8 to +2.7‰), the largest orebody in the E1 Group, are mostly consistent with sulfur isotopes from other magmatic-dominated Cu-Au deposits in the Eastern Fold Belt such as Ernest Henry and Eloise. These values increase away from the E1 North orebody to E1 East and South. A similar trend may be observed at Ernest Henry, where $\delta^{34}\text{S}$ values decrease from the sub-economic footwall into the ore zone (Twyrould, 1997). Thus, zones with calculated $\delta^{34}\text{S}_{\Sigma\text{S}}$ values between ~0 and +7‰ may represent the high-grade, magmatic fluid-dominated $\delta^{34}\text{S}_{\Sigma\text{S}}$, hydrothermal

centers. However, it is cautioned that much more isotopic data is needed over greater distances to fully verify these trends, as well as to better understand the rate at which sulfur isotope fractionation changes in space. *In-situ* isotopic analysis via SHRIMP may be necessary to obtain accurate results in fine-grained alteration samples for IOCG deposits characterised by replacement-style orebodies, such as E1.

Conclusions

Fluid inclusion and stable isotope data reveal a complex ore genesis process in the E1 Group of IOCG deposits. Pre-ore fluids, hosted in quartz associated with the main phase of Fe-oxide input, are characterised by hypersalinity and an oxygen isotope signature that together suggest a dominantly magmatic origin. In contrast, ore-stage fluids, hosted in barite associated with chalcopyrite, are characterised by a lower salinity and mixed sulfur isotope signatures. The E1 Group can therefore be placed into the mixed magmatic-non-magmatic family of IOCG deposits. E1 North ore-bearing fluid is dominated by a magmatic sulfur signature with oxidized sediment input, while E1 South has a much heavier isotopic signature resulting from contribution of sulfur from metasedimentary host rocks in the Corella Formation and an external fluid which equilibrated with these rocks and obtained their isotopic signature. Alternatively, but less likely, the higher E1 South signature could be caused by batch distillation through oxidation of a reduced magmatic fluid by the oxidized metasedimentary rocks of the Corella Formation. The most likely scenario involves a combination of both processes. Ore precipitation was probably caused by a salinity decrease that resulted from mixing of the hypersaline magmatic fluid with the less-saline external fluid – possibly of basinal or meteoric origin. Barite precipitation was probably driven by a combination of sulfate input from mixing with the Corella Formation-derived fluid, hydrolysis of magmatic SO₂, and minor variations in oxygen fugacity caused by fluid mixing. The magmatic fluid was most likely derived from an oxidized, evolved, F-U-REE-bearing, and alkaline, A-type granite. It is speculated that such a granite was related to the 1550–1490 Ma Williams-Naraku Batholith. Barium may have been derived from evaporites in the Corella, or from leaching of feldspars in the abundant Mount Fort Constantine Volcanics. The variation in sulfur isotope signature between E1 North, the largest and most concentrated orebody in the E1 Group, and E1 South, suggests that sulfur isotopes may be useful for vectoring to the magmatic-dominated, high-grade, centers of economic mineralisation.

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Chapter 5

Conclusions

A Genetic Model of the E1 Group

This chapter combines the interpretations of the previous chapters into a comprehensive ore genesis model for the E1 Group. The model is presented chronologically, and as such the geological, paragenetic, structural and geochemical aspects discussed separately in the previous chapters are interwoven to form a timeline, from host rock deposition to mineralisation. The model is shown visually in Figure 5.1.

Phase 1: Host rock deposition and early intrusions.

E1 Group ores are hosted mostly in marble and carbonaceous metasiltstone and schist of the Corella Formation, and also in metatuffs and metavolcanic breccia portions of the Mount Fort Constantine Volcanics; these rocks are intercalated with mostly barren meta-andesite and meta-andesite-basalt that are also part of the latter formation. From bottom to top, the local stratigraphy is: variably amygdaloidal, massive and porphyritic meta-andesite, siliceous marble intercalated with metatuff and metavolcanic breccia, porphyritic meta-andesite, carbonaceous metasiltstone grading up into schist.

Regionally, the Corella Formation was deposited between 1750 and 1720 Ma as part of the regional Cover Sequence 2. The 1750–1740 Ma old Mount Fort Constantine Volcanics probably represent volcanic flows erupted onto the sediments of the Corella Formation while hypabyssal sills intruded into it. It is likely that the Mount Margaret Fault, which forms the northern portion of the regional Cloncurry Fault Zone, was active during this time as a basin-bounding normal fault. The rocks were intruded by diorite that is probably part of the local Ernest Henry Diorite suite that crystallized around 1650 Ma.

Phase 2: Pre-ore deformation.

The S_1 foliation is not well-preserved and is related to a local D_1 event. The axial planar S_2 foliation is related to the formation of the major north-northwest-plunging folds that dominate the E1 Group geometry, namely the E1 North Antiform, E1 South Synform, and E1 East Antiform. These folds formed from east-northeast and west-southwest shortening during regional peak metamorphism (D_2), which has been dated to between 1600 and 1580 Ma. The Mount Margaret Fault was likely reactivated with components of reverse and strike-slip movement during this time. The northeast-southwest-trending orientation of the west limb of the E1 North Antiform caused by D_2 folding and

faulting/shearing provided the structural architecture for later mineralisation. The regional D₃ event does not appear to be preserved in the mine lease.

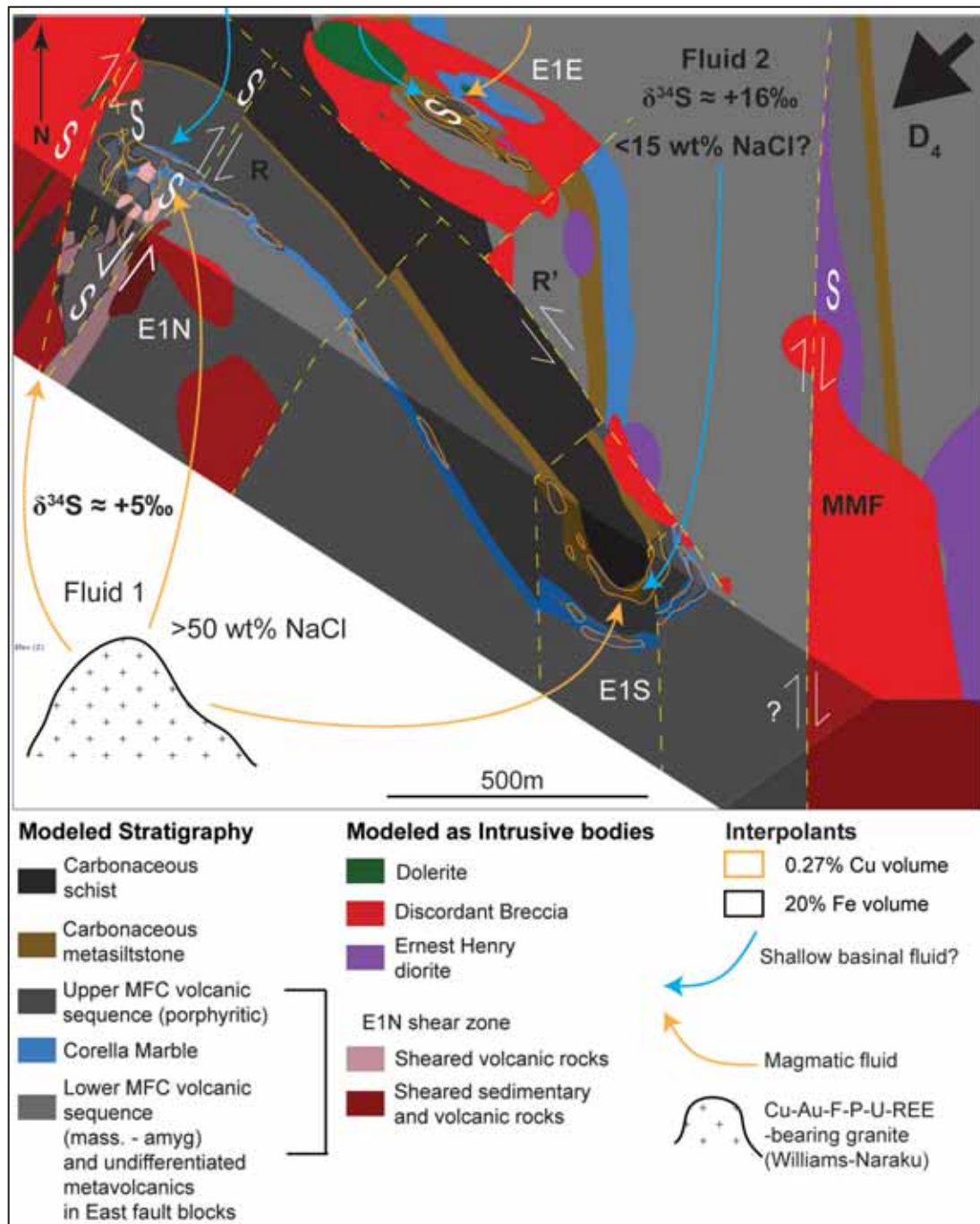


Figure 5.1: Generalized genetic model for an E1 Group-style, Cloncurry-type IOCG, based on the 3-D geological model presented in Chapter 3. A magmatic fluid, most likely oxidized and enriched in Cu-Au-F-U-REE-H₂S-SO₂, permeates through the E1 North shear zone, or a dilated fold hinge, and mixes with a fluid that interacted with sulfur in the Corella Formation. The mixing process takes place during D₄, in a Riedel brittle-ductile system (marked as R and R') that was formed by transpressional movement along the Mount Margaret Fault (MMF). Temperature decrease initiates SO₂ hydrolysis. The mixing decreases salinity and initiates ore precipitation. Sulfate is generated through hydrolysis, and additional contribution from Corella Formation metaevaporites. At E1 North, the magmatic fluid dominates the system and results in low $\delta^{34}\text{S}$ values. E1 East and South, more distal from the magma source, are dominated by the Corella Formation-hosted fluids and consequently have higher $\delta^{34}\text{S}$ values. S, shear zone.

Phase 3: Local D₃ / regional D₄ deformation and early alteration paragenesis.

During local D₃ / regional D₄, the shortening direction shifted to northeast-southwest, and the Mount Margaret Fault was reactivated as a transpressional Riedel fault-shear system. The northeast-southwest-trending structures comprising the E1 North Shear Zone formed as oblique extensional, antithetic, R-shears to this Riedel system. The northeast-southwest trend and northwest dip of the E1 North Shear Zone was at least partly controlled by the dip of the west limb of the E1 North Antiform. These brittle-ductile R-shears, along with the hinges of the E1 North Antiform and E1 South Synform, provided the permeability necessary for the hydrothermal fluids. The local stratigraphy at the E1 Group – ductile marble and metavolcaniclastic rocks in between coherent, competent, massive to porphyritic metavolcanic rocks – caused D₄ ductile strain to be partitioned into the metasedimentary rock horizons, as well as into the clastic metavolcanic rocks. As a result, the ore fluids were focused into chemically-reactive marble of the Corella Formation, which in other instances can be a fluid barrier. Unlike Ernest Henry, fluid pressure was insufficient to cause brecciation; instead, the mineralisation formed as stratabound replacement bodies in the shear zones and fold hinges. This, coupled with the chemical favourability of the marble host rocks, resulted in the observed layer-controlled ore textures in metasedimentary rocks and layered metatuffs, along with matrix-controlled replacement of metavolcanic breccias. The marble of the Corella Formation was also chemically receptive to replacement, causing mineralisation to extend over 500 m along the limbs of the folds.

A discordant, barren, breccia found throughout the E1 Group mine lease, as well as at nearby targets, is post-regional D₂ to syn-regional D₄ in timing. The breccia is strongly altered by Stage 1 albite (-hematite), Stage 2 K-feldspar-biotite, and later carbonate. Many clasts show evidence of chemical abrasion. The breccia is similar to many sodic-calcic-altered breccias around the area. The breccia, however, does not appear to be related to mineralisation.

Stage 2a quartz and magnetite formed from a fluid characterised by a $\delta^{18}\text{O}_{\text{VSMOW}}$ composition from +8 to +12 ‰. Fluid inclusions in the quartz were heterogeneously trapped from a fluid with a salinity exceeding 50 wt% NaCl_{eq}. The $\delta^{18}\text{O}$ values and fluid salinities are most consistent with a magmatic-hydrothermal fluid. The calculated formation temperature range for these two minerals is 400° to 550°C.

Phase 4: Mineralisation

Stage 2a alteration was followed by a minor albite-rutile stage (Stage 2b), and then by Stage 2c carbonate flooding; some mineralisation probably formed during Stage 2c. The main Cu-Au mineralising event was Stage 3; local D₃ / regional D₄ deformation was ongoing during this time.

The $\delta^{34}\text{S}$ values of Stage 3 barite and chalcopyrite suggest a mineralisation temperature range of 230° to 330°C. The bulk system (ΣS) $\delta^{34}\text{S}_{\text{CDT}}$ values of Stage 3 chalcopyrite and barite range from +4.9‰ at E1 North to +15.9‰ at E1 South. Low-salinity (< 15 wt% NaCl) fluid inclusions in Stage 3 barite fluid inclusions homogenised between 160° and 190°C. Trapping pressure estimates for the fluid inclusions, derived from the barite-chalcopyrite formation temperatures and barite fluid inclusion homogenisation temperatures, are between 2200 and 3300 bar, corresponding to a depth range of 8–12 km. Such a depth range is consistent with the brittle-ductile transition zone.

The most likely ore genesis hypothesis to explain these fluid and isotope characteristics is a hybrid magmatic-non-magmatic fluid-fluid mixing model. The increase in $\delta^{34}\text{S}_{\Sigma\text{S}}$ of the fluids between E1 North and E1 South was the result of mixing of a sulfur-bearing magmatic fluid with another fluid that equilibrated with sulfur derived locally from the Corella Formation. Alternatively, but less likely, oxidation of the magmatic fluid through interaction with the second fluid may have caused batch distillation, which could explain the values. The second fluid probably originated from shallower depths, possibly from a basinal source, and descended through the shear zones and fold hinges. The magmatic fluid dominated $\delta^{34}\text{S}$ values at E1 North; it was probably sourced from an evolved, alkaline, A-type granite, which is speculated to be part of the Williams-Naraku Batholith. The fluid-fluid mixing model also explains the presence of insoluble barite. The magmatic fluid likely contributed most of the Cu, Au, F, U and REE to the ores, as well as sulfur in the form of both H_2S and SO_4^{2-} ; the second fluid also contributed SO_4^{2-} . It is unlikely that either fluid carried Ba, and its source is not clear. It may have been derived from metavolcanic rocks during Stage 1 and 2 alterations, or locally from meta-evaporite rock layers in the Corella Formation. Precipitation of the ores was driven mainly by a salinity decrease caused by mixing of the high-salinity magmatic fluid with the lower-salinity fluid. Locally, rapid oxidation may have precipitated much of the barite. In contrast to the nearby Ernest Henry deposit, the Stage

2 and 3 fluids were not CO₂-rich, which may partly explain why fluid pressure was insufficient to cause Ernest Henry-style brecciation.

Implications for IOCG Genesis and Exploration

The geochemistry and paragenesis, structural controls and ore genesis model of the E1 Group carry implications for IOCG formation and exploration in the Cloncurry District, and globally.

The similarities in paragenesis, ore chemistry and timing (1530–1500 Ma) between the E1 Group, Ernest Henry and Monakoff suggests these systems formed from a similar type of hydrothermal fluid that was present over an area of 120 km² between the deposits, thus making the area highly prospective for additional exploration. This does not necessarily imply, however, that these deposits formed at exactly the same time, or from the same hydrothermal system. Fluorine and barium may serve as vectoring elements to orebodies in this region. Anomalously-high fluorine is traceable for at least 100 m around the E1 Group orebody, and is probably mostly hosted in apatite and biotite in this zone. Barium is also above background levels for at least 100 m outside of the ore zone.

The absence of brecciation at E1 Group may help explain the high barite and fluorite concentrations in the ores. Barium and fluorine in Stage 2 K-feldspar and fluorapatite indicate that both elements were present in the magmatic hydrothermal fluid throughout the evolution of the system. It is possible that protracted replacement over multiple paragenetic stages, probably associated with minor volume change, led to increasing total Ba-F content over time. This is consistent with the observed tendency for fluorite to replace F-rich biotite in the E1 Group ores, and explains the apparent lack of fluorapatite in ores, which was probably also replaced by fluorite. On the other hand, brecciation during ore formation at Ernest Henry probably caused a much greater increase in the overall volume of the system, and resulted in dilution of these elements with each paragenetic stage. The same principle may apply to other breccia-hosted IOCG deposits like Olympic Dam and Prominent Hill in the Gawler Craton

In the northeast Cloncurry District, northeast-trending ductile-brittle structures that intersect folded metasedimentary rock horizons, and are hosted within Riedel strike-slip structures, can form fault-shear systems ideal for both Ernest Henry and E1 Group-

styles of mineralisation. These structures formed in the regional D₄ event, but may appear to be D₃-related if the latter event is not locally preserved. Where such D₄ structures occur, the degree of fluid overpressure and relative permeability of the host rocks are important characteristics that probably influence the formation of stratabound replacement-style E1 Group orebodies, as opposed to breccia-hosted Ernest Henry-style ores. These parameters may also influence the size and grade of the deposits. In some cases, juxtaposition of competent lithologies, such as metavolcanic rocks, between impermeable metasedimentary rock horizons, may have generated fluid overpressure and facilitated the brecciation needed to form an IOCG deposit like Ernest Henry, rather than a stratabound replacement orebody such as the E1 Group. When the E1 Group is compared to IOCG deposits in other districts such as Fennoscandia and Carajás, an obvious association can be seen between ductile structural regimes and replacement orebodies. Given the 8–12 km depth of ore genesis at the E1 Group, it is suggested that replacement orebodies probably form at similar depths. Conversely, breccia ores are typically, but not always, formed in dominantly brittle regimes. Such regimes may be shallower, but do not have to be if hydrostatic pressure is high. If precise lithostatic pressure constraints are known, fluid inclusion data can provide estimates of fluid overpressure and potential for breccia-hosted mineralisation.

The genetic model of the E1 Group can yield understanding into the characteristics of a prospective IOCG system. The magmatic and external fluid mixing process that formed the E1 Group ores generated the highest Cu and Au grades at the intersection of a shear zone with another conduit, such as a steeply-plunging regional D₂ fold hinge. This intersection enables shallow fluids to permeate deep enough to interact with a magmatic fluid at depth (>6 km); similar controls are observed at other Cloncurry District Cu-Au deposits (e.g. Ernest Henry, Eloise). Fold hinges alone can still focus economic mineralisation, albeit with slightly lower tonnage and grade. Meta-evaporitic rocks and marbles, like those in the Corella Formation, likely lost most of their original connate waters to metamorphism before mineralisation; they can nevertheless result in a distinct $\delta^{34}\text{S}$ signature on ores hosted in these rocks, like those at E1 South. Furthermore, they can serve as a chemical sink for ores over distances of at least 2 km along strike. The $\delta^{34}\text{S}$ values of sulfides and sulfates may potentially serve as vectors to the high-grade, magmatic fluid-dominated, areas of these mixed magmatic-hydrothermal systems, where values of $\delta^{34}\text{S}_{\Sigma\text{S}}$ are between 0 and $\sim +7$ ‰.

Appendix A

Drill Core Sample Locations and Descriptions

Table A-1: Diamond Drillhole Location Information

Hole ID	Easting (m)	Northing (m)	RL (ASL + 2000 m)	Total depth (m)	Azimuth (°)	Design Inclination (°)
EMDT008	477525	7739492	2148	253	90	-60
EMDT061	477641	7739575	2147	264	0	-90
EMDT063	478604	7738576	2147	277	0	-90
EMDT065	478648	7738626	2147	325	0	-90
EMDT066	478573	7738626	2147	262	270	-60
EMDT067	478593	7738526	2147	253	270	-60
EMDT073	477653	7739492	2147	222	0	-90
EMDT077	477622	7739615	2147	216	90	-60
EMDT080	477583	7739575	2147	222	90	-60
EMDT081	477611	7739689	2147	222	90	-60
EMDT191	477627	7739534	2147	165	90	-60
EMDT197	477683	7739554	2147	182	0	-90
EMDT202	477663	7739576	2147	166	90	-70
EMDT203	477663	7739556	2147	194	0	-90
EMDT210	477583	7739376	2148	143	0	-90
EMDT214	477601	7739576	2147	267	0	-90
EMDT216	477678	7739576	2147	192	0	-90
EMDT217	477640	7739596	2147	237	0	-90
EMDT219	477672	7739641	2147	252	0	-90
EMDT223	477657	7739513	2147	198	0	-90
EMDT225	478123	7739776	2146	198	90	-60
EMDT231	478220	7739828	2146	277	0	-90
EMM001	477549	7739496	2148	254	90	-70
EMM002	477527	7739576	2149	315	90	-70
EMM003	477597	7739656	2147	343	90	-75
EMM004	477635	7739696	2147	241	90	-80
EMM005	477866	7739571	2147	141	270	-60
EMM006	477938	7739574	2147	246	270	-60
EMM007	477650	7739657	2147	171	90	-60
EMM008	478359	7739799	2145	381	270	-60
EMM009	478322	7739747	2145	207	270	-56
EMM010	478399	7739750	2145	312	270	-60
EMM011	478386	7739699	2145	224	270	-60
EMM012	478454	7739596	2145	174	270	-60
EMM013	478471	7739551	2146	146	270	-60
EMM014	478589	7738726	2148	201	90	-75
EMM015	478515	7738770	2146	300	90	-75
EMM016	478587	7738726	2147	241	270	-80
EMM017	478513	7738770	2147	192	270	-80
EMM018	478633	7738627	2147	210	90	-75
EMM019	478614	7738674	2147	340	270	-80
EMM020	478483	7738676	2147	204	270	-65
EMM021	478584	7738626	2147	270	270	-80
EMM022	478523	7738625	2147	201	270	-65
EMM023	478652	7738705	2147	180	90	-70
EMM024	478634	7738574	2147	250	90	-85
EMM025	478525	7738645	2148	249	270	-80
EMM026	478659	7738529	2147	213	270	-75
EMM027	478693	7738325	2148	45	270	-75
EMM028	478514	7738588	2138	50	190	-55
EMM029	478590	7738492	2138	65	276	-80
EMM030	478678	7738461	2130	90	180	-55
EMM031	478775	7738502	2147	151	292	-60

Holes with physical (visual) logs in App. E are in **bold**

RL, relative level mine datum; ASL, above sea level; all data in GDA94 UTM Zone 54

Table A-1: Diamond Drillhole Location Information

Hole ID	Easting (m)	Northing (m)	RL (ASL + 2000 m)	Total depth (m)	Azimuth (°)	Design Inclination (°)
EMM032	478374	7739660	2121	60	155	-55
EMM033	478280	7739711	2120	60	43	-55
EMM034	478272	7739694	2120	55	24	-60
EMM035	478673	7738526	2130	111	165	-60
EMM036	478720	7738567	2131	100	160	-60
EMM037	478671	7738588	2130	160	283	-65
EMM038	478711	7738572	2130	90	75	-60
EMM039	478627	7738437	2138	65	225	-70
EMM040	478218	7739744	2120	70	95	-55
EMM041	478343	7739646	2120	135	90	-68
EMM042	478448	7739674	2135	165	230	-57
EMMD001	477572	7739615	2147	279	96	-60
EMMD002	477677	7739666	2147	251	0	-90
EMMD003	477603	7739531	2147	214	96	-60
EMMD004	477638	7739596	2147	222	90	-60
EMMD005	478247	7739701	2146	192	91	-60
EMMD006	478262	7739774	2146	306	0	-90
EMMD007	478277	7739829	2146	225	270	-60
EMMD008	478440	7739630	2146	150	270	-60
EMMD009	478499	7739629	2145	201	270	-60
EMMD010	478370	7739700	2146	163	270	-60
EMMD011	478383	7739776	2145	393	268	-60
EMMD012	478356	7739830	2145	361	276	-65
EMMD013	478400	7739627	2146	172	0	-90
EMMD014	478213	7739776	2146	297	0	-90
EMMD015	478183	7739876	2146	200	270	-70
EMMD016	478158	7739828	2146	277	88	-76
EMMD017	478406	7739626	2146	101	90	-60
EMMD018	478405	7739626	2146	139	270	-60
EMMD019	478413	7739701	2146	241	270	-60
EMMD020	478333	7739782	2146	248	227	-60
EMMD021	477522	7739576	2147	379	0	-90
EMMD022	477470	7739518	2148	369	90	-65
EMMD023	477524	7739634	2147	402	90	-60
EMMD024	477573	7739396	2148	208	90	-60
EMMD025	477574	7739715	2147	412	90	-70
EMMD026	477520	7739476	2148	359	90	-80
EMMD027	478280	7739874	2146	247	270	-70
EMMD028	477584	7739275	2148	144	90	-60
EMMD029	477541	7739276	2148	192	90	-60
EMMD030	478454	7739529	2146	120	270	-60
EMMD031	478493	7739527	2145	179	270	-60
EMMD032	477502	7739276	2148	268	90	-60
EMMD033	477565	7739224	2148	147	90	-60
EMMD034	477526	7739225	2148	295	90	-60
EMMD035	477564	7739122	2148	208	90	-60
EMMD036	477521	7739124	2148	203	90	-60
EMMD037	478423	7738774	2147	238	270	-60
EMMD038	478703	7738434	2148	150	180	-60
EMMD039	478637	7738747	2147	175	90	-60
EMMD040	478699	7738534	2147	222	174	-75
EMMD041	477472	7739124	2148	291	90	-60
EMMD042	478492	7738628	2147	191	270	-60
EMMD043	478462	7738624	2147	173	270	-60
EMMD044	478576	7738871	2147	179	90	-60
EMMD045	478598	7738673	2147	322	200	-80

Table A-1: Diamond Drillhole Location Information

Hole ID	Easting (m)	Northing (m)	RL (ASL + 2000 m)	Total depth (m)	Azimuth (°)	Design Inclination (°)
EMMD046	478372	7738877	2146	200	270	-60
EMMD047	478701	7738585	2147	250	200	-70
EMMD048	478754	7738455	2148	150	180	-75
EMMD049	478623	7738626	2147	284	200	-80
EMMD050	478601	7738440	2148	101	180	-75
EMMD051	478651	7738436	2148	153	180	-75
EMMD052	478598	7738626	2147	376	0	-90
EMMD053	478703	7738486	2148	182	180	-75
EMMD054	478623	7738676	2147	354	0	-90
EMMD055	477652	7739615	2147	324	0	-90
EMMD056	478596	7738675	2147	382	270	-75
EMMD057	477688	7739456	2147	116	0	-90
EMMD058	477744	7739658	2147	96	0	-90
EMMD059	477623	7739535	2147	282	0	-90
EMMD060	477732	7739494	2147	297	270	-60
EMMD061	478573	7738726	2147	448	0	-90
EMMD062	477648	7739666	2147	308	0	-90
EMMD063	477698	7739666	2147	274	0	-90
EMMD064	477683	7739696	2147	165	90	-60
EMMD065	477723	7739656	2147	87	90	-60
EMMD066	477673	7739616	2147	186	90	-60
EMMD067	477713	7739616	2147	254	90	-60
EMMD068	477563	7739456	2148	225	90	-60
EMMD069	477540	7739532	2148	253	90	-60
EMMD070	477603	7739426	2148	156	90	-60
EMMD071	478713	7738576	2147	144	90	-60
EMMD072	478648	7738626	2147	201	90	-70
EMMD073	477479	7739535	2148	313	90	-60
EMMD074	477563	7739426	2148	203	90	-60
EMMD075	477603	7739616	2147	231	90	-60
EMMD076	478733	7738526	2147	108	90	-60
EMMD077	477561	7739615	2147	315	90	-60
EMMD078	478723	7738626	2147	103	90	-75
EMMD079	477509	7739573	2148	267	90	-60
EMMD080	478656	7738375	2148	87	270	-60
EMMD081	478673	7738576	2147	275	0	-90
EMMD082	478705	7738376	2148	104	90	-70
EMMD083	478693	7738425	2148	151	0	-90
EMMD084	477484	7739492	2148	321	90	-60
EMMD085	477483	7739616	2147	402	90	-60
EMMD086	477643	7739616	2147	202	90	-60
EMMD087	477683	7739656	2147	247	90	-60
EMMD088	477579	7739695	2147	238	90	-60
EMMD089	477642	7739693	2147	182	90	-60
EMMD090	477718	7739694	2147	130	90	-60
EMMD091	477701	7739425	2148	76	0	-90
EMMD092	478631	7738474	2148	105	270	-70
EMMD093	478670	7738476	2148	127	0	-90
EMMD094	478747	7738477	2148	84	90	-60
EMMD095	478532	7738575	2147	189	270	-60
EMMD096	478521	7738723	2147	150	270	-70
EMMD097	478596	7738624	2147	276	270	-70
EMMD098	478681	7738676	2147	121	90	-60
EMMD099	478631	7738675	2147	183	90	-60
EMMD100	478585	7738670	2147	159	90	-60
EMMD101	478695	7738376	2148	169	0	-90

Table A-1: Diamond Drillhole Location Information

Hole ID	Easting (m)	Northing (m)	RL (ASL + 2000 m)	Total depth (m)	Azimuth (°)	Design Inclination (°)
EMMD102	478728	7738376	2148	84	90	-70
EMMD103	478658	7738426	2148	114	270	-70
EMMD104	478497	7739578	2145	194	270	-65
EMMD105	478341	7739732	2146	352	270	-65
EMMD106	478391	7739732	2146	346	270	-65
EMMD107	478125	7739735	2146	157	90	-60
EMMD108	478608	7738476	2148	90	270	-60
EMMD109	478492	7738576	2147	124	270	-60
EMMD110	478608	7738572	2147	276	270	-70
EMMD111	478688	7738573	2147	167	90	-70
EMMD112	478757	7738573	2147	96	90	-60
EMMD113	477741	7739614	2147	108	90	-60
EMMD114	477810	7739616	2147	256	90	-60
EMMD115	477884	7739616	2147	103	90	-60
EMMD116	477574	7739776	2147	345	90	-60
EMMD117	477822	7739877	2146	367	90	-60
EMMD118	477798	7739774	2146	508	90	-60
EMMD119	477624	7739876	2147	297	90	-60
EMMD120	478561	7738526	2147	70	270	-65
EMMD121	478621	7738526	2147	139	270	-70
EMMD122	478677	7738525	2147	234	270	-80
EMMD123	478707	7738524	2147	138	90	-70
EMMD124	478758	7738524	2147	81	90	-60
EMMD125	478706	7738426	2148	114	90	-70
EMMD126	478656	7738477	2148	129	270	-70
EMMD127	477822	7739526	2147	249	90	-60
EMMD128	477922	7739524	2147	97	90	-60
EMMD129	477922	7739422	2147	254	90	-60
EMMD130	478017	7739427	2147	268	90	-60
EMMD131	477822	7739292	2147	238	0	-90
EMMD132	477922	7739294	2147	253	0	-90
EMMD133	478023	7739295	2147	297	0	-90
EMMD134	478040	7739123	2147	295	270	-60
EMMD135	477910	7739525	2147	366	270	-65
EMMD136	477886	7739618	2147	378	270	-60
EMMD137	478127	7739734	2146	316	90	-70
EMMD138	477815	7739526	2147	311	270	-60
EMMD139	478269	7739692	2146	159	270	-60
EMMD140	478322	7739828	2145	314	270	-60
EMMD141	478320	7739773	2146	354	270	-60
EMMD142	477832	7739573	2147	316	270	-60
EMMD143	477776	7739614	2147	339	90	-60
EMMD144	477827	7739672	2147	340	270	-65
EMMD145	477787	7739473	2147	189	270	-60
EMMD146	477758	7739613	2147	222	0	-90
EMMD147	478270	7739728	2146	177	270	-60
EMMD148	478219	7739731	2146	169	90	-60
EMMD149	478190	7739730	2146	289	90	-70
EMMD150	477620	7739659	2147	205	90	-60
EMMD151	477624	7739679	2147	77	315	-60
EMMD151A	477628	7739677	2147	191	315	-60
EMMD152	478073	7739523	2147	354	270	-60
EMMD153	477686	7739627	2147	317	90	-60
EMMD154	477665	7739532	2147	211	125	-60
EMMD155	477569	7739568	2147	191	260	-60
EMMD156	478701	7738584	2147	140	85	-60

Table A-1: Diamond Drillhole Location Information

Hole ID	Easting (m)	Northing (m)	RL (ASL + 2000 m)	Total depth (m)	Azimuth (°)	Design Inclination (°)
EMMD157A	478706	7738476	2148	141	125	-60
EMMD158	478606	7738475	2148	140	240	-60
EMMD159	478550	7738626	2147	140	300	-60
EMMD160	478338	7739731	2146	133	55	-60
EMMD161	478302	7739668	2146	130	225	-60
EMMD162	477643	7739495	2147	159	90	-70
EMMD163	478701	7738524	2147	130	90	-75
EMMD164	478570	7738623	2147	81	270	-60
EMMD165	478331	7739702	2146	129	270	-70
EMMD166	478237	7739776	2146	120	270	-75
EMMD167	478075	7739625	2147	291	270	-60
EMMD168	477973	7739724	2147	295	270	-60
EMMD169	478121	7739424	2147	378	270	-60
EMMD170	478123	7739294	2147	334	270	-60
EMMD171	478223	7739177	2146	322	270	-60
EMMD172	478421	7739375	2146	330	270	-60
EMMD173	478522	7739423	2145	250	0	-90
EMMD174	478726	7739175	2146	209	0	-90
EMMD175	478971	7739173	2146	91	0	-90
EMMD176	478962	7739175	2146	107	0	-90
EMMD177	477973	7739572	2147	265	270	-60
EMMD178	477973	7739572	2147	367	270	-70
EMMD179	477973	7739576	2147	387	270	-80
EMMD180	477967	7739524	2147	210	270	-60
EMMD181	478023	7739525	2147	273	270	-60
EMMD182	477935	7739626	2147	285	270	-60
EMMD183	478074	7739480	2147	306	270	-60
EMMD184	478152	7739236	2147	174	270	-60
EMMD185	478216	7739156	2146	197	270	-60
EMMD187	478347	7738996	2146	237	270	-60
EMMD188	478411	7738916	2146	270	270	-60
EMMD190	478475	7738836	2147	62	270	-60
EMMD191	477963	7739496	2147	180	270	-60
EMMD192	478187	7739196	2146	165	270	-60
EMMD193	478251	7739116	2146	194	270	-60
EMMD194	477923	7739456	2147	125	270	-60
EMMD195	478315	7739036	2146	255	270	-60
EMMD196	478243	7739076	2146	237	270	-60
EMMD197	478443	7738876	2146	246	270	-60
EMMD198	479223	7739176	2146	246	270	-60
EMMD199	477965	7739824	2146	253	0	-90
EMMD200	477923	7739496	2147	119	270	-60
EMMD201	477963	7739456	2147	157	270	-60
EMMD202	478003	7739416	2147	189	270	-60
EMMD203	478043	7739416	2147	215	270	-60
EMMD204	478025	7739376	2147	162	270	-60
EMMD205	478102	7739375	2147	249	270	-60
EMMD206	478062	7739337	2147	165	270	-60
EMMD207	478084	7739295	2147	108	270	-60
EMMD208	478066	7739373	2147	163	270	-60
EMMD209	478083	7739417	2147	263	270	-60
EMMD210	478002	7739456	2147	257	270	-60
EMMD211	478004	7739497	2147	203	270	-60
EMMD212	477904	7739576	2147	192	270	-60
EMMD213	478041	7739335	2147	90	270	-60
EMMD214	478042	7739294	2147	129	270	-60

Table A-1: Diamond Drillhole Location Information

Hole ID	Easting (m)	Northing (m)	RL (ASL + 2000 m)	Total depth (m)	Azimuth (°)	Design Inclination (°)
EMMD215	478140	7739333	2147	204	270	-60
EMMD216	478209	7739112	2146	132	270	-60
EMMD217	478176	7739153	2146	147	270	-60
EMMD218	478151	7739189	2146	85	270	-60
EMMD219	478112	7739234	2147	112	270	-60
EMMD220	478146	7739191	2146	129	270	-60
EMMD221	477696	7739974	2147	175	180	-60
EMMD222	478684	7738524	2147	173	270	-80
EMMD223	477709	7739972	2147	174	180	-60
EMMD224	477560	7738972	2148	400	270	-60
EMMD225	479271	7738776	2147	367	270	-60
EMMD226	477972	7736373	2149	251	225	-60
EMMD227	478364	7739627	2146	120	90	-60
EMMD228	478413	7739574	2146	151	0	-90
EMMD229	478420	7739673	2146	251	270	-60
EMMD230	478223	7739825	2146	239	180	-60
EMMD231	477459	7739317	2149	774	31	-60
EMMD232	477849	7739772	2147	648	227	-60

Appendix A: Sample Locations and Descriptions

Table A-2: Sample Descriptions

Hole ID	Down-hole depth (m)	Sample ID*	Description	Type
E1 North				
EMMD001	43.95	EMMD001-1	altered breccia; carbonate vein	TS - only
EMMD001	44.5	EMMD001-3	unknown sulfides	TS - only
EMMD001	59.2	EMMD001-4	metavolcanic rock with quartz - carbonate infill	TS - only
EMMD001	59.9	EMMD001-5	metavolcanic rock with quartz - carbonate infill	TS - only
EMMD001	62.25	EMMD001-6	multiple generations of carbonate veining in metavolcanic	TS - only
EMMD001	119.6	EMMD001-7	mineralized breccia	TS - only
EMMD001	133.9	EMMD001-9	breccia	TS - only
EMMD001	141.7	EMMD001-10	altered fabric or bedding	TS - only
EMMD001	155.1	EMMD001-11	amygdules	TS - only
EMMD001	190.6	EMMD001-13	brecciated metavolcanics	TS - only
EMMD001	194.7	EMMD001-14	barite? Vein	TS - only
EMMD001	195.25	EMMD001-15	possible bedding	TS - only
EMMD001	202.95	EMMD001-16	metaconglomerate	TS - only
EMMD001	235.5	EMMD001-17	brown carbonate vein	TS - only
EMMD001	233.4	EMMD001-18	carbonate and unknown mineral small vein	TS - only
EMMD001	139.6	EMMD001-19	red-altered trachyte	TS - only
EMMD001	225.8	EMMD001-22	heavily altered "flattened" breccia	TS - only
EMMD001	273.5	EMMD001-24	albite vein overprinted by biotite (partially chloritized?)	TS - only
EMMD142	65	EMMD142-1	psammite?	TS - only
EMMD142	84.9	EMMD142-2	intercalated metasediments and metatuff?	TS - only

*This is the label associated with the sample. BU, bulk whole-rock; IS, isotope; FL, fluid inclusion; GC, geochronology. The abbreviations indicate that the sample was initially collected for the given type of analysis, but not all collected samples were analyzed.

Appendix A: Sample Locations and Descriptions

Table A-2: Sample Descriptions

Hole ID	Down-hole depth (m)	Sample ID*	Description	Type
EMMD142	95.5	EMMD142-3	intercalated metasediments and metatuff?	TS - only
EMMD142	133.65	EMMD142-4A	brecciated metavolcanics	TS - only
EMMD142	133.65	EMMD142-4B	brecciated metavolcanics	TS - only
EMMD142	165.5	EMMD142-5A	calcite infill of brecciated meta-andesite	TS - only
EMMD142	165.5	EMMD142-5B	calcite infill of brecciated meta-andesite	TS - only
EMMD142	310.95	EMMD142-7	silicified breccia	TS - only
EMMD142	117.5	EMMD142-8A	dolomitic carbonate infill	TS - only
EMMD142	117.5	EMMD142-8B	dolomitic carbonate infill	TS - only
EMMD142	147.5	EMMD142-9A	quartz infill	TS - only
EMMD142	147.5	EMMD142-9B	quartz infill	TS - only
EMMD142	156.98	EMMD142-10	multiple generations of carbonate veining in metavolcanic	TS - only
EMMD142	156.2	EMMD142-12A	multiple generations of carbonate veining in metavolcanic	TS - only
EMMD142	156.2	EMMD142-12B	multiple generations of carbonate veining in metavolcanic	TS - only
EMMD142	171.75	EMMD142-13	Fe-rich carbonate	TS - only
EMMD142	179.7	EMMD142-15A	magnetite alteration in metavolcanic rock	TS - only
EMMD142	179.7	EMMD142-15B	magnetite alteration	TS - only
EMMD055	95	EMMD055-2	pink calcite veining,	TS - only
EMMD055	103.25	EMMD055-3	porphyritic andesite, pink calcite veining	TS - only
EMMD055	104	EMMD055-5B	pink calcite veining, unknown stage	TS - only
EMMD055	96	EMMD055-6	quartz-magnetite-sericite vein and alteration	TS - only
EMMD055	114.5	EMMD055-7	barite-fluorite calcite veining cutting E, magnetite and sulfides overprinting barite-calcite?	TS - only
EMMD055	111	EMMD055-8	barite-fluorite calcite veining	TS - only
EMMD055	99	EMMD055-9	barite-fluorite calcite veining? cutting quartz - sericite - magnetite	TS - only

Appendix A: Sample Locations and Descriptions

Table A-2: Sample Descriptions

Hole ID	Down-hole depth (m)	Sample ID*	Description	Type
EMMD055	135.45	EMMD055-10	barite-fluorite calcite veining,	TS - only
EMMD055	140.1	EMMD055-11	barite? cutting quartz - sericite - magnetite	TS - only
EMMD055	132.4	EMMD055-12	magnetite and sulfides overprinting barite-calcite?	TS - only
EMMD055	155.35	EMMD055-14	calcite - fluorite? overprinted by calcite?	TS - only
EMMD055	141.7	EMMD055-15	barite?	TS - only
EMMD055	139.7	EMMD055-16	magnetite and sulfides alteration	TS - only
EMMD055	200	EMMD055-17	barite-fluorite calcite veining cutting quartz	TS - only
EMMD153	31.25	EMMD153-1	hematite alteration	TS - only
EMMD153	50.1	EMMD153-2	Mn-calcite veining	TS - only
EMMD153	58.35	EMMD153-3	multiple generations of carbonate - quartz chlorite fluorite veining	TS - only
EMMD153	58.4	EMMD153-4	quartz - biotite alteration	TS - only
EMMD153	65.5	EMMD153-5	quartz - magnetite - sericite and calcite veining	TS - only
EMMD153	69.35	EMMD153-6	quartz - biotite alteration and veining?	TS - only
EMMD153	76.55	EMMD153-7	sulfide foliation/fabric?	TS - only
EMMD153	71.2	EMMD153-8	possible fabric	TS - only
EMMD153	70.2	EMMD153-9	multiple sulfide and magnetite alteration stages	TS - only
EMMD153	92.55	EMMD153-10	ore zone and "worm-like" magnetite vein	TS - only
EMMD153	304.2	EMMD153-11	apatite alteration	TS - only
EMMD153	153.2	EMMD153-12	magnetite banding in volcanoclastic rock	TS - only
EMMD153	311.7	EMMD153-13	porphyroblastic marble; apatite-chlorite alteration of actinolite porphyroblasts	TS - only
EMMD153	229.5	EMMD153-14	altered scapolites?	TS - only
EMMD153	286.5	EMMD153-15	multiple quartz, sulfide and magnetite stages	TS - only
EMMD153	288	EMMD153-16	siltstone and marble contact	TS - only

Appendix A: Sample Locations and Descriptions

Table A-2: Sample Descriptions

Hole ID	Down-hole depth (m)	Sample ID*	Description	Type
EMMD153	267.25	EMMD153-17	calcite veining	TS - only
EMMD153	288.9	EMMD153-18	quartz - magnetite veining?	TS - only
EMMD153	208	EMMD153-19	deformed quartz veining	TS - only
EMMD153	306.5 - 306.7	IS005	collected for isotope analysis of the marble as well as a better TS	core+TS
EMMD153	301.55	IS006	distinct calcite stage cut by pink calcite	core+TS
EMMD153	288	IS007	very late pink calcite+-fluorite+-quartz+-cpy (which cuts the yellow calcite); TS for the host rock fragments	core
EMMD153	287.6	IS008	Large, 20 cm pink calcite-chalcopryrite-fluorite vein in marble; some reworking of the calcite	core
EMMD153	293.2	IS009	pink calcite-pyrite-chalcopryrite vein cutting marble	core
EMMD153	301.55	IS010 (301.55C)	chalcopryrite associated w/ yellow calcite vein stage	core
EMMD153	277.5	IS011	yellow calcite stage w/ cpy and qtz; marked C, A, B respectively; TS for host rock portion	core+TS
EMMD153	283.6	IS013	very coarse, late magnetite+- sulfide banding; also carbonate and qtz?	core
EMMD146	216.3	IS014	massive metavolcanic rock, irregular chalcopryrite infill? And alteration	core
EMMD146	214.9 - 215.05	IS015	large irregular yellow calcite infill	core+TS
EMMD146	111.4	IS016	very fine-grained (early) magnetite layer in suspected corella marble, w/ some Fe-calcite	core+TS
EMMD146	78	IS017	also minor magnetite; try and separate??	core
EMMD146	154.6	FL001	going to try and find fluid inclusions in the albite	core+TS
EMMD135	153	GC03	metavolcanic rock?; minor carbonate veining & alteration	core
EMMD182	82.3	EMMD182-82.3	calcite-biotite vein in andesite; also may be viable for carbonate isotopes	core+TS
EMMD182	91.7- 92.3	GC06	relatively "fresh" andesite w/ some minor chlorite alteration and carbonate and albite? veining	core

Appendix A: Sample Locations and Descriptions

Table A-2: Sample Descriptions

Hole ID	Down-hole depth (m)	Sample ID*	Description	Type
EMMD182	94.5	IS050	yellow calcite-magnetite irregular vein in heavily-fractured and chlorite-altered trachyte	core+TS
EMMD182	129.1	IS049	chalcopyrite infill and/or alteration associated w/ yellow calcite vein	core
EMMD182	239.75	BU14	altered porphyroblastic marble	core+TS
EMMD182	249.6	EMMD182-249.6	biotite-calcite-chalcopyrite vein	core+TS
EMMD182	255.9	IS048	fine-grained banded magnetite (and siderite?) alteration in marble	core+TS
EMMD182	238.5	IS025	~0.5m-wide yellow calcite- chalcopyrite vein in trachyte	core
EMMD001	199.3	BU04	barite-fluorite-altered ore in banded/sheared? Psammities or metavolcanics	core
EMMD001	207.9	BU05	banded barite-fluorite ore w/ tuffaceous clast?	core+TS
EMMD001	194.3	GT01/IS018	barite-fluorite-altered ore in banded/sheared? Psammities or metavolcanics	core
EMMD001	117.5 - .6	IS020	ironstone (formerly metabasalt)	core
EMMD001	220.5	IS053	yellow-brown calcite-chalcopyrite-barite vein cutting ore zone	core
EMMD001	242.1	IS054	yellow-brown calcite+chalcopyrite vein cutting altered porphyritic metabasalt	core+TS
EMDT077	179	IS027	calcite(pink)-fluorite-barite-chalcopyrite vein hosted in banded/sheared ore similar in appearance to EMMD001	core+TS
EMMD004	161.5	IS028	barite-chalcopyrite vein w/ associated disseminated chalcopyrite alteration, hosted in heavily sheared and chlorite-altered metavolcanics; high, wispy magnetite alteration	core
EMMD002	120.5	EMMD002-120.5	very ductile-folded quartz veins? In chlorite-magnetite altered groundmass	core+TS
EMMD002	121.5	IS029	fluorite-calcite (pink)-barite-chalcopyrite vein cutting a yellow calcite-pink qtz vein, hosted in massive metavolcanic rock magnetite-sulfide-red-altered of unknown affinity--no banding	core
EMMD002	132.2	IS030	calcite (pink)-fluorite vein hosted in heavily magnetite-sulfide-altered of unknown affinity; wispy sulfide veining/alteration and red veining/alteration)	core

Appendix A: Sample Locations and Descriptions

Table A-2: Sample Descriptions

Hole ID	Down-hole depth (m)	Sample ID*	Description	Type
EMDT203	101.0-101.29	EMDT203-101.0-101.29	banded altered sediment with 1mm barite? Fluorite-calcite veins	core+TS
EMDT203	101.3-101.4	IS057	barite-fluorite-calcite vein in mag-sulf altered banded sediment	core
EMDT203	102.8-103	EMDT203-102.8-103	slightly banded altered metaseds; may be able to get a TS?	core
EMMD075	154	IS025	chalcopryrite infill; weathered, may not be suitable	core
EMMD075	192.5	IS021	barite-calcite-fluorite-chalcopryrite vein in magnetite-sulfide-altered ore zone (metasediment?)	core+TS
EMMD075	205.3 - 205.7	IS022	barite-calcite-fluorite-chalcopryrite vein in barite-fluorite-magnetite-sulfide-altered ore zone (metasediment?); blebby red alteration present as well	core+TS
EMMD075	227	FL002	Fe-calcite-albite (hem.) vein; proof of an intermediate Na (albite) stage	core+TS
EMMD026	221.3	IS037	large (>20cm) chalcopryrite-magnetite-apatite-calcite vein? cut by pink calcite vein	core
EMMD026	106.9	IS038	yellow calcite+magnetite+apatite+chalcopryrite vein	core
EMMD033	79.5m	IS051	apatite-magnetite-calcite-chalcopryrite vein w/ minor albite alteration in host rock clasts	core
EMMD143	83.7	IS031	Fe-calcite-magnetite stage with ~5mm euhedral magnetite	core+TS
EMMD167	108.8	IS059	calcite-chalcopryrite vein	core
EMMD167	254.05	IS060	calcite-quartz vein in heavily-chloritized andesite; also thin section?	core+TS
EMMD067	208.3	IS062	calcite vein in heavily-altered andesite	core+TS
EMMD196	27.5	GC04	metavolcanic rock? mostly fresh except some sericitization of phenocrysts; carb veining	core
EMMD196	162	GC05	metavolcanic rock? minor carbonate veining and alteration	core
EMMD085	56.2	EMMD085-56.2	bedded Corella Calc-silicate clast in Corella Breccia	core
EMMD085	87.3	EMMD085-87.3	clast-supported Corella Brec	core

Appendix A: Sample Locations and Descriptions

Table A-2: Sample Descriptions

Hole ID	Down-hole depth (m)	Sample ID*	Description	Type
EMMD085	147.3	EMMD085-147.3	clast-supported Corella Brec	core
EMMD085	161	EMMD085-161	matrix-supported Corella Brec	core
EMMD085	231.7	EMMD085-231.7	Corella Brec. w/ calcite infill	core
EMMD085	393.2	EMMD085-393.2	tuff clast? In Corella Brec	core
EMMD085	386.2	EMMD085-386.2	clast-supported Corella Brec	core
EMMD085	169	EMMD085-169	altered phaneritic clast in Corella Breccia	core
EMMD085	112.8	EMMD085-112.8	slightly altered metadolerite intruding Corella Breccia	core
EMMD085	310.5	EMMD085-310.5	mineralized tuff	core
EMMD085	344.1	EMMD085-344.1	mineralized tuff	core
EMMD085	366.8	EMMD085-366.8	mineralized tuff	core
EMMD085	288.75	EMMD085-288.75	tuff with fabric; mostly unmineralized	core
EMMD086	105.9	EMMD086-105.9	vein-like "autobreccia" features?; chlo mtx; qtz-mag "veins"/clasts	core
EMMD086	194.9	EMMD086-194.9	massive metavolcanic rock; minor stg-3 veining; most likely albite-altered; very little magnetite	core
EMMD086	167.9	EMMD086-167.9	metadolerite? Fine- to fine-med-grained (coarser than basalt); massive metavolcanic rock; mag+mafic minerals	core
EMMD086	48.4	EMMD086-48.4	moderate clast flattening-alignment; mag-rich clasts in chlo-serc mtx;	core
EMMD086	125	EMMD086-125	clastic; flattened; aligned; chlo-mag-qtz-carb matrix w/ blotchy py+cpy	core
EMMD136	124	EMMD136-124	porphyritic; 0.5x2mm phenocrysts (sericitized); red alteration and sulfides	core
EMMD136	71.9	EMMD136-71.9	porphyritic; altered	core

Appendix A: Sample Locations and Descriptions

Table A-2: Sample Descriptions

Hole ID	Down-hole depth (m)	Sample ID*	Description	Type
EMMD136	215	EMMD136-215	massive metavolcanic rock; carbonate altered?	core
EMMD136	361.8	EMMD136-361.8	massive metavolcanic rock; altered; contacts with sample 362.2	core
EMMD136	321.03	EMMD136-321.03	porphyritic and amygdaloidal metavolcanic rock; phenocrysts red-altered	core
EMMD136	267.5	EMMD136-267.5	disseminated pyrite; sheared amygdales nearby (no O-line)	core
EMMD136	362.2	EMMD136-362.2	heavily-altered w/ mag-sulf; wispy banding = tuff?; split into two samples: B = fresher basalt 361.8	core
EMMD136	170	EMMD136-170	bedded/layered but some 1-5mm clasts; siderite-mag-chlo-sulfide alteration	core
EMMD075	166	EMMD075-166	massive metavolcanic rockcontacting thin banded layer (sample is basalt); porphyritic? (now partially carb-altered? 0.5 - 1mm	core
EMMD075	116.2	EMMD075-116.2	chlo-alb; minor magnetite; weathered	core
EMMD075	39.4	EMMD075-39.4	clastic tuff? Clasts aligned but not much flattening; mostly qtz-ser-chlo clasts (w/ some mag); chlo-mag-ser mtx; plag phenocrysts 0.5 - 2mm (not tabular); dissem sulfides	core
EMMD077	37.5	EMMD077-37.5	phaneritic clast in breccia; red-altered	core
EMMD077	162.4	EMMD077-162.4	could be metadolerite? Med-grained but may be alteration texture (chlorite); not much mica	core
EMMD077	81.7	EMMD077-81.7	amygdaloidal metavolcanic rock; chlorite-mag-alt	core
EMMD077	249.95	EMMD077-249.95	clastic; aligned; partially-flattened clasts; very angular; mtx-spt; mag mtx; qtz-ser clasts w/ alteration haloes; stg 3 veins	core
EMMD077	201.5	EMMD077-201.5	clastic tuff; moderately-aligned; similar alt-style to sample 249.95; clast-supported, 1-20mm	core
EMMD077	290	EMMD077-290	clastic tuff; moderate-well aligned; somewhat flattened; angular to subrounded, 1-30mm; similar alt style to 249.95	core
EMMD113	97.6	EMMD113-97.6	weathered; bedded; mostly hematite+sulfides; carbonate?; moderate magnetite; [probably supergene]; med-grained; stg 3 veins	core
EMMD167	105.5	EMMD167-105.5	qtz-py layers; stg 4 veins	core
EMMD167	127	EMMD167-127	see 105.5	core

Appendix A: Sample Locations and Descriptions

Table A-2: Sample Descriptions

Hole ID	Down-hole depth (m)	Sample ID*	Description	Type
EMMD167	234	EMMD167-234	red-altered phenocrysts, 1-30mm; chlorite groundmass	core
EMMD167	279.8	EMMD167-279.8	stg 3? 4? Veining w/ red alteration; phenocrysts (1-20mm) heavily altered and hard to tell from groundmass (which is bio-chlo)	core
EMMD167	180.3	EMMD167-180.3	chlorite groundmass; blebby carb alt; vesicular? 2 - 15mm phenocrysts	core
EMMD067	187	EMMD067-187	porphyritic	core
EMMD067	127	EMMD067-127	clastic tuff? Flattened	core
EMMD067	76	EMMD067-76	clastic tuff? Weathered	core
EMMD114	70.8	EMMD114-70.8	porphyritic; dark-gray (relatively-fresh?) groundmass	core
EMMD114	198.4	EMMD114-198.4	metaandesite contacting w/ heavily-altered "flow"? (sample is from less-altered portion)	core
E1 East				
EMMD007	58.4	BU001	relatively unaltered, some calcite veining and chloritization of matrix	core
EMMD007	63.5	BU002	presumably unaltered? (hematite-stained) calc-silicate layer	core
EMMD007	110.2	BU003	banded ore, w/ magnetite, sulfides and siderite? Stage uncertain	core
EMMD007	112.8	IS001	late pink calcite-barite vein	core
EMMD007	203.5	IS002	late pink calcite-barite vein	core
EMMD007	104.4	IS003	2cm band of fine-grained magnetite (early)	core
EMMD007	211.2	IS004	late pink calcite-barite vein	core+TS
EMMD007	223.6	IS012	large, euhedral magnetite infill in white (pink?) calcite+mag+cpy vein	core+TS
EMM011	176.5	IS026		core
EMM011	202	IS055	barite-calcite vein cut by calcite vein; in magnetite-altered laminated Corella	core+TS
EMM011	208.1	EMM011-208.1	albite?-rich banded and mineralized Corella	core+TS
EMM008	93.1	EMM008-93.1	epidote-chlorite-albite altered diorite	core+TS

Appendix A: Sample Locations and Descriptions

Table A-2: Sample Descriptions

Hole ID	Down-hole depth (m)	Sample ID*	Description	Type
EMM008	134.5	IS039	pink calcite+qtz+minor chalcopyrite partially brecciating a chlorite-calcite altered metabasal	core
EMMD008	60.55	EMMD008-1	unknown sulfide? Clast, unit 1 breccia	TS - only
EMMD008	114.45	EMMD008-2	barite cutting calcite vein?	TS - only
EMMD008	119.09	EMMD008-3	multiple calcite vein stages	TS - only
EMMD008	119	EMMD008-4	multiple calcite vein stages	TS - only
EMMD008	118.95	EMMD008-5	multiple calcite vein stages	TS - only
EMMD008	139.5	EMMD008-6	calcite cutting barite?	TS - only
EMMD008	143.75	EMMD008-7	feldspar veining cut by calcite	TS - only
EMMD008	77.35	EMMD008-8	stage M multiple stages	TS - only
EMMD008	69.2	EMMD008-9	altered marble	TS - only
EMMD008	76.8	EMMD008-10	psammite?	TS - only
EMMD008	108.8	EMMD008-11	metavolcaniclastic rock	TS - only
EMMD008	108.1	EMMD008-12	altered porphyroblastic metasediment	TS - only
EMMD008	145.8	EMMD008-14A	calcite - barite - fluorite veining	TS - only
EMMD008	134.25	EMMD008-15	calcite chlorite veining	TS - only
EMMD008	134.35	EMMD008-16	calcite chlorite veining	TS - only
EMMD008	131.35	EMMD008-17	barite veining?	TS - only
EMMD008	70.5	EMMD008-18	chalcopyrite veining	TS - only
EMMD008	116.15	EMMD008-19	relict scapolite?	TS - only
EMMD007	63.2	EMMD007-1	rounded breccia	TS - only
EMMD007	89.6	EMMD007-2	diorite	TS - only

Appendix A: Sample Locations and Descriptions

Table A-2: Sample Descriptions

Hole ID	Down-hole depth (m)	Sample ID*	Description	Type
EMMD007	107.4	EMMD007-3	flaser cross-bedding in psammite	TS - only
EMMD007	53.7	EMMD007-4	unidentified alteration assemblage	TS - only
EMMD007	174.6	EMMD007-5	unknown volcanic material	TS - only
EMMD007	146.15	EMMD007-6	metavolcanic rock	TS - only
EMMD007	220.7	EMMD007-7	unknown lithology with carbonate veining	TS - only
EMMD007	212	EMMD007-8	carbonate vein and sedimentary clast	TS - only
EMMD007	118.5	EMMD007-9A	carbonate veining and sulfides	TS - only
EMMD007	118.5	EMMD007-9B	carbonate veining and sulfides	TS - only
EMMD007	155.9	EMMD007-10A	carbonate veining cutting chlorite?	TS - only
EMMD007	155.9	EMMD007-10B	carbonate veining cutting chlorite?	TS - only
EMMD007	159	EMMD007-11	carbonate veining cutting chlorite?	TS - only
EMMD007	113.9	EMMD007-12	possibly multiple stages of sulfide and magnetite alteration	TS - only
EMMD007	107.9	EMMD007-13	carbonate veining	TS - only
EMMD007	114.6	EMMD007-14A	possibly multiple stages of sulfide and magnetite alteration	TS - only
EMMD007	114.6	EMMD007-14B	possibly multiple stages of sulfide and magnetite alteration	TS - only
EMMD007	115.5	EMMD007-15A	quartz-magnetite infill and alteration	TS - only
EMMD007	115.5	EMMD007-15B	quartz-magnetite infill and alteration	TS - only
EMMD008	60.5	EMMD008-60.5	matrix-supported Corella Brec	core
EMMD008	125.9	EMMD008-125.9	porphyritic (1mm); red alteration	core
EMMD008	93.3	EMMD008-93.3	laminated silt, mineralized	core
EMMD013	170.9	EMMD013-170.9	uncertain lith; biotite mtx, red-altered clasts; clasts not well-defined; lots of qtz veining	core

Appendix A: Sample Locations and Descriptions

Table A-2: Sample Descriptions

Hole ID	Down-hole depth (m)	Sample ID*	Description	Type
EMMD013	150.8	EMMD013-150.8	heavily-veined; not logged before; lots of qtz-veining parallel & perpendicular to bedding	core
EMMD013	101.6	EMMD013-101.6	laminated silt, mineralized; mag-altered; carbonaceous?	core
EMMD066	40	EMMD066-40	metaandesite flow in porphyritic volcaniclastic	core
EMMD066	123.6	EMMD066-123.6	massive metavolcanic rock	core
EMMD066	176	EMMD066-176	massive metavolcanic rock	core
EMMD066	53.6	EMMD066-53.6	psammite? in layered clastic tuff	core
EMMD066	100.4	EMMD066-100.4	clastic tuff; mineralized; in footwall of major FZ	core
EMMD009	182.3	EMMD009-182.3	unmineralized, laminated; heavily-veined; similar to EMMD013 150.8	core
EMMD009	131.9	EMMD009-131.9	partially-mineralized; heavily-veined	core
EMMD018	101	EMMD018-101	0.5mm phenocrysts	core
EMMD018	139	EMMD018-139	massive metavolcanic rock; similar to 101	core
EMMD018	60.9	EMMD018-60.9	fine psammite-silt; boudinaged siliceous layer	core
EMMD097	128.5	EMMD097-128.5	massive metavolcanic rock; blebby carbonate alt	core
EMMD097	174.1	EMMD097-174.1	massive metavolcanic rock; carbonate veining	core
EMMD097	269	EMMD097-269	porphyritic? Partially carbonate-altered (blebby carbonate instead?)	core
EMMD097	74.14	EMMD097-74.14	partially-mineralized; interbedded calcereous and chlo-altered layers; supergene w/ native-Cu	core
EMMD097	226.15	EMMD097-226.15	calcereous (Fe-rich, not much fizz); magnetite-laminae;	core
EMMD078	89	EMMD078-89	massive metavolcanic rock; chrysocolla in weathered veins	core

Appendix A: Sample Locations and Descriptions

Table A-2: Sample Descriptions

Hole ID	Down-hole depth (m)	Sample ID*	Description	Type
EMMD161	105	EMMD161-105	lineation fabric; chlo-bio-spec.hem matrix & clast alteration; wispy alt	core
EMMD126	104	EMMD126-104	massive metavolcanic rock; carbonate veining	core
EMMD074	105.5	EMMD074-105.5	uncertain lith; volcanoclastic or brecciated basalt? Clasts somewhat aligned; vesicular clasts; mtx mostly mag-py	core
EMMD074	195	EMMD074-195	red-altered porphyritic basalt or volcanoclastic? Red "phenocrysts" are irregular and angular	core
EMMD041	154.75	EMMD041-154.75	heavily-altered metabasalt with lots of magnetite-chlorite-biotite? Alteration (fine-gr); minor chalcopyrite, abundant magnetite (euhedral), apatite, carbonate veining; veins deformed; cut by stage 4 veinlets	core
EMMD060	150.5	EMMD060-150.5	mineralized volcanoclastic tuff; massive metavolcanic rock mag mtx w/ disseminated sulfides; red alteration - albite or barite?	core
EMMD064	150	EMMD064-150	mostly albite? - carbonate (blebby-disseminated) altered w/ intense chlo-bio altered portions	core
EMMD076	107	EMMD076-107	uncertain protolith; metasedimentary? Some apparent laminae visible; patchy-blebby Fe-carbonate, biotite-chlo, albite?-qtz?-apa? (red) alteration	core
E1 South				
EMM018	158.9	EMM018-1	fluorite - calcite veining cutting quartz	TS - only
EMM018	159.4	EMM018-2	fluorite veining cutting red - altered and magnetite banded metasediment	TS - only
EMM018	200.3	EMM018-3	calcite cutting feldspar alteration?	TS - only
EMM018	86.9	EMM018-4	black shale with disseminated pyrite	TS - only
EMMD052	159.2	EMMD052-1	possible sulfide fabric	TS - only
EMMD052	162.5	EMMD052-2	crackly metabasalt near metased contact	TS - only
EMMD052	189.2	EMMD052-3	basalt? Alteration	TS - only
EMMD052	200	EMMD052-4	metaandesite and alteration	TS - only
EMMD052	256.55	EMMD052-5	heavily altered metased of uncertain mineralogy	TS - only

Appendix A: Sample Locations and Descriptions

Table A-2: Sample Descriptions

Hole ID	Down-hole depth (m)	Sample ID*	Description	Type
EMMD052	263.6	EMMD052-6	altered metasediment?	TS - only
EMMD052	285.85	EMMD052-7	metasediment? w/ disseminated sulfides	TS - only
EMMD052	362.65	EMMD052-8	carbonate-cemented breccia	TS - only
EMM019	163.5	96739	collected by R. Taylor	TS - only
EMM019	unknown	96740	collected by R. Taylor	TS - only
EMMD046	59.7	GC07	metavolcanic rock? Andesite w/ carbonate vein	core
EMM018	134.5	IS061	calcite-quartz-chalcopy veining in altered metabasalt?	core
EMMD042	171.2	GC02	metavolcanic rock? some disseminated Fe-calcite alteration & veining, but little chlorite-sericite	core
EMM023	178.3	EMM023-178.3	albite vein (possibly stage 3? or overprinted by it)	core+TS
EMM023	153.1	BU06	bulk mineralized metasediment	core
EMMD052	314.5	BU13/IS041	slightly mineralized, banded dolomitic marble w/ fluorite alteration	core
EMMD052	343	IS042	yellow calcite vein in massive metavolcanic rock-amygdaloidal metavolcanic rock metabasalt	core
EMMD045	178.9- 179.3	BU09/IS021	multiple samples; one for bulk ore, one for carbonate isotopes?	core+TS
EMMD043	82.5	EMMD043-82.5	calcite vein in andesite/trachyte	core
EMMD043	116.9	BU08	E1S metasediments; bulk	core+TS
EMMD043	115.8	BU07	bulk ore	core
EMMD043	168.9	IS058	large irregular infill in amygdaloidal metavolcanic rock metabasalt; calcite+quartz	core+TS
EMM019	126.8	IS023	bulk sample of black shale for C isotopes? + TS; contains significant pyrrhotite	core
EMM019	137.65	IS024	epigenetic (late stage) pyrite alteration in qtz-rich layer of black shale	core
EMM019	177.7	IS044	yellow-brown calcite+qtz+chalcopyrite+pyrite vein in metasilt	core
EMM019	192	IS040	yellow calcite-chalcopyrite vein cutting metasilts; remaining 1/4 core taken	core
EMM019	202.5	EMM019-202.5	coarse arsenopyrite for probing; chlorite-altered groundmass	core+TS
EMM019	205.4	IS043	fine-grained sulfide alteration and birds-wing calcite veining	core

Appendix A: Sample Locations and Descriptions

Table A-2: Sample Descriptions

Hole ID	Down-hole depth (m)	Sample ID*	Description	Type
EMM019	280.6	BU10	bulk marble (somewhat mineralized)	core
EMM019	310.9, 311.1	IS025	barite-calcite-fluorite-chalcopryrite vein in magnetite-sulfide-altered metasediment/marble?	core+TS
EMM019	317.7	BU11	bulk sample (and TS) of metabasalt adjacent to ore zone	core
EMM019	318	IS045	yellow calcite + magnetite+chalcopryrite+pyrite heavily fracturing metabasalt?	core
EMM019	338	BU12	bulk sample (and TS) of carbonate-altered amygdaloidal metavolcanic rock metabalt, further from ore zone	core
EMM018	87	EMM018-87	qtz-py layers	core
EMM018	175.5	EMM018-175.5	marble or calcereous silt; mineralized; enechelon biotite veins	core
EMM018	133	EMM018-133	massive metavolcanic rock; moderate carbonate veining	core
EMM022	71.6	EMM022-71.6	massive metavolcanic rock	core
EMM022	167.1	EMM022-167.1	fine-psammite or silt	core
E8				
EMMD226	87.55	EMMD226-1	mag-barren amygdaloidal metavolcanic rock basalt	TS - only
EMMD226	130.4	EMMD226-2	ore alteration	TS - only
EMMD226	148.1	EMMD226-3	ore-chlorite alteration	TS - only
EMMD226	240.8	EMMD226-4	barite?-cal-chlo alteration	TS - only
E1C				
EMMD184	50	EMMD184-50	heavily-altered porph. Ands. w/ chlo-bio mtx; 5 - 20mm phenocrysts	core
EMMD184	125.9	EMMD184-125.9	laminated silt; weathered	core
EMMD184	150.1	EMMD184-150.1	amygdaloidal metavolcanic rock	core
E1 North Open Pit				
Easting (m)**	Northing (m)	SampleID	Description	Type
477721	7739400	E1N1	"red-rock" altered breccia	TS - only
477588	7739399	E1N2	volcaniclastic breccia	TS - only
477590	7739399	E1NO1A	mineralized volcanics?	TS - only
477644	7739383	E1NO1B	mineralized volcanics?	TS - only

**GDA94 UTM Zone 54

Appendix B

Whole-Rock Geochemical Data

Analytical methods and data tables

The whole-rock samples were analyzed by AMCE Analytical Laboratories, Inc. in Vancouver, British Columbia, Canada. The ACME method codes mentioned below were listed in 2014 and may be different to current codes. Samples were jaw crushed and sieved to 10 mesh (2 mm), and a 250 g aliquot was pulverized and sieved to 150 mesh (100 μm).

For major oxides, LOI, total C and S and Sc, a 0.2g aliquot was fused with 1.5 g of LiBO_2 / LiB_4O_7 flux at 1000° C. The resulting fusion was digested in 100 ml of 5% HNO_3 , and analyzed by inductively coupled plasma emission spectroscopy (ICP-ES) for the major oxides. All iron is reported as Fe_2O_3 . Loss on Ignition was measured by igniting a 1g pulp at 1000° C (ACME code TG001). Total carbon and sulfur were determined by Leco analysis of 0.2 g pulps (ACME code TC000). For elements Ba, Cs, Ga, Hf, Nb, Rb, Sn, Sr, Ta, Th, U, V, W, Y, Zr, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu, aliquots of the LiBO_2 / LiB_4O_7 fusions were measured by inductively coupled plasma mass spectrometry (ICP-MS) (ACME package G4NI, code LF200).

For elements Au, Ag, As, B, Be, Bi, Cd, Co, Cr, Cu, Ge, Hg, In, Li, Mn, Mo, Ni, Pb, Pd, Pt, Re, Sb, Se, Te, Tl, and Zn, a 30 g pulp was digested in 180ml of 95° C modified Aqua Regia (equal parts HCl , HNO_3 and H_2O) for one hour, then cooled and added to 5% HCl to yield a 600 ml solution which was analyzed by ICP-MS (ACME package G4NI, code AQ252). Total digestion was not guaranteed for B, Be, Cr, Ge, Li, Mn, Ni, Pd, and Pt. Nickel was also analyzed by ICP-ES after being digested in 20 ml of Aqua Regia + HF at 190° C, dried, and dissolved again in 16 ml of 50% HCl at 95° C for an hour, and then reacted with 5% HCl to form a 100 ml solution.

X-ray fluorescence (XRF) single-element analyses were also performed on fused discs of samples ($n = 55$ for Ba, F; $n = 61$ for Cu) suspected to contain greater than the 5% maximum detection limit for Ba (ACME code LF700-Ba), F (ACME code GC841), and Cu (ACME code LF700).

Duplicate analyses were conducted on 28 samples for quality control. Precision was sufficient to report all elements analyzed, and reproducibility was approximately <1–2% for major oxides, and <5% for trace elements; these values are much higher (>10–15%)

near detection limits. Hollings et al. (2011) demonstrated that ACME protocols yielded comparable results to other laboratories. Detection limits and reproducibility data are shown in Table B-1. Table B-2 contains the raw data for all samples, while Table B-3 shows the CLR-transformed data for all samples. Tables B-2 and B-3 are spread over multiple pages and print left-to-right, then down.

References

Hollings, P., Cooke, D.R., Waters, P.J., and Cousens, B., (2011). Igneous geochemistry of mineralized rocks of the Baguio district, Philippines: Implications for tectonic evolution and the genesis of porphyry-style mineralization: *Economic Geology*, 106, p.1317–1333.

Table B-1: Whole-rock geochemical detection limits and duplicate reproducibility

Analyte	Method	Detection Limit	Reproducibility (%)	Analyte	Method	Detection Limit	Reproducibility (%)	Analyte	Method	Detection Limit	Reproducibility (%)
SiO ₂	LF200	0.01 wt%	1.0	Sr	LF200	0.5 ppm	4.0	Pb	AQ252	0.01 ppm	2.9
Al ₂ O ₃	LF200	0.01	1.0	Ta	LF200	0.1	15.2	Zn	AQ252	0.1	8.1
Fe ₂ O ₃	LF200	0.04	0.9	Th	LF200	0.2	2.0	Ni	AQ252	0.1	3.7
MgO	LF200	0.01	1.2	U	LF200	0.1	4.5	Co	AQ252	0.1	3.9
CaO	LF200	0.01	0.7	V	LF200	8	2.4	Mn	AQ252	1	1.7
Na ₂ O	LF200	0.01	1.5	W	LF200	0.5	5.5	As	AQ252	0.1	20.5
K ₂ O	LF200	0.01	0.6	Zr	LF200	0.1	2.9	Cd	AQ252	0.01	10.5
TiO ₂	LF200	0.01	1.0	Y	LF200	0.1	3.5	Sb	AQ252	0.02	8.4
P ₂ O ₅	LF200	0.01	1.3	La	LF200	0.1	1.2	Bi	AQ252	0.02	1.9
MnO	LF200	0.01	0.8	Ce	LF200	0.1	1.8	Cr	AQ252	0.5	4.6
Cr ₂ O ₃	LF200	0.002	16.4	Pr	LF200	0.02	2.3	B	AQ252	1	40.0
Ba	LF700	0.01	0.3	Nd	LF200	0.3	4.7	Tl	AQ252	0.02	6.1
Cu	LF700	0.01	2.0	Sm	LF200	0.05	4.6	Se	AQ252	0.1	0.0
F	GC841	0.01	0.8	Eu	LF200	0.02	9.0	Te	AQ252	0.02	16.2
LOI	TG001	-5.1	3.6	Gd	LF200	0.05	4.9	Ge	AQ252	0.1	46.2
Total C	TC000	0.01	3.4	Tb	LF200	0.01	4.3	In	AQ252	0.02	0.9
Total S	TC000	0.01	2.2	Dy	LF200	0.05	5.2	Be	AQ252	0.1	43.3
Ba	LF200	1 ppm	3.2	Ho	LF200	0.02	4.8	Li	AQ252	0.1	6.1
Sc	LF200	1	0.0	Er	LF200	0.03	7.6	Pd	AQ252	10 ppb	BDL
Cs	LF200	0.1	13.5	Tm	LF200	0.01	4.7	Pt	AQ252	2	BDL
Ga	LF200	0.5	9.5	Yb	LF200	0.05	3.6	Hg	AQ252	5	16.9
Hf	LF200	0.1	6.6	Lu	LF200	0.01	1.0	Au	AQ252	0.2	49.7
Nb	LF200	0.1	3.5	Ni	MA370	10	3.9	Ag	AQ252	2	17.2
Rb	LF200	0.1	3.2	Mo	AQ252	0.01	3.7	Re	AQ252	1	10.6
Sn	LF200	1	7.3	Cu	AQ252	0.01	2.0				

Table B-2: Raw whole-rock data from ACME Labs

Hole ID	Depth	Lithology	Wgt kg	SiO ₂ wt%	Al ₂ O ₃ wt%	Fe ₂ O ₃ * wt%	MgO wt%	CaO wt%	Na ₂ O wt%	K ₂ O wt%	TiO ₂ wt%	P ₂ O ₅ wt%	MnO wt%	Cr ₂ O ₃ wt%	Ba ppm	Sc ppm	Sum wt%	Cs ppm	Ga ppm
EMM018	87	carbonaceous schist	0.26	61.85	16.57	6	1.91	0.35	0.14	4.82	0.84	0.19	0.01	0.009	763	19	99.77	8.5	24.4
EMM019	126.8	carbonaceous schist	0.07	56.44	13.14	6.75	3.76	4.91	1.5	3.46	0.77	0.19	0.17	0.008	563	16	99.79	6	18.7
EMMD097	269	carbonaceous schist	0.17	50.78	16.72	9.02	1.73	4.59	5.1	2.78	1.57	0.18	0.28	0.01	2353	28	99.59	1.4	21.6
EMMD117	140.8	carbonaceous schist	0.12	68.93	16.89	1.99	1.07	0.38	1.1	4.88	0.85	0.15	0.03	0.008	816	14	99.79	2.5	18.4
EMMD167	105.7	carbonaceous schist	0.12	56.52	13.53	11.26	3.83	1.72	0.07	3.78	0.91	0.23	0.12	0.008	825	16	99.72	4.3	15.1
EMMD167	127	carbonaceous schist	0.18	49.22	21.18	7.29	2.78	1.62	0.11	7.13	1.35	0.13	0.08	0.005	2134	23	99.54	7.4	24
EMM008	93.1	diorite	0.07	50.21	13.76	12.16	6.07	7.68	4.45	1.61	1.46	0.08	0.17	0.018	469	40	99.75	3.6	19.8
EMMD077	37.65	diorite	0.18	52.11	15.11	14.02	4.77	2.3	5.42	0.25	1.27	0.17	0.08	0.005	44	24	99.84	0.2	22.9
EMMD008	60.5	discordant breccia	0.1	52.59	12.45	11.32	5.78	4.87	4.82	1.27	0.53	0.13	0.08	0.007	245	11	99.81	1.5	16.3
EMMD013	151	discordant breccia	0.11	47.74	10.06	3.48	2.77	14.85	3.02	3.02	0.37	0.24	0.18	0.006	980	8	99.73	3	15.1
EMMD0153	306.5	discordant breccia	0.15	32.82	7.5	23.39	4.48	13.96	0.37	1.9	0.62	0.31	0.54	0.002	2113	13	99.48	0.8	10
EMMD030	96.2	discordant breccia	0.46	47.58	11.88	3.59	0.37	15.21	6.93	0.12	0.48	0.12	0.13	0.008	23	9	99.92	0.1	14.2
EMMD077	290.00	discordant breccia	0.27	37.25	9.26	35.25	1.16	5.98	3.95	0.94	0.78	0.42	0.21	0.003	524	13	99.75	0.1	13
EMMD078	89	discordant breccia	0.17	53.19	14.35	15.6	4.31	2.17	2.68	1.62	1.36	0.15	0.1	0.009	1454	26	99.66	0.6	21
EMMD085	56.00	discordant breccia	0.21	48.48	5.29	2.74	0.38	20.03	0.18	4.48	0.53	0.17	0.26	0.004	370	7	99.88	0.2	5.1
EMMD085	87.3	discordant breccia	0.38	50.12	12.61	10.22	5.29	6.16	0.72	6.2	0.56	0.15	0.14	0.008	623	10	99.79	0.4	16.7
EMMD085	147.3	discordant breccia	0.42	54.5	15.23	7.73	2.98	4.58	4.65	3.79	0.59	0.15	0.1	0.01	553	15	99.84	0.1	18.6
EMMD085	161	discordant breccia	0.41	53.73	13.82	10.45	2.76	5.23	5.93	1.26	0.59	0.15	0.1	0.009	158	12	99.87	<0.1	16.6
EMMD085	295	discordant breccia	0.14	48.24	12.54	23.37	2.14	0.84	0.08	4.41	1.12	0.15	0.04	0.004	4811	17	99.28	0.9	16.7
EMMD085	386.2	discordant breccia	0.15	49.07	11.66	16.64	7.09	4.16	2.71	0.43	0.67	0.2	0.12	0.008	194	12	99.77	0.4	23.8
EMMD085	393.2	discordant breccia	0.33	60.76	13.1	5.36	1.94	5.16	1.16	5.3	0.62	0.18	0.09	0.003	1237	15	99.76	1.3	23.6
EMMD114	198.4	discordant breccia	0.2	58.35	17.19	10.01	0.49	1.52	7.45	1.28	1.48	0.18	0.13	0.002	564	12	99.85	0.3	15.9
EMMD161	105	discordant breccia	0.1	54.48	13.32	7.33	3.37	6.82	6.48	0.42	0.55	0.16	0.08	0.006	52	11	99.9	0.6	15.7
EMDT203	102.8	marble	0.11	12.64	0.43	23.96	0.23	14.56	<0.01	0.03	0.02	0.54	0.05	<0.002	>50000	<1	55.22	<0.1	<0.5
EMM018	175.5	marble	0.22	22.58	8.86	27.51	3.22	8.63	0.79	1.04	0.72	0.32	1.12	0.003	49034	8	86.07	1.2	6.2
EMMD001	117.5	marble	0.3	18.54	1.23	75.96	1.03	2.66	0.02	0.03	0.15	1.02	0.05	<0.002	130	2	99.8	<0.1	4.9
EMMD001	207.9	marble	0.22	19.56	1.29	40.46	0.44	10.55	0.25	0.06	0.1	0.63	0.05	0.002	>50000	2	74.58	<0.1	1.5
EMMD007	110.2	marble	0.19	14.29	1.87	48.56	1.56	11.02	0.34	0.14	0.12	0.98	0.94	0.003	9660	2	86.39	<0.1	1.9
EMMD013	101.6	marble	0.24	30.33	1.9	37.4	1.46	12.4	0.97	0.13	0.12	0.45	0.64	<0.002	6169	3	91.96	<0.1	4.3
EMMD0136	170.00	marble	0.26	14.53	6.06	62.61	1.89	6.16	0.07	1.72	0.64	0.32	0.38	0.003	4630	12	98.85	0.8	13.2
EMMD0136	362.20	marble	0.23	23.78	8.15	28.82	2.01	16.21	0.04	2.37	0.4	1.45	0.44	<0.002	1297	7	92.28	0.4	18.4
EMMD018	60.9	marble	0.18	30.8	0.7	53.42	0.69	6.09	0.03	<0.01	0.04	0.73	0.3	<0.002	148	1	99.76	<0.1	1.2
EMMD043	116.9	marble	0.18	10.24	2.77	47.03	2.89	13.97	0.1	0.27	0.17	0.23	1.36	0.002	28291	7	84.36	2	6.3
EMMD052	314.5	marble	0.13	2.91	0.96	21.44	5.58	34.88	0.04	0.16	0.01	0.04	1.61	<0.002	590	<1	99.68	0.3	2.1
EMMD060	150.5	marble	0.22	24.21	7.31	48.14	1.6	5.86	0.25	2.21	0.67	0.74	0.07	0.004	15436	9	97.17	0.4	10.4
EMMD066	100.5	marble	0.12	19.11	4.85	31.48	1.63	17.32	1.58	0.32	0.54	0.74	0.47	0.003	4139	8	82.8	0.6	6.9
EMMD075	192.5	marble	0.15	10.62	2.28	55.04	2.24	14.44	<0.01	0.04	0.12	0.62	0.49	<0.002	1467	5	87.08	0.4	4.6
EMMD075	205.30	marble	0.16	5.22	1.61	41.17	1.51	17.18	0.23	0.33	0.15	0.72	1.2	0.011	>50000	3	71.42	1	2.9
EMMD077	174	marble	0.19	6.37	2.46	78.22	1.71	3.21	0.08	0.33	0.22	1.01	0.05	0.003	3500	3	97.41	0.1	6.8
EMMD077	225.4	marble	0.17	7.29	2.6	51.26	1.05	10.61	0.25	0.39	0.17	0.37	0.18	<0.002	>50000	8	76.27	<0.1	6.7
EMMD085	231.7	marble	0.42	49.97	11.02	3.71	2.33	12.47	2.36	4.7	0.49	0.12	0.2	0.008	583	12	99.85	0.2	13.4

*Total Fe reported as Fe₂O₃

Table B-2: Raw whole-rock data from ACME Labs

Hole ID	Depth	Lithology	Hf ppm	Nb ppm	Rb ppm	Sn ppm	Sr ppm	Ta ppm	Th ppm	U ppm	V ppm	W ppm	Zr ppm	Y ppm	La ppm	Ce ppm	Pr ppm	Nd ppm	Sm ppm
EMM018	87	carbonaceous schist	5.4	16.9	200.6	4	25.4	1	17.8	4.5	157	6.2	192.7	26.4	23	39.9	4.57	15.8	3.36
EMM019	126.8	carbonaceous schist	5.1	19.5	137.1	3	34.8	0.8	15	4.6	110	3	181	26.1	38.5	77.4	8.82	31.8	6.2
EMMD097	269	carbonaceous schist	6.1	10.8	63	2	84.7	0.8	13.2	4.7	255	4.1	230.8	38.7	25.7	51.6	5.98	22.5	5.11
EMMD117	140.8	carbonaceous schist	6.6	14.1	153.5	3	18.5	1.1	18.6	4.4	106	68.7	239.8	35.5	104.8	193.7	21.06	73.7	12.55
EMMD167	105.7	carbonaceous schist	5.4	11.7	136	4	14	0.8	16.1	4.6	124	5.4	200.3	32.1	50.3	96.1	10.97	40.4	6.96
EMMD167	127	carbonaceous schist	7.3	14.4	278.4	5	12.3	1.2	21.8	9.3	247	8.2	277.7	43.7	67.8	123.3	14.46	52.9	8.71
EMM008	93.1	diorite	3.1	10.9	43.8	1	141.1	0.5	2.5	1.3	318	0.5	103.2	24.5	10.8	21.2	2.83	12.8	3.51
EMMD077	37.65	diorite	4.5	9.2	9.2	3	37.7	0.7	8.8	2.6	213	17.3	165.1	26.1	22.6	46	5.5	21.9	5.02
EMMD008	60.5	discordant breccia	3.6	8.8	67.2	4	24.2	0.8	12.2	6.5	131	4.9	135	10.7	49.4	77.2	7.85	25.6	4.06
EMMD013	151	discordant breccia	2.8	9.1	100.6	2	84.6	0.6	12	7.9	90	2.7	100	25.7	46.7	88.4	10.09	35.9	6.37
EMMD0153	306.5	discordant breccia	2.5	4.6	60	12	47.8	0.3	8.6	25.4	140	18.5	87.5	27.4	120.8	143.7	12.67	40	6.39
EMMD030	96.2	discordant breccia	3.4	8.2	8.2	3	69	0.7	12.8	4.5	69	4.2	119.4	18.3	57	94.2	10.35	36.8	5.97
EMMD077	290.00	discordant breccia	2.6	6.5	23	5	36.1	0.3	7.7	36.6	218	12.1	98.2	12.8	115.7	144.7	12.58	40.7	6.29
EMMD078	89	discordant breccia	5.3	9.7	41.9	6	35.4	0.8	11.6	2.7	239	31.2	201	20.5	49.1	71.1	7.89	29.4	5.97
EMMD085	56.00	discordant breccia	10.1	7.9	99.2	2	51.4	0.6	11	5.2	52	2.6	397.8	22.7	17	32.9	3.95	16	3.38
EMMD085	87.3	discordant breccia	4.9	10.4	113.8	3	61.5	0.9	13.8	11.2	96	2.1	178	19.6	31.6	61.1	7.13	26.7	4.64
EMMD085	147.3	discordant breccia	3.4	9.5	87.9	3	40	0.8	15.1	4.3	120	3.5	117.7	21.2	28.9	56.2	6.65	25.9	4.61
EMMD085	161	discordant breccia	3.5	9.2	22.5	2	50.8	0.8	14.5	5.4	114	1.6	128.8	21.3	51.6	97	11	41.9	7.11
EMMD085	295	discordant breccia	4	9.9	103	49	13.2	0.6	4.4	18.6	157	62.2	147	13	11.7	15.4	1.48	4.9	1.32
EMMD085	386.2	discordant breccia	6.2	11.1	9.4	7	17.3	1	14.2	12.8	141	7.9	235.9	17.8	59.6	102.8	11.55	40.7	7.13
EMMD085	393.2	discordant breccia	7.2	10.8	148.3	9	27.7	0.9	9.8	14.6	61	10.1	271.5	23.9	19.3	34.6	4.04	14.9	3.06
EMMD114	198.4	discordant breccia	5.5	9.8	46.2	4	60.6	0.7	13.1	4.1	169	8.2	208	30	59.8	91.1	9.92	35.7	6.95
EMMD161	105	discordant breccia	3.1	8.2	27.1	2	27.9	0.6	11.2	3.4	108	3.2	109.4	18	7.1	13	1.62	6.8	1.8
EMDT203	102.8	marble	0.5	3.3	0.8	122	4620.3	1.7	0.9	202.2	57	33.2	2.9	21.3	816.3	710.5	44.28	97.3	10.12
EMM018	175.5	marble	3.1	7.3	24.8	21	843	0.7	6.8	42.6	105	78.8	109.1	12.2	219.2	208.9	13.94	36	3.76
EMMD001	117.5	marble	0.6	9.7	0.6	30	17.5	<0.1	5.9	10.9	94	5.4	23.7	14.8	399.8	408.5	32.54	94.8	13.59
EMMD001	207.9	marble	0.5	15.1	1.5	63	1481.8	0.4	3.7	451.4	62	298.4	17	24.7	316.5	307.4	20.71	50	5.95
EMMD007	110.2	marble	0.8	9.9	3.4	82	871.7	0.3	2.4	150.7	43	13	21.9	7	286.8	223.1	13.53	27.2	2.9
EMMD013	101.6	marble	0.8	7.8	2.8	78	527.1	0.1	3.2	145.1	69	157.2	26.1	22.4	458.6	447.3	30.07	71.6	7.63
EMMD0136	170.00	marble	1.9	7.5	48.6	34	52.4	0.3	5.4	38.3	207	19.2	69.2	16.9	79.7	96	7.8	22.5	3.68
EMMD0136	362.20	marble	4.2	8.7	52.1	22	69.6	0.6	14.2	30.6	214	21.9	167.7	53.5	187.7	256.1	22.95	77.1	11.39
EMMD018	60.9	marble	0.2	13.1	<0.1	40	104.6	<0.1	1	65.5	48	15.3	8.8	19.2	285.2	286.7	19.73	46.7	5.03
EMMD043	116.9	marble	0.6	6.3	10.8	121	713	0.4	2.2	59.7	76	40.7	22.3	28.9	485.1	456.2	29.89	68.8	7.07
EMMD052	314.5	marble	0.2	0.3	3.8	3	242.6	<0.1	0.5	5.7	12	1.7	7.6	15.5	76.5	79.7	6.38	20	3.76
EMMD060	150.5	marble	2.3	8.6	47.9	51	155.5	0.3	8.3	122.8	214	60.8	91.1	31.9	386.7	393.3	28.22	75.7	9.5
EMMD066	100.5	marble	2.2	11	11.1	99	201.7	0.5	6.6	192.2	128	26.5	85.4	41.7	619.7	557.2	37.4	91.2	11.11
EMMD075	192.5	marble	0.5	6.7	2.8	81	140.8	1.3	2.7	236.4	89	16.7	19.2	17.9	329.6	292.7	18.48	44.1	5.03
EMMD075	205.30	marble	0.9	12.2	7.3	134	1112.9	1.5	3.6	245.9	92	278.6	20.5	25.5	904.6	802.4	49.46	113.2	10.36
EMMD077	174	marble	0.9	12.3	8.9	100	45.3	0.3	5.3	338.7	180	26.6	33.6	40.8	867.2	923	77.15	227.8	30.34
EMMD077	225.4	marble	0.8	4.8	15.4	108	1291.4	0.3	3.1	66.8	153	318.1	23	20.7	227.2	211.2	14.94	37	4.83
EMMD085	231.7	marble	3.6	9.1	98.7	2	52.2	0.6	13	5	92	2.4	129.6	26.8	23.3	44.9	5.11	18.8	3.94

Table B-2: Raw whole-rock data from ACME Labs

Hole ID	Depth	Lithology	Eu ppm	Gd ppm	Tb ppm	Dy ppm	Ho ppm	Er ppm	Tm ppm	Yb ppm	Lu ppm	Ni ppm	LOI wt%	Total C wt%	Total S wt%	Mo ppm	Cu ppm	Pb ppm
EMM018	87	carbonaceous schist	0.77	3.6	0.71	4.44	0.91	2.82	0.43	2.82	0.44	25	7.1	1.25	1.49	4.37	54.71	25.25
EMM019	126.8	carbonaceous schist	1.1	5.19	0.86	4.5	0.89	2.63	0.39	2.43	0.39	20	8.7	2	1.33	1.32	52.58	13.66
EMMD097	269	carbonaceous schist	1.4	5.81	1.08	6.83	1.39	4.11	0.58	3.64	0.53	15	6.8	1.61	0.03	1.18	192.75	2.75
EMMD117	140.8	carbonaceous schist	2.61	9.8	1.27	6.52	1.19	3.47	0.51	3.12	0.48	<10	3.5	1.06	<0.01	1.77	14.83	2.24
EMMD167	105.7	carbonaceous schist	1.23	6.37	1.01	5.66	1.12	3.35	0.44	2.86	0.41	65	7.7	0.88	3.78	2.2	127.95	16.02
EMMD167	127	carbonaceous schist	1.4	7.32	1.14	7.02	1.36	4.3	0.6	3.94	0.64	35	8.6	1.89	2.98	11.78	496.93	8.36
EMM008	93.1	diorite	1.49	3.93	0.77	4.74	0.96	2.65	0.4	2.69	0.42	51	2.1	0.15	0.04	0.53	52.12	2.8
EMMD077	37.65	diorite	1.44	4.95	0.83	4.67	1.01	3.04	0.44	2.92	0.45	22	4.3	0.48	0.13	0.45	74.9	0.83
EMMD008	60.5	discordant breccia	0.75	3.03	0.36	1.9	0.33	1.08	0.16	1.17	0.18	30	6	1.08	0.26	1.38	41.9	1.42
EMMD013	151	discordant breccia	0.74	5.41	0.89	5.02	0.9	2.55	0.39	2.46	0.37	40	14	3.24	0.62	6.57	379.49	3.48
EMMD0153	306.5	discordant breccia	2.87	6.27	0.92	5.25	1.02	2.86	0.41	2.57	0.37	24	13.6	4.14	1.96	77.3	774.19	5.06
EMMD030	96.2	discordant breccia	1.41	4.94	0.64	3.58	0.68	2.02	0.29	1.7	0.27	<10	13.5	3.11	0.1	0.2	136.62	1.58
EMMD077	290.00	discordant breccia	2.89	5.37	0.67	3.03	0.5	1.26	0.18	1.13	0.16	29	4.5	1.54	0.47	28.87	652.47	1.7
EMMD078	89	discordant breccia	2.41	6.06	0.91	4.4	0.81	2.25	0.32	2.16	0.37	44	4.1	0.34	0.05	0.46	147.95	1.2
EMMD085	56.00	discordant breccia	0.85	3.76	0.67	4.04	0.81	2.3	0.35	2.33	0.37	<10	17.3	4.29	<0.01	0.2	6.61	0.72
EMMD085	87.3	discordant breccia	1.03	4.19	0.66	3.64	0.69	1.93	0.28	1.7	0.26	28	7.6	1.33	0.09	0.32	20.7	1.37
EMMD085	147.3	discordant breccia	0.93	4.2	0.63	3.77	0.74	2.24	0.32	1.95	0.29	36	5.5	1	0.02	0.21	5.01	0.5
EMMD085	161	discordant breccia	1.12	5.57	0.76	4.14	0.74	2	0.28	1.88	0.29	31	5.9	1.1	0.17	4.67	6.26	0.71
EMMD085	295	discordant breccia	0.7	1.73	0.31	1.74	0.44	1.27	0.21	1.52	0.27	31	6.3	0.25	5.54	34.49	277.7	8.94
EMMD085	386.2	discordant breccia	1.58	6.01	0.77	3.61	0.62	1.68	0.27	1.64	0.26	45	7	0.86	1.37	3.11	11.57	1.78
EMMD085	393.2	discordant breccia	0.85	3.57	0.7	4.06	0.89	2.63	0.43	2.69	0.41	<10	6.1	1.14	0.26	30	44.44	2.18
EMMD114	198.4	discordant breccia	2.14	6.12	0.91	5.04	1.03	3.05	0.42	2.61	0.41	<10	1.8	0.23	<0.01	0.78	13.41	1.59
EMMD161	105	discordant breccia	0.49	2.38	0.44	2.81	0.58	1.67	0.23	1.65	0.28	24	6.9	1.46	<0.01	0.92	23.93	1.46
EMDT203	102.8	marble	12.09	11.28	1.01	4.68	0.74	1.96	0.26	1.32	0.12	22	2.8	0.34	8	252.15	>10000.00	46.81
EMM018	175.5	marble	3.08	4.66	0.51	2.81	0.56	1.68	0.28	1.97	0.32	23	10.6	3.33	6.28	53.01	803.92	25.34
EMMD001	117.5	marble	7.43	11.62	1.1	4.08	0.54	0.94	0.11	0.53	0.07	<10	-0.9	0.28	0.04	33.27	128.71	3.41
EMMD001	207.9	marble	9.37	6.77	0.92	5.76	1.09	3.05	0.4	2.33	0.25	26	1.2	0.11	8.09	414.41	>10000.00	141.55
EMMD007	110.2	marble	5.81	2.66	0.29	1.4	0.3	0.68	0.13	0.78	0.09	<10	6.6	2.79	4.88	90.42	8495.77	67.02
EMMD013	101.6	marble	11.41	7.41	0.79	3.98	0.75	2.22	0.31	1.79	0.21	15	4.5	2	3.8	121.91	>10000.00	84.82
EMMD0136	170.00	marble	1.89	3.88	0.59	3.41	0.67	1.94	0.32	1.93	0.3	57	4.5	1.65	3.69	43.33	3751.87	9.72
EMMD0136	362.20	marble	3.21	11.56	1.75	9.86	2.08	5.14	0.77	4.95	0.74	83	8.6	3.16	6.46	18.86	1570.37	5.22
EMMD018	60.9	marble	9.11	4.88	0.65	3.41	0.6	1.6	0.19	0.91	0.1	<10	7	2.29	0.01	8.52	590.6	27.51
EMMD043	116.9	marble	10.02	7.58	0.84	4.24	0.81	2.37	0.34	1.91	0.23	19	4.9	2.77	4.75	85.79	7556.74	29.74
EMMD052	314.5	marble	3.17	4.48	0.56	2.44	0.39	0.84	0.09	0.46	0.05	12	32	9.78	0.99	4.16	685.5	10.63
EMMD060	150.5	marble	7.5	9.84	1.15	5.59	1.11	3.08	0.43	2.86	0.43	39	6.1	0.33	9.89	135.55	6869.52	29.96
EMMD066	100.5	marble	14.42	11.69	1.51	8.32	1.41	3.92	0.57	3.38	0.45	44	4.7	3.65	5.5	221.82	>10000.00	72.89
EMMD075	192.5	marble	8.39	4.59	0.61	3.28	0.59	1.73	0.26	1.45	0.18	25	1.2	1.23	5.44	259	>10000.00	47.26
EMMD075	205.30	marble	19.18	10.99	1.06	5.58	1.08	2.97	0.46	2.72	0.33	21	2.1	1.78	5.84	264.92	>10000.00	54.08
EMMD077	174	marble	16.44	28.53	2.72	11	1.58	3.48	0.44	2.51	0.28	59	3.7	0.25	5.82	484.6	>10000.00	79.77
EMMD077	225.4	marble	6.01	5.31	0.69	3.85	0.86	2.52	0.3	2.16	0.31	14	1.8	0.92	4.77	100.02	8442.18	31
EMMD085	231.7	marble	0.8	4.12	0.73	4.47	0.89	2.62	0.42	2.53	0.36	34	12.5	2.75	0.02	0.07	8.02	0.62

Table B-2: Raw whole-rock data from ACME Labs

Hole ID	Depth	Lithology	Zn ppm	Ag ppb	Ni ppm	Co ppm	Mn ppm	As ppm	Au ppb	Cd ppm	Sb ppm	Bi ppm	Cr ppm	B ppm	Tl ppm	Hg ppb	Se ppm	Te ppm
EMM018	87	carbonaceous schist	331.5	418	25.4	9.9	76	26.6	0.9	0.3	2.09	0.44	4.1	4	0.3	<5	0.3	0.07
EMM019	126.8	carbonaceous schist	76.4	124	21.6	9.8	1258	4.2	1.1	0.15	0.33	0.38	15	3	0.53	<5	0.1	<0.02
EMMD097	269	carbonaceous schist	21.2	125	22.7	12.9	1896	23.1	2.4	0.01	0.96	0.04	29	<1	0.15	<5	<0.1	<0.02
EMMD117	140.8	carbonaceous schist	5.1	66	5.6	2.6	169	8.6	<0.2	<0.01	0.15	0.04	6.7	<1	0.05	<5	<0.1	<0.02
EMMD167	105.7	carbonaceous schist	309	1393	67.8	15.9	980	64.8	2.8	1.1	3.86	2.88	17.2	2	0.42	17	0.3	0.09
EMMD167	127	carbonaceous schist	7	1680	36.8	8.9	653	21.9	<0.2	0.08	0.96	1.92	3.8	3	0.17	<5	0.4	0.16
EMM008	93.1	diorite	31.7	75	28.1	18.6	842	2.1	7.9	<0.01	0.24	0.03	74.6	2	<0.02	<5	0.1	<0.02
EMMD077	37.65	diorite	13	27	24.4	23.5	567	2.3	0.8	<0.01	0.07	0.04	26.2	<1	<0.02	<5	<0.1	<0.02
EMMD008	60.5	discordant breccia	35.6	68	32.3	28.2	529	3.6	1.5	0.02	0.14	0.26	43.7	<1	0.05	<5	0.2	0.05
EMMD013	151	discordant breccia	7.1	237	33.5	25.8	1345	56.9	16.3	<0.01	0.22	0.64	35.5	<1	0.2	<5	0.6	0.13
EMMD0153	306.5	discordant breccia	13	263	23.5	146.6	3909	52.8	21	0.1	0.71	1.78	11.8	<1	0.34	24	<0.1	0.2
EMMD030	96.2	discordant breccia	0.4	28	11.2	10.6	1078	1.8	1.5	0.02	0.04	0.07	21.6	<1	<0.02	<5	<0.1	0.04
EMMD077	290.00	discordant breccia	3.9	103	19.3	26	1458	6.4	12.8	0.02	0.22	0.56	11.4	1	<0.02	<5	0.2	<0.02
EMMD078	89	discordant breccia	32.3	24	46.8	14.5	723	3.8	<0.2	0.02	0.33	0.02	46.8	<1	<0.02	<5	0.1	0.02
EMMD085	56.00	discordant breccia	2.1	14	9	2.4	2115	2.9	<0.2	0.03	0.04	0.04	10.1	<1	<0.02	<5	<0.1	<0.02
EMMD085	87.3	discordant breccia	13.9	29	29.2	16.5	1023	16	0.6	<0.01	0.05	0.05	30.8	<1	<0.02	10	<0.1	0.07
EMMD085	147.3	discordant breccia	9.1	28	35.7	9	774	2.7	1.1	0.01	0.09	0.02	31.1	<1	<0.02	15	<0.1	0.03
EMMD085	161	discordant breccia	8.6	20	32.4	24.3	756	8.3	11.4	<0.01	0.12	0.06	54	<1	<0.02	<5	0.3	<0.02
EMMD085	295	discordant breccia	10	1420	37.2	364.6	265	113.4	103.9	0.03	2	5.56	12.9	3	0.15	36	0.9	1.88
EMMD085	386.2	discordant breccia	27.1	129	44.6	56	946	20.9	11.5	<0.01	0.09	1.08	34.2	<1	<0.02	11	0.4	0.18
EMMD085	393.2	discordant breccia	9.1	83	11.8	29.2	704	9.1	6.7	<0.01	0.23	0.53	11	3	0.06	12	<0.1	0.19
EMMD114	198.4	discordant breccia	4.3	13	7.5	3.3	270	1	1.5	<0.01	0.2	0.02	16.7	<1	<0.02	5	<0.1	0.08
EMMD161	105	discordant breccia	10.7	64	23	8.6	638	2.2	5.2	0.02	0.06	0.04	40.5	<1	0.05	5	<0.1	<0.02
EMDT203	102.8	marble	3.8	6188	15.6	176.1	291	173.3	411.1	<0.01	5.4	28.94	1.2	1	0.03	259	1.6	0.9
EMM018	175.5	marble	29.7	4745	20	267.4	8224	255.2	140	<0.01	3.2	41.3	19.6	5	1.3	58	0.9	0.76
EMMD001	117.5	marble	23.8	475	5.5	4.4	314	24.4	20.1	<0.01	4.12	0.56	2	<1	<0.02	17	<0.1	0.07
EMMD001	207.9	marble	48	30526	21.5	475.5	256	434.1	1667.7	<0.01	24.07	64.35	1.8	4	0.06	768	3	1.95
EMMD007	110.2	marble	32.6	3135	9	224.6	7301	350.9	237	<0.01	5.69	12.32	1.5	<1	0.24	18	1.4	0.9
EMMD013	101.6	marble	213	6474	12.3	212.2	4891	322.9	325.5	0.31	5.56	38.02	3.1	3	0.11	115	1.9	0.69
EMMD0136	170.00	marble	12.1	658	36.2	288.5	2619	134	134.1	0.02	1.72	3.73	8.2	2	0.22	63	0.7	0.7
EMMD0136	362.20	marble	11	521	73.1	350.8	3379	283.6	133.2	<0.01	0.53	2.43	2.2	1	0.06	11	2.9	0.21
EMMD018	60.9	marble	54.8	653	4.4	52.7	2266	43.8	152.9	0.16	3.28	2.56	3	4	<0.02	8	<0.1	0.07
EMMD043	116.9	marble	139	12563	16.2	261.8	>10000	52.2	213.5	0.03	5.18	19.75	7.5	<1	1.07	86	1.2	0.53
EMMD052	314.5	marble	32.5	177	14.2	25.1	>10000	11.8	12	0.1	0.58	0.86	0.6	<1	0.02	16	<0.1	>0.02
EMMD060	150.5	marble	14.9	1342	32.7	527	506	371.7	252.3	0.02	3.63	12.14	8.4	5	0.16	47	2.5	1.32
EMMD066	100.5	marble	39.9	7162	45	589.4	3687	327.5	582.2	<0.01	4.65	22.39	10.3	3	0.45	74	2.4	1.37
EMMD075	192.5	marble	23.3	4306	23.5	408.2	3642	289.9	782.9	<0.01	3.49	16.98	2.7	2	0.13	30	2.7	1.29
EMMD075	205.30	marble	11.2	8550	16.7	239.9	8689	201.2	389.3	<0.01	4.4	41.89	2.7	2	0.05	*	2.2	1.13
EMMD077	174	marble	9.1	4057	44.7	446.4	295	227.9	164.3	0.17	5.98	13.17	3.4	2	0.29	116	2.8	1.83
EMMD077	225.4	marble	29.7	8906	14.4	149.1	1259	97.2	227.5	0.09	6.98	14.61	2.5	<1	0.09	<5	0.7	0.76
EMMD085	231.7	marble	6.1	23	40.9	26.1	1584	1.5	3.3	0.01	0.04	<0.02	44.9	<1	<0.02	<5	<0.1	<0.02

Table B-2: Raw whole-rock data from ACME Labs

Hole ID	Depth	Lithology	Ge ppm	In ppm	Re ppb	Be ppm	Li ppm	Pd ppb	Pt ppb	Ba-XRF wt%	Cu-XRF wt%	F-XRF wt%
EMM018	87	carbonaceous schist	0.1	0.03	<1	0.4	15.7	<10	4	N.A.	N.A.	0.28
EMM019	126.8	carbonaceous schist	<0.1	<0.02	<1	0.4	12.5	<10	<2	N.A.	N.A.	0.18
EMMD097	269	carbonaceous schist	<0.1	<0.02	<1	0.4	4.5	23	<2	N.A.	N.A.	0.07
EMMD117	140.8	carbonaceous schist	<0.1	<0.02	1	0.6	3.3	<10	<2	N.A.	N.A.	0.15
EMMD167	105.7	carbonaceous schist	<0.1	0.07	1	0.5	21.2	<10	<2	0.09	0.02	0.19
EMMD167	127	carbonaceous schist	<0.1	<0.02	4	0.7	6.4	15	19	0.23	0.05	0.31
EMM008	93.1	diorite	0.3	0.03	3	0.2	9	12	<2	N.A.	N.A.	0.02
EMMD077	37.65	diorite	0.2	0.03	<1	0.6	16.1	<10	3	N.A.	N.A.	0.11
EMMD008	60.5	discordant breccia	0.3	<0.02	<1	0.4	25	<10	<2	0.03	0.01	0.35
EMMD013	151	discordant breccia	0.1	0.03	6	0.7	9.1	<10	<2	N.A.	N.A.	0.18
EMMD0153	306.5	discordant breccia	<0.1	0.02	14	0.2	13.8	<10	<2	0.23	0.08	0.16
EMMD030	96.2	discordant breccia	<0.1	0.04	<1	0.1	1	38	<2	<0.01	0.02	0.04
EMMD077	290.00	discordant breccia	<0.1	<0.02	<1	0.1	2.9	<10	<2	0.06	0.07	0.09
EMMD078	89	discordant breccia	0.2	<0.02	<1	0.6	21	<10	<2	N.A.	N.A.	0.18
EMMD085	56.00	discordant breccia	<0.1	0.03	<1	<0.1	2	<10	5	0.04	0.01	0.03
EMMD085	87.3	discordant breccia	<0.1	0.03	<1	1.1	45.7	<10	2	0.07	0.01	0.12
EMMD085	147.3	discordant breccia	<0.1	<0.02	<1	1.1	16.8	<10	<2	0.06	<0.01	0.08
EMMD085	161	discordant breccia	0.2	<0.02	2	0.5	9.2	<10	3	0.02	<0.01	0.07
EMMD085	295	discordant breccia	<0.1	0.04	27	0.5	17.2	87	<2	0.48	0.03	0.46
EMMD085	386.2	discordant breccia	0.4	<0.02	5	1	36.8	14	3	0.03	<0.01	0.17
EMMD085	393.2	discordant breccia	<0.1	<0.02	8	0.6	11.7	11	<2	N.A.	N.A.	0.16
EMMD114	198.4	discordant breccia	<0.1	<0.02	<1	0.6	1.3	10	<2	N.A.	N.A.	0.09
EMMD161	105	discordant breccia	0.2	0.03	2	0.3	14.1	28	3	<0.01	<0.01	0.15
EMDT203	102.8	marble	0.7	0.48	49	0.2	2.8	*	2	22.65	1.76	8.23
EMM018	175.5	marble	0.4	0.09	8	1	14.6	17	<2	7.09	0.09	0.44
EMMD001	117.5	marble	0.6	<0.02	<1	0.2	6.4	<10	<2	0.05	0.03	0.17
EMMD001	207.9	marble	0.7	0.61	169	0.4	3.8	*	<2	9.16	2.74	6.44
EMMD007	110.2	marble	1.2	0.2	17	1.1	1.2	<10	<2	0.99	0.84	2.49
EMMD013	101.6	marble	1	0.58	39	0.7	0.8	18	<2	0.66	1.08	5.18
EMMD0136	170.00	marble	0.1	0.07	17	0.6	9.7	17	5	0.47	0.36	0.3
EMMD0136	362.20	marble	<0.1	0.15	9	0.3	7.9	25	12	0.14	0.16	0.32
EMMD018	60.9	marble	1.1	0.39	1	0.7	3.5	<10	<2	0.04	0.06	0.12
EMMD043	116.9	marble	0.6	0.46	17	1	28.7	36	<2	3.07	0.74	5.42
EMMD052	314.5	marble	0.3	0.1	<1	0.3	3.1	<10	<2	0.06	0.08	0.05
EMMD060	150.5	marble	0.4	0.07	52	0.9	20.7	54	<2	1.51	0.67	2.54
EMMD066	100.5	marble	0.5	0.58	93	0.8	35.8	*	<2	0.46	1.85	0.42
EMMD075	192.5	marble	1.2	0.48	72	1	18.3	*	<2	0.16	2.15	5.67
EMMD075	205.30	marble	0.9	1.59	66	0.7	4.1	*	<2	10.45	2.02	7.29
EMMD077	174	marble	0.3	0.16	156	0.7	11.6	<10	6	0.43	1.76	0.67
EMMD077	225.4	marble	0.7	0.26	52	1	10.2	<10	<2	9.01	0.84	4.05
EMMD085	231.7	marble	<0.1	<0.02	1	0.5	17	<10	<2	0.06	<0.01	0.06

Table B-2: Raw whole-rock data from ACME Labs

Hole ID	Depth	Lithology	Wgt kg	SiO ₂ wt%	Al ₂ O ₃ wt%	Fe ₂ O ₃ * wt%	MgO wt%	CaO wt%	Na ₂ O wt%	K ₂ O wt%	TiO ₂ wt%	P ₂ O ₅ wt%	MnO wt%	Cr ₂ O ₃ wt%	Ba ppm	Sc ppm	Sum wt%	Cs ppm	Ga ppm
EMMD085	310.5	marble	0.29	9.44	3.03	50.64	1.04	8.68	0.02	0.88	0.26	0.71	0.05	0.006	>50000	4	73.58	0.1	5.2
EMMD097	226.15	marble	0.22	20.14	12.3	33.68	4.15	8.9	0.22	2.67	1.09	0.33	0.79	0.011	40937	16	94.89	6	14.5
EMMD136	361.85	marble	0.11	54.09	12.07	11.74	1.64	5.86	0.11	4.21	0.36	0.2	0.11	<0.002	2044	11	99.65	0.8	21.5
EMMD182	239.75	marble	0.15	19.28	4.8	28.22	6.52	14.88	0.06	1.55	0.46	0.89	0.65	0.002	2102	5	90.3	1.4	8.2
EMM017	154.3	metaandesite	0.11	56.08	15.55	11.39	3.49	1.62	4.33	1.66	1.6	0.18	0.08	0.006	2985	26	99.51	1.8	20
EMM018	133	metaandesite	0.18	43.4	15.25	20.17	5.21	3.66	0.18	2.02	1.56	0.16	0.18	0.006	3932	25	99.36	2	20.8
EMM019	338	metaandesite	0.09	51.94	14.37	10.34	1.63	6.45	4.56	1.76	1.48	0.15	0.25	0.006	2599	27	99.62	1	19.5
EMM022	74.6	metaandesite	0.19	63.1	14.96	8.86	1.14	1.11	4.97	1.9	1.57	0.19	0.06	0.006	1071	20	99.8	1.5	19.4
EMMD002	120.5	metaandesite	0.12	44.1	13.77	25.37	3.81	1.92	0.12	3.87	2.13	0.28	0.19	0.003	4869	24	99.07	3.8	21.1
EMMD008	126	metaandesite	0.09	52.94	14.91	12.35	4.05	2.66	5.57	2.02	1.45	0.15	0.07	0.009	607	24	99.72	3.6	18.9
EMMD018	101	metaandesite	0.14	52.05	15.12	12.14	3.78	2.93	6.02	2.42	1.43	0.17	0.07	0.009	568	25	99.78	3	19.2
EMMD041	154.75	metaandesite	0.12	48.39	14.04	21.52	3.79	0.87	5.99	0.88	1.01	0.08	0.05	<0.002	84	17	99.83	1.3	17.9
EMMD042	171.2	metaandesite	0.09	51.46	14.17	12.65	2.81	3.77	5.54	1.56	1.42	0.14	0.25	0.005	754	25	99.79	5	18.2
EMMD043	169.9	metaandesite	0.1	48.09	17.4	7.91	1.51	7.14	4.72	2.95	1.28	0.14	0.28	0.005	2297	22	99.66	1.4	20.4
EMMD064	150	metaandesite	0.21	53.44	17.24	9.14	3.28	3.06	6.24	1.96	1.44	0.1	0.18	0.003	630	19	99.77	3.4	22.2
EMMD066	40	metaandesite	0.16	49.28	18.85	15.98	2.91	0.38	4.77	2.29	1.65	0.2	0.11	0.004	11197	19	98.6	1.6	20.6
EMMD066	123.6	metaandesite	0.17	54.18	14.41	13.05	2	3.16	5.09	1.69	2.13	0.25	0.18	0.002	1901	26	99.62	1.4	22.6
EMMD066	176	metaandesite	0.16	50.14	14.94	10.42	1.62	5.81	2.29	3.59	1.44	0.14	0.34	0.005	4879	27	99.29	1.3	21.1
EMMD067	187	metaandesite	0.18	51.02	16.67	12.31	2.17	2.83	4.74	2.45	2.01	0.26	0.2	0.003	2104	24	99.62	1.1	23.8
EMMD074	195	metaandesite	0.14	62.96	13.91	1.97	0.49	4.12	0.47	11.19	0.27	0.07	0.1	<0.002	1821	2	99.74	0.3	8
EMMD075	116.2	metaandesite	0.2	42.41	15.45	24.53	1.99	0.56	0.13	2.91	2.39	0.3	0.57	0.003	5018	29	99.24	1.5	23.1
EMMD077	81.7	metaandesite	0.24	41.24	14.79	24.46	3.16	3.6	0.88	5.04	1.48	0.16	0.25	0.005	7079	28	99.02	2.1	20.8
EMMD077	162.4	metaandesite	0.25	33.28	13.16	41.95	2.62	0.52	3.65	1.82	1.52	0.18	0.04	0.007	2798	23	99.55	0.5	18.5
EMMD085	366.8	metaandesite	0.35	49.71	10.32	18.45	1.64	4.14	0.06	3.35	0.55	0.8	0.1	<0.002	3996	7	99.29	0.3	12.2
EMMD086	167.9	metaandesite	0.24	27.18	17.42	33.4	4.4	2.16	0.2	5.27	2.6	0.33	0.23	0.002	34998	26	95.71	6	29.5
EMMD097	74.14	metaandesite	0.16	44.14	8.14	30.93	2.97	3.68	0.07	0.01	0.48	0.23	0.11	<0.002	121	9	99.47	0.2	8.2
EMMD097	174.1	metaandesite	0.24	57.47	16.33	7.58	2.19	3.13	5.99	1.18	1.66	0.25	0.11	0.006	963	27	99.75	0.9	22.4
EMMD114	71	metaandesite	0.13	58.59	18.08	4.76	1.03	3.23	7.64	1.19	1.56	0.2	0.12	0.003	862	13	99.77	0.5	16.8
EMMD118	143.8	metaandesite	0.29	54.82	15.58	13.86	3.68	1.65	3.22	0.99	1.3	0.09	0.11	0.005	2116	23	99.63	0.7	26
EMMD119	174.9	metaandesite	0.35	55.4	9.98	8.41	4.41	7.82	0.08	5.32	0.44	0.11	0.16	0.006	699	9	99.8	0.3	16.4
EMMD126	104	metaandesite	0.16	49.94	15.24	12.07	3.62	4.84	4.73	0.66	1.44	0.15	0.26	0.009	224	22	99.82	0.9	19
EMMD129	155	metaandesite	0.2	57.42	16.56	7.22	1.93	3.43	5.63	1.44	1.48	0.32	0.14	<0.002	707	18	99.75	1.2	15.2
EMMD136	71.9	metaandesite	0.24	54.43	17.52	6.4	1.63	4.64	5.91	2.06	1.49	0.3	0.14	0.003	1070	18	99.72	1.6	21.4
EMMD136	124	metaandesite	0.19	53.09	15.98	8.66	1.25	5.11	7.57	0.72	1.27	0.26	0.21	0.003	494	12	99.7	0.3	15.3
EMMD136	215	metaandesite	0.17	47.06	14.34	6.79	2.23	8.66	4.73	2.34	1.39	0.15	0.37	0.004	1741	27	99.67	1.4	18.9
EMMD136	267.5	metaandesite	0.27	61.4	6.3	25.32	0.7	0.87	0.06	2.2	0.22	0.07	0.04	<0.002	4583	5	99.31	1.6	11.9
EMMD136	321	metaandesite	0.15	58.36	16.61	10.29	0.6	1.84	4.58	3.42	1.28	0.11	0.13	0.005	2551	22	99.65	0.5	19.8
EMMD167	180.3	metaandesite	0.15	51.93	17.32	6.38	1.94	4.37	7.6	1.16	1.48	0.16	0.3	0.005	771	20	99.82	1.3	15.9
EMMD167	234	metaandesite	0.26	47.14	15.94	16.02	4.78	3.62	3.05	0.84	1.25	0.03	0.18	<0.002	433	18	99.71	0.7	22.9
EMMD167	279.7	metaandesite	0.08	53.15	15	12.13	3.69	3.39	3.6	1.4	1.24	0.25	0.13	<0.002	456	17	99.76	0.8	18.4
EMMD182	91.7	metaandesite	0.13	58.29	18.96	5.75	0.6	1.59	8.75	1.37	1.42	0.18	0.1	0.002	783	11	99.84	0.6	12.4

Table B-2: Raw whole-rock data from ACME Labs

Hole ID	Depth	Lithology	Hf ppm	Nb ppm	Rb ppm	Sn ppm	Sr ppm	Ta ppm	Th ppm	U ppm	V ppm	W ppm	Zr ppm	Y ppm	La ppm	Ce ppm	Pr ppm	Nd ppm	Sm ppm
EMMD085	310.5	marble	1.2	11	22.9	76	1439.1	0.5	5.4	246.5	198	42.8	40.6	27	302.5	296.3	20.08	49.9	6.67
EMMD097	226.15	marble	3.9	8.8	123.2	61	384.3	0.7	10.4	45.5	199	98.5	139.7	22.8	398.2	365	25.59	64.5	7.47
EMMD136	361.85	marble	6.2	12	89.2	24	20.2	0.6	8.2	26.1	44	30.6	267.1	19.9	41.7	57.7	5.62	17.7	3.43
EMMD182	239.75	marble	1.7	5.7	54	18	58	0.3	12	25.6	164	15.6	71.7	40.3	173.4	215.9	19.29	61.9	8.86
EMM017	154.3	metaandesite	5.6	9.9	51.6	2	53	0.9	13	3.5	275	2.5	216.3	32.4	28.4	54.7	6.73	25.4	5.33
EMM018	133	metaandesite	5.7	15.5	56.4	2	38.7	0.8	12.9	4.4	248	23.1	207.8	26.3	37.6	66.2	7.6	29.5	5.9
EMM019	338	metaandesite	4.9	16.1	40.3	5	62.3	0.8	9.6	5.2	206	4.8	174.7	21.2	5.7	9.4	1.09	4.2	1.23
EMM022	74.6	metaandesite	5.7	10.1	72.1	3	28.8	0.8	12.6	4	189	3.1	205.9	27.2	2.2	4.4	0.6	3	1.07
EMMD002	120.5	metaandesite	7.8	14.8	172.3	16	27	1.2	14.4	16.1	276	29.5	283.4	35.2	35.6	46.6	4.39	15.5	3.19
EMMD008	126	metaandesite	6.2	24.4	86.6	7	55.4	0.9	12.7	3	223	10.9	214.5	35.7	167.5	220.2	19.97	64.6	12.98
EMMD018	101	metaandesite	5.6	21.9	122.2	4	54.8	0.8	11.7	3.3	243	6.8	206.4	33.8	59.1	96.2	10.6	37.9	8.46
EMMD041	154.75	metaandesite	3.5	4	39.2	3	16.5	0.4	7.1	2.7	165	1.4	123	14.9	33.3	55.2	5.86	21.4	3.84
EMMD042	171.2	metaandesite	4.7	11.6	89	2	69.7	0.6	10.2	3.1	240	2.3	173.5	26	27.3	50.5	5.66	22.3	4.83
EMMD043	169.9	metaandesite	3.9	11.1	105.2	3	41.6	0.6	6.9	5	209	7.5	139.2	23.7	6.9	13.7	1.68	7.4	2.21
EMMD064	150	metaandesite	5.6	9.9	89	2	77.6	0.8	13.7	3.7	179	3	206.6	26.8	34.1	60.1	7.11	26.1	5.26
EMMD066	40	metaandesite	5.9	11.5	63.4	12	39.6	0.9	15	31.6	183	26.2	220.2	22.5	20.1	27.5	2.56	8.4	2.01
EMMD066	123.6	metaandesite	7.8	14.3	46.8	4	111.9	1.2	17.7	5.6	277	5.9	290.3	39.5	45.5	87.5	10.49	39.9	8.36
EMMD066	176	metaandesite	5.1	9	112.2	4	30.7	0.7	10.2	3.2	234	7.5	179	23.7	32.9	57.2	6.31	23.8	4.74
EMMD067	187	metaandesite	8.2	13.7	92.2	9	26.7	1.1	17.4	8.1	266	8.8	287.5	29.7	41.4	67.7	7.4	26.5	5.46
EMMD074	195	metaandesite	8.2	11.2	145.7	2	47.2	0.7	17.2	8.8	<8	7.3	351.5	18.4	9.8	17.3	1.91	7.8	1.75
EMMD075	116.2	metaandesite	8.3	15.1	78.5	5	31.3	1.2	17.6	14.1	319	37.7	312.1	45.2	47.1	79.6	9.16	35.2	7.54
EMMD077	81.7	metaandesite	5.1	9.1	150.1	20	31.6	0.8	11.5	12.3	256	9.4	180.4	24.6	167.1	219.4	20.98	68.6	11.93
EMMD077	162.4	metaandesite	4.8	8.5	41.3	8	25.9	0.6	9.9	7.6	350	32.6	182.4	13.3	5.5	6.4	0.65	2.5	0.69
EMMD085	366.8	metaandesite	3.6	12.2	64.3	32	27.7	0.7	13.8	62.7	86	42.3	134.3	31.1	89	121.7	10.94	35.8	5.87
EMMD086	167.9	metaandesite	9.6	17.3	186.1	75	77.7	1.5	19.2	19.5	354	51.9	350	26.2	148.8	143	10.23	27.4	3.98
EMMD097	74.14	metaandesite	2.3	4.4	0.3	27	58.2	0.3	5.8	21.5	102	46.1	79.8	11.4	67	80.4	5.6	15.1	2.21
EMMD097	174.1	metaandesite	6.2	11.7	37.1	4	59.2	0.9	13.9	4.4	264	5.5	228.9	29	33.5	62.6	7.56	29.4	6.19
EMMD114	71	metaandesite	6	11	41	4	76.2	1	14.4	4.2	164	8.4	221.3	23.8	109.7	178.6	17.76	59.9	10.56
EMMD118	143.8	metaandesite	4.1	7.4	29.9	3	19.6	0.5	9.9	4.8	265	12	160	18.1	15.9	25.5	2.68	9.8	2.14
EMMD119	174.9	metaandesite	4.2	8.5	86.9	3	45	0.9	10.3	3.6	81	2.6	155.8	17.4	33.5	65.4	7.26	25.9	4.59
EMMD126	104	metaandesite	5.5	9.8	21.6	2	91.2	0.8	12.3	3.6	216	3	211.1	31.8	30.5	57	6.69	26.2	5.62
EMMD129	155	metaandesite	5.4	9.7	50.3	3	61.6	0.8	13.5	3.8	164	2	204.9	26.7	44.4	78.7	8.25	29.9	5.68
EMMD136	71.9	metaandesite	5.7	10.5	72.5	3	95.8	0.8	13.9	4.8	180	5.3	214.9	29	99.4	149.2	15.2	50.9	9.66
EMMD136	124	metaandesite	5	9.3	25.6	3	57.2	0.7	13.1	4.1	136	8.1	184.8	28.7	96.1	138.5	13.85	49.2	9.49
EMMD136	215	metaandesite	4.8	8.4	93.6	4	41.4	0.6	9.9	2.7	232	4.8	176.1	36.3	31	52.8	6.14	22.9	5.01
EMMD136	267.5	metaandesite	0.8	6.3	58.7	43	5.8	0.1	3.1	8.5	113	11.9	31.7	3.9	21.3	20.8	1.74	5.3	0.96
EMMD136	321	metaandesite	4	7.7	102.6	4	16.9	0.5	7.5	4.3	220	8.4	143.8	14.7	3.6	5.9	0.7	2.9	0.81
EMMD167	180.3	metaandesite	4.8	8.3	45.9	3	35.8	0.5	10.2	4.4	193	3.9	179.1	25.2	15.7	24.9	2.94	12.1	2.62
EMMD167	234	metaandesite	5	8.4	37.3	2	27.3	0.7	10.7	4.3	200	4.1	174.4	27.6	34.4	63.5	7.06	26.3	4.76
EMMD167	279.7	metaandesite	4.7	8.9	46.5	5	33.1	0.7	12.3	2.4	185	7	170.8	36.2	110.1	168.6	18.5	66.7	13.73
EMMD182	91.7	metaandesite	5.4	8.5	56.8	2	53.4	0.7	12.2	3.7	112	11.5	198.8	36.6	35.2	53.7	5.71	20.7	4.25

Table B-2: Raw whole-rock data from ACME Labs

Hole ID	Depth	Lithology	Eu ppm	Gd ppm	Tb ppm	Dy ppm	Ho ppm	Er ppm	Tm ppm	Yb ppm	Lu ppm	Ni ppm	LOI wt%	Total C wt%	Total S wt%	Mo ppm	Cu ppm	Pb ppm
EMMD085	310.5	marble	8.2	6.68	0.97	5.53	1.2	2.95	0.43	2.55	0.33	29	-1.2	0.33	6.97	277.43	>10000.00	28.83
EMMD097	226.15	marble	7.62	7.59	0.83	4.56	0.95	2.85	0.43	3	0.44	33	10.6	2.9	1.36	234.94	1542.29	13.25
EMMD136	361.85	marble	1.14	3.54	0.56	3.2	0.66	2.15	0.36	2.8	0.55	12	9.3	1.28	3.76	2.21	31.73	8.83
EMMD182	239.75	marble	2.82	8.99	1.36	7.42	1.59	4.3	0.62	3.82	0.56	54	13	5.38	4.87	39.1	3273.16	9.14
EMM017	154.3	metaandesite	1.21	5.87	0.97	5.75	1.14	3.44	0.49	3.04	0.45	36	3.5	0.35	<0.01	0.47	26.9	1.89
EMM018	133	metaandesite	1.31	5.01	0.83	5	1.14	3.43	0.53	3.42	0.52	31	7.6	0.83	0.02	0.76	42.21	2.14
EMM019	338	metaandesite	0.28	1.86	0.43	3.28	0.79	2.51	0.41	2.71	0.4	24	6.7	1.49	<0.01	0.08	7.26	3.68
EMM022	74.6	metaandesite	0.3	2.12	0.58	4.43	1.06	3.21	0.47	2.93	0.43	13	1.9	0.19	0.02	1.67	13.03	3.11
EMMD002	120.5	metaandesite	1.16	3.85	0.78	5.38	1.39	4.55	0.73	4.69	0.66	28	3.5	0.32	0.38	61.09	1641.84	2.12
EMMD008	126	metaandesite	5.34	13.64	2.35	11.41	1.54	3.19	0.42	2.69	0.47	53	3.5	0.54	0.05	1.1	82.81	2.82
EMMD018	101	metaandesite	2.35	7.84	1.24	6.57	1.25	3.66	0.55	3.72	0.54	58	3.6	0.64	0.03	3.04	11.22	1.74
EMMD041	154.75	metaandesite	0.62	3.51	0.48	2.58	0.51	1.45	0.21	1.48	0.24	40	3.2	0.21	0.84	1.02	321.21	1.42
EMMD042	171.2	metaandesite	1.17	4.6	0.78	4.49	0.92	2.68	0.39	2.61	0.37	48	6	1.32	<0.01	1.2	30.03	2.43
EMMD043	169.9	metaandesite	0.72	2.92	0.67	4.35	0.95	2.8	0.41	2.63	0.4	16	8.2	1.7	0.04	2.17	7.65	1.26
EMMD064	150	metaandesite	1.43	5.26	0.87	5.29	1.06	2.86	0.42	2.75	0.43	36	3.7	0.63	0.02	0.22	153.08	4.58
EMMD066	40	metaandesite	0.73	2.44	0.49	3.55	0.8	2.55	0.4	2.69	0.43	30	2.2	0.12	0.03	2.75	163.45	2.63
EMMD066	123.6	metaandesite	1.81	7.86	1.36	7.68	1.57	4.51	0.69	4.48	0.66	24	3.5	0.72	0.02	2.39	97.83	3.46
EMMD066	176	metaandesite	1.21	4.64	0.71	4.16	0.84	2.63	0.41	2.73	0.44	13	8.5	1.88	0.06	0.69	494.58	1.25
EMMD067	187	metaandesite	1.59	5.5	0.85	5.06	1.05	3.54	0.55	3.63	0.57	27	5	1.01	0.03	3.33	63.86	1.87
EMMD074	195	metaandesite	0.41	2.08	0.42	2.81	0.68	2.17	0.36	2.63	0.42	<10	4.2	0.94	0.29	1.77	17.03	1.9
EMMD075	116.2	metaandesite	2.33	8.2	1.36	8.08	1.67	4.97	0.74	4.75	0.71	35	8	1.36	0.1	7.04	276.85	2.58
EMMD077	81.7	metaandesite	4.37	10.22	1.23	5.48	0.85	2.52	0.4	2.81	0.44	36	3.9	0.84	0.41	9.8	33.28	1.49
EMMD077	162.4	metaandesite	0.51	1.27	0.27	2.04	0.49	1.75	0.26	2.05	0.33	70	0.8	0.02	0.03	17.46	21.94	2.1
EMMD085	366.8	metaandesite	1.62	5.88	0.92	5.43	1.1	3.35	0.51	3.42	0.54	37	10.2	0.92	9.65	10.43	955.52	14.26
EMMD086	167.9	metaandesite	2.38	4.74	0.69	4.28	1.05	3.83	0.69	4.74	0.79	16	2.5	0.33	0.14	40.81	1059.45	2.32
EMMD097	74.14	metaandesite	1.58	2.2	0.33	1.92	0.42	1.29	0.19	1.23	0.21	17	8.7	1.4	0.05	6.81	2505.01	209.69
EMMD097	174.1	metaandesite	1.39	6.02	0.91	5.17	1.05	3.2	0.49	3.2	0.49	13	3.8	0.64	0.03	0.4	126.66	1.67
EMMD114	71	metaandesite	3.62	8.41	1.11	5.07	0.88	2.57	0.39	2.74	0.42	<10	3.4	0.61	0.02	0.74	37.06	3.11
EMMD118	143.8	metaandesite	0.6	2.49	0.47	3.12	0.69	2.21	0.34	2.06	0.35	52	4.3	0.34	0.08	1.07	20.76	1
EMMD119	174.9	metaandesite	0.95	3.95	0.61	3.21	0.6	1.59	0.26	1.52	0.23	20	7.7	1.65	0.25	0.29	7.35	0.64
EMMD126	104	metaandesite	1.41	5.69	0.95	5.48	1.12	3.07	0.49	3.12	0.48	44	6.8	1.22	<0.01	1.92	3.51	1.04
EMMD129	155	metaandesite	1.68	5.44	0.8	4.83	0.99	2.99	0.46	3.16	0.5	20	4.2	0.69	0.06	0.44	568.24	1.49
EMMD136	71.9	metaandesite	3.48	8.56	1.17	5.89	1.08	2.97	0.44	3.04	0.5	14	5.2	0.91	0.03	3.78	251.85	9.73
EMMD136	124	metaandesite	3.66	9.22	1.26	5.7	0.96	2.67	0.42	2.52	0.42	<10	5.6	1.33	0.15	0.45	1205.06	1.94
EMMD136	215	metaandesite	1.53	5.58	0.94	6.05	1.29	3.66	0.52	3.18	0.47	20	11.6	2.69	0.01	0.72	158.35	1.2
EMMD136	267.5	metaandesite	0.4	1.09	0.15	0.88	0.13	0.38	0.06	0.33	0.05	21	2.1	0.21	1.35	91.93	838.61	2.39
EMMD136	321	metaandesite	0.28	1.39	0.31	2.37	0.54	1.71	0.26	2	0.31	<10	2.4	0.36	<0.01	0.31	104.52	0.69
EMMD167	180.3	metaandesite	0.93	3.44	0.62	4	0.83	2.56	0.4	2.57	0.42	<10	7.2	1.51	<0.01	0.47	32.23	1.19
EMMD167	234	metaandesite	1.29	4.62	0.75	4.45	0.94	2.96	0.42	2.71	0.43	47	6.8	0.84	0.09	0.17	672.07	0.92
EMMD167	279.7	metaandesite	4.42	12.52	1.67	7.56	1.34	3.18	0.42	2.63	0.38	39	5.8	0.71	0.08	0.19	180.87	0.79
EMMD182	91.7	metaandesite	1.24	4.34	0.82	5.68	1.28	3.75	0.53	3	0.47	<10	2.8	0.44	<0.01	2.85	19.44	1.77

Table B-2: Raw whole-rock data from ACME Labs

Hole ID	Depth	Lithology	Zn ppm	Ag ppb	Ni ppm	Co ppm	Mn ppm	As ppm	Au ppb	Cd ppm	Sb ppm	Bi ppm	Cr ppm	B ppm	Tl ppm	Hg ppb	Se ppm	Te ppm
EMMD085	310.5	marble	9	4160	23.8	342.8	386	524.5	597.5	<0.01	3.7	7.38	4.4	4	0.2	64	2.2	1.16
EMMD097	226.15	marble	85.4	2336	26.6	82.8	5755	48.9	48.1	0.13	4.01	6.9	54.1	7	1.09	<5	0.4	0.18
EMMD136	361.85	marble	6.7	334	13.2	189.4	770	83.2	60.1	0.03	1.24	3.2	1.1	1	0.06	12	0.9	0.37
EMMD182	239.75	marble	20.9	538	44.6	270.4	4829	101.9	127.8	0.05	1.86	4.21	5.2	<1	0.26	52	1.1	0.51
EMM017	154.3	metaandesite	66.3	22	32.7	14.7	297	0.8	<0.2	0.03	0.37	<0.02	28.8	4	0.25	<5	<0.1	<0.02
EMM018	133	metaandesite	116.8	34	28.7	9.2	1257	2.3	0.5	0.03	0.42	<0.02	26.4	7	0.04	<5	<0.1	<0.02
EMM019	338	metaandesite	32.4	28	26.3	7.9	1551	1.1	<0.2	0.03	0.69	0.02	27.3	2	0.06	<5	<0.1	0.03
EMM022	74.6	metaandesite	11.4	45	15.6	4.4	191	1.8	1.1	<0.01	0.18	<0.02	24.1	<1	0.02	<5	<0.1	0.02
EMMD002	120.5	metaandesite	54.4	298	31.4	45.6	752	18.5	31.6	0.12	0.3	0.35	10.6	2	0.36	<5	0.3	0.04
EMMD008	126	metaandesite	93.7	56	52.1	13.2	479	3.2	0.4	<0.01	0.29	0.02	54.5	<1	0.62	<5	<0.1	<0.02
EMMD018	101	metaandesite	16	39	49.2	13.4	511	3	1.6	0.02	0.12	<0.02	54.9	<1	0.6	<5	<0.1	<0.02
EMMD041	154.75	metaandesite	14.8	45	38.5	64.5	320	20.3	2.4	0.02	0.17	0.38	2	<1	0.11	<5	0.4	0.04
EMMD042	171.2	metaandesite	43.6	40	40.1	12	1692	1.6	1.5	0.01	0.22	0.04	34.8	<1	0.49	<5	<0.1	<0.02
EMMD043	169.9	metaandesite	8.9	23	11.2	7.9	1956	3.4	0.6	<0.01	0.2	0.06	16.9	3	0.06	<5	<0.1	0.02
EMMD064	150	metaandesite	45.8	37	28.5	22.3	848	2.9	2	0.01	0.22	0.03	15.5	1	0.28	<5	<0.1	<0.02
EMMD066	40	metaandesite	41.1	58	32.5	15.3	491	4.5	2.4	0.01	0.44	0.05	15.1	3	0.11	<5	<0.1	0.03
EMMD066	123.6	metaandesite	33.1	38	27	6.6	659	3.9	1.3	0.01	1.11	<0.02	13.4	<1	0.21	<5	<0.1	<0.02
EMMD066	176	metaandesite	4.5	72	13.6	1.9	2345	<0.1	2.9	<0.01	0.2	<0.02	12.9	<1	0.06	<5	<0.1	0.03
EMMD067	187	metaandesite	8.2	13	27.9	6.4	1261	0.7	1.3	<0.01	0.12	<0.02	15.3	<1	0.03	<5	0.1	<0.02
EMMD074	195	metaandesite	7.9	42	1.7	15.8	741	3.6	2.1	0.07	0.08	0.14	1.6	<1	<0.02	<5	<0.1	0.02
EMMD075	116.2	metaandesite	26.4	112	32.4	74.3	3971	18.5	7	0.02	1.32	0.22	12.7	6	0.14	13	<0.1	0.03
EMMD077	81.7	metaandesite	23.6	51	39.2	28.2	1292	20.3	2.5	<0.01	0.63	0.14	21.7	2	0.39	<5	0.4	<0.02
EMMD077	162.4	metaandesite	8.7	83	45.2	4.7	262	3.1	2.6	0.06	0.43	0.16	26.4	1	0.05	<5	<0.1	<0.02
EMMD085	366.8	metaandesite	12.8	963	33.7	282.8	750	147.9	109	0.05	0.92	6.86	2.7	2	0.06	21	2.7	1.73
EMMD086	167.9	metaandesite	30.5	317	17.2	4.8	622	4.1	14.4	<0.01	1.58	0.18	9.8	2	0.61	<5	<0.1	<0.02
EMMD097	74.14	metaandesite	991	638	14.9	67.4	769	118.6	85.2	0.7	1.34	2.83	10.2	13	0.03	16	0.1	0.13
EMMD097	174.1	metaandesite	26.6	21	21.7	16.3	448	5.1	2	<0.01	0.25	0.02	32.5	<1	0.02	8	0.1	<0.02
EMMD114	71	metaandesite	8.3	21	16.7	8.3	502	1.3	2.5	0.02	0.19	0.04	15.5	2	0.02	<5	<0.1	0.02
EMMD118	143.8	metaandesite	33.1	85	49.7	18.2	694	5.5	22.2	<0.01	0.06	0.06	29.3	1	<0.02	<5	<0.1	0.05
EMMD119	174.9	metaandesite	8.3	24	26.5	14.8	1155	17.5	1.4	<0.01	0.06	0.05	32.8	<1	<0.02	<5	<0.1	<0.02
EMMD126	104	metaandesite	41	14	48.6	14.4	1709	1.4	<0.2	<0.01	0.2	<0.02	52	2	0.08	<5	<0.1	<0.02
EMMD129	155	metaandesite	10.9	59	24.5	11.2	778	0.8	3.4	<0.01	0.08	0.04	13.8	2	0.02	<5	<0.1	<0.02
EMMD136	71.9	metaandesite	24.3	33	22.9	11.2	777	2.5	1.3	<0.01	0.16	0.05	11.7	3	0.09	<5	<0.1	<0.02
EMMD136	124	metaandesite	9.8	125	14.3	9.2	1443	2.1	6.3	<0.01	0.16	0.04	15.8	<1	<0.02	<5	<0.1	<0.02
EMMD136	215	metaandesite	6.7	33	14.8	5.4	2734	4.5	1.2	0.03	0.1	0.03	12.3	<1	0.06	<5	<0.1	0.02
EMMD136	267.5	metaandesite	2.4	436	18.1	273	215	78	229.8	<0.01	0.77	11.94	3.6	2	0.06	75	3.2	4.69
EMMD136	321	metaandesite	1.6	23	7	0.8	343	0.7	2.1	0.01	0.11	<0.02	25	<1	<0.02	<5	<0.1	0.03
EMMD167	180.3	metaandesite	7.7	32	17.2	8	2093	0.6	1.6	<0.01	0.09	0.03	28.2	<1	<0.02	<5	<0.1	0.02
EMMD167	234	metaandesite	53.6	64	46.1	41.6	1235	4.3	3.1	<0.01	0.08	0.05	12.5	1	<0.02	<5	0.2	<0.02
EMMD167	279.7	metaandesite	25.4	34	43.5	17.6	989	7.5	7.3	<0.01	0.13	0.05	14	3	<0.02	<5	<0.1	<0.02
EMMD182	91.7	metaandesite	2.3	28	3.8	1.2	577	0.6	1.3	0.04	0.1	0.04	15.9	3	0.02	<5	<0.1	0.03

Table B-2: Raw whole-rock data from ACME Labs

Hole ID	Depth	Lithology	Ge ppm	In ppm	Re ppb	Be ppm	Li ppm	Pd ppb	Pt ppb	Ba-XRF wt%	Cu-XRF wt%	F-XRF wt%
EMMD085	310.5	marble	0.7	0.23	128	1.2	12.6	*	<2	9.25	2.61	4.3
EMMD097	226.15	marble	0.2	0.21	43	0.7	38.9	*	<2	4.23	0.16	1.28
EMMD136	361.85	marble	<0.1	0.02	<1	0.1	9.3	<10	<2	N.A.	N.A.	0.3
EMMD182	239.75	marble	<0.1	0.07	37	0.1	11.6	<10	2	0.23	0.33	0.32
EMM017	154.3	metaandesite	<0.1	<0.02	<1	0.4	18.4	11	<2	N.A.	N.A.	0.09
EMM018	133	metaandesite	0.1	0.02	<1	0.5	28.8	<10	<2	N.A.	N.A.	0.11
EMM019	338	metaandesite	<0.1	<0.02	<1	0.2	9.9	<10	<2	N.A.	N.A.	0.08
EMM022	74.6	metaandesite	<0.1	<0.02	2	0.4	6.9	20	4	N.A.	N.A.	0.14
EMMD002	120.5	metaandesite	0.2	0.05	20	0.5	20	20	11	0.5	0.16	0.53
EMMD008	126	metaandesite	0.2	<0.02	1	1.7	10.9	13	<2	N.A.	N.A.	0.32
EMMD018	101	metaandesite	0.4	<0.02	<1	0.6	10.6	<10	9	N.A.	N.A.	0.32
EMMD041	154.75	metaandesite	0.1	<0.02	3	0.7	10.8	<10	3	0.01	0.04	0.1
EMMD042	171.2	metaandesite	0.3	<0.02	1	0.4	14	17	<2	N.A.	N.A.	0.15
EMMD043	169.9	metaandesite	<0.1	0.03	<1	0.5	8.7	19	<2	N.A.	N.A.	0.13
EMMD064	150	metaandesite	0.1	<0.02	<1	0.5	11	<10	<2	N.A.	N.A.	0.12
EMMD066	40	metaandesite	<0.1	<0.02	4	0.4	27.2	<10	8	N.A.	N.A.	0.34
EMMD066	123.6	metaandesite	<0.1	<0.02	<1	0.4	8	<10	5	N.A.	N.A.	0.16
EMMD066	176	metaandesite	<0.1	0.02	<1	0.6	2.1	17	<2	N.A.	N.A.	0.16
EMMD067	187	metaandesite	<0.1	<0.02	2	0.3	5.7	13	<2	N.A.	N.A.	0.16
EMMD074	195	metaandesite	<0.1	<0.02	<1	0.1	2.4	<10	<2	0.19	<0.01	0.03
EMMD075	116.2	metaandesite	0.1	0.02	5	0.9	21.4	<10	<2	0.55	0.03	0.29
EMMD077	81.7	metaandesite	<0.1	0.03	2	0.7	18.9	30	<2	N.A.	N.A.	0.61
EMMD077	162.4	metaandesite	0.2	<0.02	<1	0.2	13.2	<10	<2	0.29	0.01	0.25
EMMD085	366.8	metaandesite	<0.1	0.03	32	0.4	7.4	<10	<2	0.41	0.1	0.36
EMMD086	167.9	metaandesite	<0.1	0.07	<1	0.9	57.1	*	5	N.A.	N.A.	1.22
EMMD097	74.14	metaandesite	1	0.12	1	1	20.9	<10	<2	0.01	0.23	0.09
EMMD097	174.1	metaandesite	0.1	0.02	<1	0.4	12.2	<10	4	N.A.	N.A.	0.07
EMMD114	71	metaandesite	<0.1	<0.02	<1	0.3	4.1	<10	7	N.A.	N.A.	0.17
EMMD118	143.8	metaandesite	<0.1	<0.02	<1	0.5	16.2	<10	<2	N.A.	N.A.	0.09
EMMD119	174.9	metaandesite	0.2	<0.02	<1	0.7	22.7	21	<2	0.06	<0.01	0.11
EMMD126	104	metaandesite	0.1	0.02	2	0.4	25	<10	3	N.A.	N.A.	0.09
EMMD129	155	metaandesite	0.1	<0.02	<1	0.2	8	<10	<2	N.A.	N.A.	0.1
EMMD136	71.9	metaandesite	<0.1	<0.02	4	0.2	6.3	<10	<2	N.A.	N.A.	0.16
EMMD136	124	metaandesite	<0.1	0.03	<1	<0.1	2.7	<10	<2	N.A.	N.A.	0.16
EMMD136	215	metaandesite	<0.1	<0.02	2	0.2	3.2	<10	<2	N.A.	N.A.	0.18
EMMD136	267.5	metaandesite	<0.1	<0.02	<1	0.2	3.6	<10	<2	N.A.	N.A.	0.19
EMMD136	321	metaandesite	<0.1	<0.02	<1	0.2	2	<10	<2	N.A.	N.A.	0.13
EMMD167	180.3	metaandesite	<0.1	<0.02	<1	0.3	3.1	<10	<2	N.A.	N.A.	0.07
EMMD167	234	metaandesite	<0.1	<0.02	<1	<0.1	19.7	<10	<2	N.A.	N.A.	0.08
EMMD167	279.7	metaandesite	<0.1	<0.02	<1	0.6	11.9	<10	<2	N.A.	N.A.	0.15
EMMD182	91.7	metaandesite	<0.1	<0.02	<1	0.3	0.7	<10	<2	N.A.	N.A.	0.08

Table B-2: Raw whole-rock data from ACME Labs

Hole ID	Depth	Lithology	Wgt kg	SiO ₂ wt%	Al ₂ O ₃ wt%	Fe ₂ O ₃ * wt%	MgO wt%	CaO wt%	Na ₂ O wt%	K ₂ O wt%	TiO ₂ wt%	P ₂ O ₅ wt%	MnO wt%	Cr ₂ O ₃ wt%	Ba ppm	Sc ppm	Sum wt%	Cs ppm	Ga ppm
EMMD184	50	metaandesite	0.27	45.85	15.88	11.33	3.69	6.19	3.88	3.3	1.35	0.13	0.22	0.003	1322	17	99.64	9.6	22.5
EMMD184	150.1	metaandesite	0.19	50.47	16.01	16.22	1.93	1.92	4.9	2.16	1.62	0.15	0.21	0.012	3301	31	99.51	2.1	21
EMMD196	27.5	metaandesite	0.12	51.57	16.93	3.74	0.49	8.5	7.71	1.28	1.57	0.19	0.24	0.003	811	18	99.81	1.2	13.1
EMMD196	162	metaandesite	0.11	51.39	14.03	14.35	1.27	4.3	3.83	2.57	1.47	0.15	0.24	0.004	773	26	99.81	1.8	18.6
EMM023	153.1	metasiltstone	0.14	3.42	0.93	66.62	2.14	8.77	<0.01	0.37	0.05	0.61	0.99	<0.002	1279	2	88.35	1.1	3.3
EMMD008	93.50	metasiltstone	0.22	14.06	1.31	44.67	0.69	2.95	<0.01	<0.01	0.04	0.45	0.22	0.002	>50000	3	66.38	0.1	2.3
EMMD009	131.9	metasiltstone	0.12	56.77	11.77	8.27	5.58	3.87	3.21	2.16	0.67	0.65	0.05	0.007	514	10	99.78	0.8	15.5
EMMD009	182.3	metasiltstone	0.23	57.08	15.11	5.97	3.06	4.31	2.03	5.75	0.72	0.31	0.13	0.009	1367	14	99.67	3.6	23.2
EMMD0113	97.60	metasiltstone	0.21	26.15	0.98	48.95	2.03	3.39	0.02	0.18	0.08	0.56	0.8	<0.002	1704	3	98.03	0.5	4.7
EMMD086	105.90	metasiltstone	0.27	44.48	13.9	25.86	3.38	0.57	2	1.46	2.1	0.32	0.38	0.002	5065	23	99.13	0.5	23.7
EMMD086	194.9	metasiltstone	0.28	51.07	16.14	6.63	1.48	7.94	3.93	2.93	1.54	0.15	0.19	0.004	2136	24	99.6	0.9	22.5
EMMD097	128.5	metasiltstone	0.17	50.5	16.77	13.54	4.3	2.12	5.95	0.79	1.68	0.19	0.06	0.006	738	21	99.76	2.1	19.2
EMMD184	125.9	metasiltstone	0.23	42.36	10.27	20.49	0.91	4.71	0.21	2.2	0.94	0.58	5	0.004	21076	17	97.09	2.4	19.5
EMMD018	139	metatuff	0.14	55.46	13.27	10.62	3.94	3.9	3.75	1.41	1.35	0.1	0.14	0.005	527	25	99.78	1.5	19
EMMD066	53.6	metatuff	0.16	52.23	1.13	31.96	0.42	2.23	0.25	0.13	0.08	0.58	1.19	<0.002	2464	3	97.56	0.4	2.3
EMMD075	166	metatuff	0.15	43.26	17.15	21.5	3.7	0.95	2.36	4.77	2.58	0.3	0.17	0.003	7041	30	99	3.7	28.4
EMMD076	107	metatuff	0.12	45.57	13.42	11.36	3.65	7.01	5.93	1.23	1.38	0.13	0.58	0.005	1064	22	99.74	4.7	13.4
EMMD085	288.75	metatuff	0.32	30.89	12.17	32.31	4.02	3.5	0.4	3.51	1.07	0.37	0.13	0.002	2790	17	99.43	2.1	17.6
EMMD067	76	metavolcanic breccia	0.19	32.2	13.58	33.92	3.87	0.79	0.26	1.97	1.89	0.32	1.32	<0.002	13732	18	98.15	1.7	19.6
EMMD067	127.1	metavolcanic breccia	0.16	37.61	12.8	33.99	1.62	0.86	0.98	3.16	1.08	0.48	0.48	0.004	17885	15	97.38	2.8	17.6
EMMD074	105.5	metavolcanic breccia	0.17	19.62	7.91	60.88	2.3	1.53	0.75	1.64	0.85	0.69	0.12	0.003	807	9	99.66	0.9	20.2
EMMD075	39.4	metavolcanic breccia	0.13	32.76	17.1	35.78	2.5	0.53	1.93	3.77	1.47	0.33	0.03	0.005	6846	19	99.08	1	20.1
EMMD077	201.5	metavolcanic breccia	0.27	37.49	8.9	34.89	1.4	2.86	0.07	2.9	0.83	0.42	0.03	0.005	>50000	11	93.49	0.6	11.1
EMMD077	250.2	metavolcanic breccia	0.14	46.72	12.64	23.17	1.67	3.48	0.32	3.86	1.35	0.24	0.08	0.008	11042	21	98.62	0.9	24.1
EMMD085	344.1	metavolcanic breccia	0.25	14.72	3.56	45.65	1.23	8.37	0.02	1.15	0.31	0.63	0.05	0.007	>50000	5	77.08	0.2	7.9
EMMD086	48.4	metavolcanic breccia	0.23	42.12	15.5	23.83	3.25	0.78	0.17	3.87	1.43	0.27	0.12	0.002	9506	18	98.41	3.5	16.9
EMMD086	125	metavolcanic breccia	0.18	39.38	11.96	31.42	3.7	1.18	0.12	4.16	1.69	0.31	0.3	<0.002	9063	22	98.47	6.6	16.5
EMM022	167.1	psammite	0.22	23.29	9.31	43.74	3.98	7.95	0.14	0.49	0.81	0.63	0.41	0.007	11981	14	96.86	0.5	12.1
EMMD013	170.9	psammite	0.15	58.97	13.78	3.31	2.26	6.21	6.98	0.8	0.49	0.15	0.06	0.008	389	10	99.89	0.8	18.5

Table B-2: Raw whole-rock data from ACME Labs

Hole ID	Depth	Lithology	Hf ppm	Nb ppm	Rb ppm	Sn ppm	Sr ppm	Ta ppm	Th ppm	U ppm	V ppm	W ppm	Zr ppm	Y ppm	La ppm	Ce ppm	Pr ppm	Nd ppm	Sm ppm
EMMD184	50	metaandesite	4.7	9.1	160.2	2	71.1	0.7	12.3	3.7	200	1.2	186.5	25.1	34.1	66.2	7.25	25.6	4.53
EMMD184	150.1	metaandesite	4.9	8	81.2	4	24.5	0.5	9.2	4.9	265	6.4	174.1	21.1	33.9	57.1	6.41	25.1	5.09
EMMD196	27.5	metaandesite	5.7	10.1	43.9	2	107.2	0.8	14.4	3.6	166	2	216.1	28	54.4	94.6	11.01	41.3	6.7
EMMD196	162	metaandesite	4.7	7.7	107.5	3	19.8	0.6	10.4	2.4	244	2.5	178.2	31.7	29.8	58.3	6.83	25.7	5.68
EMM023	153.1	metasiltstone	0.4	11.9	16.2	22	181.8	0.1	1.9	45.1	43	6.4	15.5	15	361.5	355.2	24.2	63.5	8.76
EMMD008	93.50	metasiltstone	0.6	2.6	<0.1	124	1233.5	1	1.3	187.2	84	218	5.2	12.6	776.3	662.4	41.84	94.5	9
EMMD009	131.9	metasiltstone	4.1	12	53.2	1	23.7	0.8	13.8	13.1	187	11.5	142.3	18.9	26.4	48.6	5.55	19.8	4.07
EMMD009	182.3	metasiltstone	4.7	20.5	192	2	61.9	1.1	15	10.7	182	5.6	173.3	25.2	40	78.5	9.12	33	6.01
EMMD0113	97.60	metasiltstone	0.3	2.5	10.8	15	63.8	<0.1	0.8	60.2	92	44	13.2	14.4	42	41.9	3.22	9.7	1.85
EMMD086	105.90	metasiltstone	7.3	13.8	37.7	13	25.5	1.2	16.1	17.7	299	24.6	273.9	31.2	65.7	95.3	9.1	31	5.95
EMMD086	194.9	metasiltstone	5.1	8.4	132	9	36.1	0.8	9.7	5	204	11.8	189.9	22.3	16.7	26.5	2.69	9.8	2.37
EMMD097	128.5	metasiltstone	6	11.5	39.5	1	53.4	0.9	14.1	4.2	225	2.1	228.9	31	10	21.1	2.57	10.2	2.6
EMMD184	125.9	metasiltstone	3.3	10.5	73.6	65	132.1	0.5	12.6	42.8	162	25.7	125.7	48.7	202.6	258.6	21.74	68.2	10.42
EMMD018	139	metatuff	4.2	7.5	45.5	2	23	0.6	9.7	3.2	234	3	159.6	23.4	27.1	52	6.05	23	4.77
EMMD066	53.6	metatuff	0.4	8.5	6.1	121	49.9	<0.1	2.5	91.1	76	13.1	13.4	35.8	515.6	489.8	34.69	86.9	11.3
EMMD075	166	metatuff	9.4	17.9	184.1	17	59.6	1.5	20.2	12.2	361	14.1	346	23.4	61.3	82.7	8.11	28.8	5.22
EMMD076	107	metatuff	4.4	6.8	63.7	3	70.9	0.5	9	4	226	4.9	160.5	26.3	20.7	33	3.55	13.4	2.71
EMMD085	288.75	metatuff	4.1	9.6	92.1	49	32.5	0.5	9.2	30	197	66.9	154.5	22.8	70.2	83.8	7.24	22.5	3.74
EMMD067	76	metavolcanic breccia	6.7	12.9	48.9	33	35.7	1	15	25.4	277	37.5	252.6	33.2	48.2	56.5	4.95	16.7	2.99
EMMD067	127.1	metavolcanic breccia	4.1	8.5	91.4	41	53.3	0.5	12.2	34.1	222	14.9	149.6	31	99.2	122.1	10.37	32.9	5.3
EMMD074	105.5	metavolcanic breccia	2.2	5.8	33.7	9	33	0.5	11.3	3.4	572	4.5	78.4	28.9	84.3	124.3	11.39	38.6	6.01
EMMD075	39.4	metavolcanic breccia	5.3	10.6	99.2	26	14.9	0.8	14.9	23.1	282	33.1	189.9	22	12.5	20.1	2.16	8.6	1.99
EMMD077	201.5	metavolcanic breccia	2.9	9.3	57.4	58	1311.2	1.2	10.4	103.9	191	199.9	109.8	34.4	293.7	286.6	21.62	58.9	8.27
EMMD077	250.2	metavolcanic breccia	4	8.6	86.6	30	23.6	0.4	7.3	37.1	208	40	154.2	20	96	110.7	9.37	29.5	4.78
EMMD085	344.1	metavolcanic breccia	1	7.7	27.1	57	1482.7	0.8	5.7	144.2	158	82.5	46.8	26.6	348.2	338.1	24.04	64.1	7.74
EMMD086	48.4	metavolcanic breccia	5.5	11	125	21	46.9	0.9	13.8	48.5	200	34.9	202.4	32.9	67.9	86.1	7.86	23.8	4.44
EMMD086	125	metavolcanic breccia	6	12.4	198.8	29	32	0.9	14.7	46.6	249	9.5	218.2	34.5	147.9	163.5	13.67	42.7	7.23
EMM022	167.1	psammite	3	15.8	15.2	144	198.5	0.4	8.9	118.6	175	15	111.4	34.4	617.1	613.4	44.04	106.8	11.57
EMMD013	170.9	psammite	4.3	7.4	48.6	1	45.3	0.8	13.9	2.4	56	1.5	153	9.6	8.9	14.9	1.77	7.3	1.61

Table B-2: Raw whole-rock data from ACME Labs

Hole ID	Depth	Lithology	Eu ppm	Gd ppm	Tb ppm	Dy ppm	Ho ppm	Er ppm	Tm ppm	Yb ppm	Lu ppm	Ni ppm	LOI wt%	Total C wt%	Total S wt%	Mo ppm	Cu ppm	Pb ppm
EMMD184	50	metaandesite	1.39	4.8	0.76	4.47	0.9	2.7	0.39	2.53	0.37	39	7.8	1.37	0.05	0.08	446.36	2.21
EMMD184	150.1	metaandesite	1.44	4.98	0.75	4.01	0.74	2.31	0.32	2.14	0.35	36	3.9	0.69	<0.01	0.16	42.74	1.08
EMMD196	27.5	metaandesite	1.7	6.52	0.96	5.35	1.08	3.06	0.46	3.06	0.45	10	7.6	1.82	<0.01	0.62	9.3	3
EMMD196	162	metaandesite	1.5	5.94	1.01	5.78	1.1	3.08	0.44	2.8	0.43	32	6.2	1.36	<0.01	1.02	64.75	1.87
EMM023	153.1	metasiltstone	8.87	8.57	0.92	3.94	0.63	1.12	0.15	0.84	0.07	43	4.4	2.98	3.98	109.46	3478.03	26.96
EMMD008	93.50	metasiltstone	4.7	10.68	0.82	3.2	0.58	1.37	0.22	1.18	0.14	15	2.7	0.5	7.24	45.32	>10000.00	182.85
EMMD009	131.9	metasiltstone	0.66	4.13	0.63	3.52	0.68	1.75	0.25	1.55	0.22	76	6.7	0.84	2.44	10.14	65.87	3.63
EMMD009	182.3	metasiltstone	0.85	5.34	0.8	4.54	0.86	2.52	0.39	2.45	0.36	42	5.2	1.11	1.07	4.5	329.34	2.61
EMMD0113	97.60	metasiltstone	3	2.78	0.5	3.13	0.56	1.27	0.13	0.78	0.1	44	14.9	4.41	2.45	80.4	>10000.00	48.74
EMMD086	105.90	metasiltstone	1.94	6.01	1.05	6.16	1.28	3.71	0.62	3.98	0.6	25	4.7	0.58	0.48	15.13	1018.82	2.12
EMMD086	194.9	metasiltstone	0.94	2.89	0.58	3.88	0.86	2.62	0.42	2.77	0.42	<10	7.6	1.75	0.08	0.96	614.51	0.75
EMMD097	128.5	metasiltstone	0.6	3.38	0.72	5.15	1.19	3.51	0.5	3.36	0.51	30	3.8	0.42	<0.01	0.72	8.82	1.46
EMMD184	125.9	metasiltstone	4.32	10.6	1.5	8.43	1.84	4.93	0.7	4.05	0.49	23	9.4	2.09	0.07	3.37	3280.01	5.34
EMMD018	139	metatuff	1.34	4.58	0.79	4.43	0.91	2.72	0.39	2.49	0.39	49	5.8	0.91	0.05	0.46	175.64	1.41
EMMD066	53.6	metatuff	12.54	11.82	1.42	6.89	1.16	2.54	0.3	1.71	0.21	19	7.4	1.74	3.9	79.9	>10000.00	66.07
EMMD075	166	metatuff	1.8	5.17	0.72	4.1	0.9	3.22	0.57	3.98	0.63	25	2.3	0.1	0.02	1.51	146.95	1.45
EMMD076	107	metatuff	1.01	3.61	0.67	4.14	0.96	2.69	0.41	2.54	0.39	55	9.5	2.36	0.22	1.87	85.68	1.31
EMMD085	288.75	metatuff	1.81	4.19	0.66	3.97	0.77	2.27	0.34	2.22	0.37	41	11	2.58	2.2	49.34	460.33	3.99
EMMD067	76	metavolcanic breccia	2.02	3.88	0.71	4.99	1.13	3.73	0.57	3.67	0.54	37	8	1.42	1.12	88.07	806.14	4.33
EMMD067	127.1	metavolcanic breccia	2.61	5.76	0.82	4.92	1.06	3.23	0.5	3.19	0.52	32	4.3	0.77	1.84	56.13	3928.8	4.94
EMMD074	105.5	metavolcanic breccia	0.9	6.33	0.88	4.76	0.98	2.89	0.41	2.68	0.4	72	3.4	0.04	5.35	1.64	505.74	2.94
EMMD075	39.4	metavolcanic breccia	1.14	2.7	0.5	3.45	0.74	2.58	0.37	2.53	0.39	43	2.9	0.02	1.13	32.47	57.45	1.96
EMMD077	201.5	metavolcanic breccia	7	8.13	1.1	6.21	1.37	4.12	0.65	4.43	0.65	30	3.7	0.08	4.46	100.9	3798.5	18.67
EMMD077	250.2	metavolcanic breccia	3.01	4.8	0.72	3.92	0.74	2.11	0.29	2.05	0.29	31	5.1	0.72	1.89	29.65	50.77	4.56
EMMD085	344.1	metavolcanic breccia	7.92	8.02	0.97	5.22	1.01	3.12	0.43	2.64	0.36	31	1.4	0.39	8.58	157.11	>10000.00	22.37
EMMD086	48.4	metavolcanic breccia	2.13	5.28	0.88	5.44	1.08	3.18	0.48	3.19	0.48	59	7.1	0.86	0.67	30.89	3028.61	9.51
EMMD086	125	metavolcanic breccia	4.15	7.13	1.11	6.28	1.29	3.63	0.55	3.56	0.55	41	4.2	0.35	2.45	83.82	2507.53	7.03
EMM022	167.1	psammite	13.07	10.53	1.22	6.88	1.36	3.79	0.57	3.25	0.44	69	6.1	0.88	3.76	343.45	>10000.00	55.96
EMMD013	170.9	psammite	0.67	2.01	0.31	1.75	0.34	1.03	0.14	1.05	0.17	24	6.9	1.37	0.09	0.72	38.04	1.55

Table B-2: Raw whole-rock data from ACME Labs

Hole ID	Depth	Lithology	Zn ppm	Ag ppb	Ni ppm	Co ppm	Mn ppm	As ppm	Au ppb	Cd ppm	Sb ppm	Bi ppm	Cr ppm	B ppm	Tl ppm	Hg ppb	Se ppm	Te ppm
EMMD184	50	metaandesite	86.9	86	34.2	27.6	1391	2.7	5.3	0.02	0.25	0.06	12.7	3	0.77	<5	0.2	<0.02
EMMD184	150.1	metaandesite	21.9	27	32.5	11.6	1141	0.8	0.8	0.02	0.25	0.03	55.7	2	0.09	<5	<0.1	0.05
EMMD196	27.5	metaandesite	10.6	16	9.6	4.1	1391	1.5	0.7	<0.01	0.3	0.02	16.4	<1	0.03	<5	<0.1	<0.02
EMMD196	162	metaandesite	4	27	28.8	13.3	1619	8.2	1.5	<0.01	0.27	0.03	21.3	2	0.05	<5	<0.1	0.03
EMM023	153.1	metasiltstone	61	5266	32.7	219.8	7478	170.4	123.7	<0.01	7.83	21.66	1.3	1	1.09	94	1.1	0.47
EMMD008	93.50	metasiltstone	68.4	11728	11.9	256.8	1665	303	441.2	0.05	3.08	11.86	1.1	4	0.04	62	1.1	0.91
EMMD009	131.9	metasiltstone	7	275	70.9	58.5	375	158.1	17	<0.01	0.27	2.02	42.4	2	<0.02	6	0.8	0.27
EMMD009	182.3	metasiltstone	13.7	336	39.7	29.6	936	114.2	0.6	0.02	0.53	0.16	38.4	1	0.28	<5	0.7	0.23
EMMD0113	97.60	metasiltstone	14	1797	36.3	280.1	5799	73	376.3	0.03	0.4	3.62	1.4	5	0.22	<5	1.2	0.34
EMMD086	105.90	metasiltstone	19.8	178	30.3	65.4	2541	54.7	26.4	<0.01	0.33	0.69	12.6	<1	<0.02	11	0.4	0.05
EMMD086	194.9	metasiltstone	6.1	49	7.3	3.2	1420	0.8	3.7	<0.01	0.09	0.02	14	<1	0.03	<5	<0.1	<0.02
EMMD097	128.5	metasiltstone	113	17	35.5	23.3	289	1	3.5	<0.01	0.49	<0.02	39.2	<1	0.15	<5	<0.1	<0.02
EMMD184	125.9	metasiltstone	7.4	76	25.6	104.4	>10000	42.3	5.7	0.11	1.11	2.46	12.9	9	0.23	9	<0.1	0.27
EMMD018	139	metatuff	23	346	44.5	24.5	927	1.6	6.2	0.01	0.05	<0.02	27.9	<1	0.1	<5	0.1	<0.02
EMMD066	53.6	metatuff	16.6	10522	21.6	431.1	8671	291.3	423	<0.01	4.07	21.32	3.3	1	0.3	131	2.1	1.26
EMMD075	166	metatuff	18.2	51	27.4	9.8	201	2.8	1.7	0.02	0.5	0.04	13.9	<1	0.38	<5	<0.1	<0.02
EMMD076	107	metatuff	41.1	70	53.9	21.4	4142	6.2	2.3	0.06	0.39	0.26	28.9	1	0.44	9	<0.1	<0.02
EMMD085	288.75	metatuff	20.2	532	32.1	238.4	907	59.9	43.2	0.02	1.07	2.96	8.4	4	0.07	17	0.2	0.3
EMMD067	76	metavolcanic breccia	50.9	423	36.6	218	8829	174.5	25.8	<0.01	0.36	5.76	8.2	3	0.11	7	0.1	0.03
EMMD067	127.1	metavolcanic breccia	13.7	648	31.4	266.6	3494	180.2	130.3	0.03	0.88	2.78	19.4	5	0.58	41	0.8	0.19
EMMD074	105.5	metavolcanic breccia	15.8	152	62.2	90.4	595	79	7.5	0.03	0.43	2.18	9.1	2	0.09	11	1.4	0.35
EMMD075	39.4	metavolcanic breccia	9.1	179	38.5	135.3	214	61.3	24.7	0.02	0.78	0.82	19.8	2	0.06	<5	0.3	0.07
EMMD077	201.5	metavolcanic breccia	9.6	1952	28	250.4	246	224.1	154.4	0.04	5.98	24.81	13.8	2	0.14	23	0.6	3.4
EMMD077	250.2	metavolcanic breccia	3.6	436	28.3	138.7	619	145.7	86	0.05	1.99	7.65	34.4	2	0.08	34	0.2	2.66
EMMD085	344.1	metavolcanic breccia	10.9	2267	21.9	324.1	404	186.5	462.2	<0.01	4	12	4.8	3	0.18	37	2	0.87
EMMD086	48.4	metavolcanic breccia	22.9	302	40.3	164.5	877	54.8	99.7	0.08	0.47	2.04	8.3	3	0.35	<5	0.3	0.19
EMMD086	125	metavolcanic breccia	22.7	630	36.5	311.1	1703	211.5	93.2	0.08	1.47	3.52	8.7	1	0.77	45	0.6	0.5
EMM022	167.1	psammite	380.9	7857	52.5	321.7	2844	215.3	246.8	<0.01	4.39	18.63	34.5	8	0.29	43	1.3	0.85
EMMD013	170.9	psammite	5.1	42	29	12.2	434	2.9	4.3	<0.01	0.1	0.08	53.3	<1	0.06	<5	<0.1	<0.02

Table B-2: Raw whole-rock data from ACME Labs

Hole ID	Depth	Lithology	Ge ppm	In ppm	Re ppb	Be ppm	Li ppm	Pd ppb	Pt ppb	Ba-XRF wt%	Cu-XRF wt%	F-XRF wt%
EMMD184	50	metaandesite	0.1	0.03	<1	0.4	22	<10	<2	N.A.	N.A.	0.21
EMMD184	150.1	metaandesite	<0.1	<0.02	1	0.3	10.7	17	<2	N.A.	N.A.	0.1
EMMD196	27.5	metaandesite	<0.1	<0.02	1	<0.1	3.1	<10	<2	N.A.	N.A.	0.05
EMMD196	162	metaandesite	<0.1	<0.02	<1	0.3	3.2	<10	2	N.A.	N.A.	0.11
EMM023	153.1	metasiltstone	1	0.25	4	0.1	4.8	27	<2	0.15	0.34	0.77
EMMD008	93.50	metasiltstone	1	0.83	15	0.5	2.3	12	<2	17.13	1.52	0.3
EMMD009	131.9	metasiltstone	0.3	<0.02	<1	0.5	23.9	<10	<2	0.05	0.01	0.22
EMMD009	182.3	metasiltstone	0.1	<0.02	2	1.1	15.8	<10	3	N.A.	N.A.	0.21
EMMD0113	97.60	metasiltstone	0.6	0.2	49	1.7	17.9	20	<2	0.17	1.65	0.18
EMMD086	105.90	metasiltstone	0.2	<0.02	8	0.5	19.2	16	<2	N.A.	N.A.	0.23
EMMD086	194.9	metasiltstone	<0.1	0.03	3	0.2	4.9	<10	5	N.A.	N.A.	0.2
EMMD097	128.5	metasiltstone	0.2	<0.02	<1	0.2	22.7	17	3	N.A.	N.A.	0.11
EMMD184	125.9	metasiltstone	0.2	0.04	2	0.2	9.9	<10	5	2.23	0.34	0.3
EMMD018	139	metatuff	0.2	0.02	<1	0.6	12.8	20	<2	N.A.	N.A.	0.12
EMMD066	53.6	metatuff	0.5	1.61	35	0.6	8.2	44	<2	0.28	2.17	0.15
EMMD075	166	metatuff	0.1	<0.02	<1	0.4	33.1	94	4	N.A.	N.A.	0.6
EMMD076	107	metatuff	0.3	<0.02	<1	0.7	13.8	<10	<2	0.11	0.02	0.32
EMMD085	288.75	metatuff	0.1	0.04	20	1	15.3	13	<2	0.29	0.05	0.38
EMMD067	76	metavolcanic breccia	0.1	0.06	20	0.6	23.2	29	6	1.42	0.08	0.3
EMMD067	127.1	metavolcanic breccia	0.2	0.05	57	0.9	28.2	23	<2	1.88	0.38	0.49
EMMD074	105.5	metavolcanic breccia	0.3	0.04	<1	0.4	18.3	<10	<2	0.09	0.06	0.4
EMMD075	39.4	metavolcanic breccia	<0.1	<0.02	11	0.3	12.4	32	<2	0.75	0.01	0.4
EMMD077	201.5	metavolcanic breccia	0.2	0.08	35	0.7	12.6	35	<2	5.07	0.36	1.52
EMMD077	250.2	metavolcanic breccia	0.1	<0.02	15	0.3	13.6	58	2	1.14	0.01	0.37
EMMD085	344.1	metavolcanic breccia	0.5	0.21	64	1.3	12.9	66	<2	8.87	1.59	4.07
EMMD086	48.4	metavolcanic breccia	0.1	0.08	14	0.4	35.9	23	<2	1.05	0.31	0.68
EMMD086	125	metavolcanic breccia	0.2	0.08	37	0.3	30.3	80	<2	0.96	0.26	0.73
EMM022	167.1	psammite	1.1	0.4	19	2.1	47.1	*	<2	1.21	1.02	3.33
EMMD013	170.9	psammite	0.2	<0.02	<1	<0.1	6	<10	<2	0.04	<0.01	0.14

Table B-3: Whole-rock data with CLR transform (unitless)

Hole ID	Depth	Lithology	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃ *	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	Ba	F	Sc	Cs	Ga	Hf	Nb	Rb	Sn	Sr	Ta
EMM018	87	carbonaceous schist	9.98	8.66	7.64	6.50	4.80	3.89	7.43	5.68	4.19	3.28	4.58	-0.41	-1.22	-0.16	-1.67	-0.53	1.94	-1.97	-0.12	-3.36
EMM019	126.8	carbonaceous schist	9.85	8.40	7.73	7.15	7.41	6.23	7.06	5.56	4.16	2.94	4.11	-0.62	-1.60	-0.46	-1.76	-0.42	1.53	-2.29	0.16	-3.61
EMMD097	269	carbonaceous schist	9.78	8.67	8.06	6.41	7.38	7.49	6.88	6.31	4.14	4.41	3.20	-0.02	-3.02	-0.28	-1.54	-0.97	0.79	-2.66	1.09	-3.58
EMMD117	140.8	carbonaceous schist	10.40	8.99	6.85	6.23	5.20	6.26	7.75	6.00	4.27	3.66	4.27	-0.41	-2.13	-0.13	-1.16	-0.40	1.99	-1.95	-0.13	-2.95
EMMD167	105.7	carbonaceous schist	9.60	8.17	7.98	6.90	6.10	2.90	6.89	5.47	4.09	3.07	3.90	-0.88	-2.19	-0.93	-1.96	-1.19	1.26	-2.26	-1.01	-3.87
EMMD167	127	carbonaceous schist	9.47	8.62	7.56	6.59	6.05	3.36	7.54	5.87	3.53	4.03	4.40	-0.50	-1.64	-0.46	-1.65	-0.97	1.99	-2.03	-1.13	-3.46
EMM008	93.1	diorite	10.20	8.90	8.78	8.08	8.32	7.77	6.76	6.66	3.75	3.22	2.37	0.76	-1.65	0.05	-1.80	-0.54	0.85	-2.93	2.02	-3.62
EMMD077	37.65	diorite	10.26	9.02	8.94	7.87	7.14	7.99	4.92	6.54	4.53	0.88	4.10	0.27	-4.52	0.22	-1.40	-0.69	-0.69	-1.81	0.72	-3.26
EMMD008	60.5	discordant breccia	10.11	8.67	8.57	7.90	7.73	7.72	6.38	5.51	4.10	2.44	5.10	-0.67	-2.66	-0.27	-1.78	-0.89	1.14	-1.68	0.12	-3.29
EMMD013	151	discordant breccia	9.61	8.06	7.00	6.77	8.45	6.85	6.85	4.75	4.32	3.43	4.03	-1.38	-2.36	-0.75	-2.43	-1.25	1.15	-2.77	0.98	-3.97
EMMD0153	306.5	discordant breccia	8.99	7.52	8.65	7.00	8.14	4.51	6.14	5.02	4.33	3.95	3.67	-1.14	-3.93	-1.41	-2.79	-2.18	0.39	-1.22	0.16	-4.91
EMMD030	96.2	discordant breccia	10.45	9.07	7.87	5.60	9.31	8.53	4.47	5.86	4.47	0.52	3.37	-0.42	-4.92	0.04	-1.39	-0.51	-0.51	-1.52	1.62	-2.97
EMMD077	290	discordant breccia	9.65	8.26	9.59	6.18	7.82	7.40	5.97	5.78	5.16	3.08	3.62	-0.62	-5.48	-0.62	-2.22	-1.31	-0.04	-1.57	0.41	-4.38
EMMD078	89	discordant breccia	10.07	8.76	8.84	7.56	6.87	7.08	6.58	6.40	4.20	4.17	4.38	0.14	-3.63	-0.07	-1.45	-0.84	0.62	-1.32	0.45	-3.34
EMMD085	56	discordant breccia	10.63	8.42	7.76	5.79	9.75	5.04	8.25	6.12	4.98	3.46	3.25	-0.51	-4.07	-0.83	-0.14	-0.39	2.14	-1.76	1.48	-2.97
EMMD085	87.3	discordant breccia	10.11	8.73	8.52	7.86	8.01	5.87	8.02	5.61	4.30	3.42	4.07	-0.71	-3.93	-0.20	-1.43	-0.67	1.72	-1.92	1.10	-3.12
EMMD085	147.3	discordant breccia	10.38	9.10	8.42	7.47	7.90	7.91	7.71	5.85	4.48	3.48	3.85	-0.12	-5.14	0.09	-1.61	-0.58	1.64	-1.73	0.86	-3.06
EMMD085	161	discordant breccia	10.22	8.86	8.58	7.25	7.89	8.01	6.47	5.71	4.34	2.09	3.58	-0.49	-5.97	-0.17	-1.72	-0.76	0.14	-2.28	0.95	-3.20
EMMD085	295	discordant breccia	9.63	8.28	8.90	6.51	5.58	3.22	7.23	5.86	3.85	5.02	4.97	-0.63	-3.57	-0.65	-2.07	-1.17	1.17	0.43	-0.88	-3.97
EMMD085	386.2	discordant breccia	9.80	8.37	8.72	7.87	7.34	6.91	5.07	5.51	4.30	1.97	4.14	-0.81	-4.22	-0.13	-1.48	-0.89	-1.06	-1.35	-0.45	-3.30
EMMD085	393.2	discordant breccia	10.05	8.51	7.62	6.60	7.58	6.09	7.61	5.46	4.22	3.85	4.11	-0.56	-3.01	-0.11	-1.30	-0.89	1.73	-1.07	0.05	-3.38
EMMD114	198.4	discordant breccia	10.46	9.24	8.70	5.68	6.82	8.41	6.64	6.79	4.68	3.52	3.99	-0.33	-4.02	-0.05	-1.11	-0.53	1.02	-1.43	1.29	-3.17
EMMD161	105	discordant breccia	10.54	9.13	8.53	7.75	8.46	8.41	5.67	5.94	4.71	1.28	4.64	-0.27	-3.18	0.08	-1.54	-0.57	0.63	-1.98	0.66	-3.18
EMDT203	102.8	marble	8.19	4.80	8.83	4.18	8.33	0.35	2.14	1.74	5.03	8.77	7.76	-4.25	-6.56	-4.95	-4.25	-2.37	-3.78	1.24	4.88	-3.03
EMM018	175.5	marble	8.21	7.27	8.40	6.26	7.25	4.85	5.13	4.76	3.95	6.68	4.27	-2.04	-3.94	-2.30	-2.99	-2.13	-0.91	-1.08	2.62	-4.48
EMMD001	117.5	marble	9.35	6.64	10.76	6.46	7.41	2.52	2.92	4.53	6.45	2.09	4.66	-2.09	-5.78	-1.19	-3.29	-0.51	-3.29	0.62	0.08	-5.78
EMMD001	207.9	marble	8.15	5.43	8.88	4.36	7.54	3.79	2.37	2.88	4.72	7.39	7.04	-3.34	-7.03	-3.63	-4.72	-1.32	-3.63	0.11	3.27	-4.95
EMMD007	110.2	marble	8.24	6.21	9.47	6.03	7.98	4.50	3.62	3.46	5.56	5.55	6.49	-2.93	-6.62	-2.99	-3.85	-1.34	-2.40	0.78	3.14	-4.83
EMMD013	101.6	marble	8.65	5.88	8.86	5.61	7.75	5.21	3.20	3.12	4.44	4.75	6.88	-2.88	-6.97	-2.52	-4.20	-1.92	-2.94	0.38	2.29	-6.28
EMMD0136	170	marble	8.17	7.29	9.63	6.13	7.31	2.83	6.03	5.05	4.35	4.72	4.29	-1.23	-3.94	-1.14	-3.08	-1.70	0.17	-0.19	0.24	-4.92
EMMD0136	362.2	marble	8.43	7.36	8.62	5.96	8.05	2.04	6.12	4.34	5.63	3.22	4.12	-2.00	-4.87	-1.04	-2.51	-1.79	0.00	-0.86	0.29	-4.46
EMMD018	60.9	marble	9.78	6.00	10.33	5.99	8.16	2.85	1.06	3.14	6.04	2.14	4.24	-2.85	-5.85	-2.67	-4.46	-0.28	-5.85	0.84	1.80	-5.85
EMMD043	116.9	marble	7.39	6.08	8.91	6.12	7.70	2.76	3.75	3.29	3.59	6.10	6.75	-2.21	-3.46	-2.31	-4.66	-2.31	-1.77	0.64	2.42	-5.07
EMMD052	314.5	marble	7.76	6.65	9.75	8.41	10.24	3.47	4.85	2.08	3.47	3.86	3.69	-3.22	-3.73	-1.78	-4.13	-3.73	-1.19	-1.42	2.97	-5.52
EMMD060	150.5	marble	8.19	6.99	8.87	5.47	6.77	3.61	5.79	4.60	4.70	5.43	5.93	-2.01	-5.13	-1.87	-3.38	-2.06	-0.34	-0.28	0.84	-5.42
EMMD066	100.5	marble	7.74	6.37	8.24	5.28	7.64	5.25	3.65	4.17	4.49	3.91	3.92	-2.34	-4.93	-2.49	-3.63	-2.02	-2.01	0.17	0.89	-5.11
EMMD075	192.5	marble	7.75	6.21	9.39	6.19	8.05	0.09	2.16	3.26	4.91	3.46	7.12	-2.22	-4.74	-2.30	-4.52	-1.92	-2.80	0.57	1.12	-3.56

*Total Fe reported as Fe₂O₃

Values are unitless

Table B-3: Whole-rock data with CLR transform (unitless)

Hole ID	Depth	Lithology	Th	U	V	W	Zr	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
EMM018	87	carbonaceous schist	-0.48	-1.85	1.70	-1.53	1.90	-0.08	-0.22	0.33	-1.84	-0.60	-2.15	-3.62	-2.08	-3.70	-1.87	-3.45	-2.32	-4.20	-2.32	-4.18
EMM019	126.8	carbonaceous schist	-0.68	-1.86	1.31	-2.29	1.81	-0.13	0.26	0.96	-1.21	0.07	-1.56	-3.29	-1.74	-3.54	-1.88	-3.51	-2.42	-4.33	-2.50	-4.33
EMMD097	269	carbonaceous schist	-0.77	-1.81	2.19	-1.94	2.09	0.30	-0.11	0.59	-1.56	-0.24	-1.72	-3.02	-1.59	-3.28	-1.43	-3.02	-1.94	-3.90	-2.06	-3.99
EMMD117	140.8	carbonaceous schist	-0.12	-1.56	1.62	1.18	2.43	0.52	1.61	2.22	0.00	1.25	-0.52	-2.09	-0.76	-2.81	-1.17	-2.87	-1.80	-3.72	-1.91	-3.78
EMMD167	105.7	carbonaceous schist	-0.87	-2.12	1.17	-1.96	1.65	-0.18	0.27	0.92	-1.25	0.05	-1.71	-3.44	-1.80	-3.64	-1.92	-3.54	-2.44	-4.47	-2.60	-4.54
EMMD167	127	carbonaceous schist	-0.56	-1.41	1.87	-1.53	1.99	0.14	0.58	1.18	-0.97	0.33	-1.47	-3.30	-1.65	-3.51	-1.69	-3.33	-2.18	-4.15	-2.27	-4.08
EMM008	93.1	diorite	-2.01	-2.67	2.83	-3.62	1.71	0.27	-0.55	0.12	-1.89	-0.38	-1.68	-2.53	-1.56	-3.19	-1.37	-2.97	-1.96	-3.85	-1.94	-3.80
EMMD077	37.65	diorite	-0.73	-1.95	2.45	-0.06	2.20	0.36	0.21	0.92	-1.20	0.18	-1.29	-2.54	-1.31	-3.09	-1.37	-2.90	-1.79	-3.73	-1.84	-3.71
EMMD008	60.5	discordant breccia	-0.56	-1.19	1.81	-1.48	1.84	-0.70	0.83	1.28	-1.01	0.18	-1.66	-3.35	-1.96	-4.09	-2.42	-4.17	-2.99	-4.90	-2.91	-4.78
EMMD013	151	discordant breccia	-0.98	-1.39	1.04	-2.47	1.14	-0.21	0.38	1.02	-1.15	0.12	-1.61	-3.76	-1.77	-3.58	-1.85	-3.57	-2.53	-4.40	-2.56	-4.46
EMMD153	306.5	discordant breccia	-1.56	-0.47	1.23	-0.79	0.76	-0.40	1.09	1.26	-1.17	-0.02	-1.85	-2.65	-1.87	-3.79	-2.05	-3.69	-2.66	-4.60	-2.77	-4.70
EMMD030	96.2	discordant breccia	-0.07	-1.11	1.62	-1.18	2.16	0.29	1.43	1.93	-0.28	0.99	-0.83	-2.27	-1.02	-3.06	-1.34	-3.00	-1.91	-3.86	-2.09	-3.93
EMMD077	290	discordant breccia	-1.14	0.42	2.20	-0.69	1.41	-0.63	1.57	1.79	-0.65	0.53	-1.34	-2.12	-1.50	-3.58	-2.07	-3.87	-2.95	-4.89	-3.06	-5.01
EMMD078	89	discordant breccia	-0.66	-2.12	2.36	0.32	2.19	-0.10	0.78	1.15	-1.05	0.27	-1.33	-2.24	-1.31	-3.21	-1.63	-3.33	-2.30	-4.26	-2.35	-4.11
EMMD085	56	discordant breccia	-0.06	-0.81	1.49	-1.50	3.53	0.67	0.38	1.04	-1.08	0.32	-1.24	-2.62	-1.13	-2.86	-1.06	-2.67	-1.62	-3.51	-1.61	-3.45
EMMD085	87.3	discordant breccia	-0.39	-0.60	1.55	-2.27	2.17	-0.04	0.44	1.10	-1.05	0.27	-1.48	-2.99	-1.58	-3.43	-1.72	-3.39	-2.36	-4.29	-2.49	-4.36
EMMD085	147.3	discordant breccia	-0.12	-1.37	1.95	-1.58	1.94	0.22	0.53	1.20	-0.94	0.42	-1.30	-2.91	-1.40	-3.30	-1.51	-3.13	-2.03	-3.97	-2.17	-4.07
EMMD085	161	discordant breccia	-0.30	-1.29	1.76	-2.51	1.88	0.08	0.97	1.60	-0.58	0.76	-1.01	-2.86	-1.26	-3.25	-1.56	-3.28	-2.28	-4.25	-2.34	-4.21
EMMD085	295	discordant breccia	-1.98	-0.54	1.60	0.67	1.53	-0.90	-1.00	-0.73	-3.07	-1.87	-3.18	-3.82	-2.91	-4.63	-2.91	-4.28	-3.22	-5.02	-3.04	-4.77
EMMD085	386.2	discordant breccia	-0.65	-0.75	1.65	-1.23	2.16	-0.42	0.79	1.33	-0.85	0.41	-1.34	-2.84	-1.51	-3.56	-2.02	-3.78	-2.78	-4.61	-2.81	-4.65
EMMD085	393.2	discordant breccia	-0.99	-0.59	0.84	-0.96	2.33	-0.10	-0.31	0.27	-1.88	-0.57	-2.15	-3.43	-2.00	-3.63	-1.87	-3.39	-2.30	-4.12	-2.28	-4.16
EMMD114	198.4	discordant breccia	-0.24	-1.40	2.32	-0.71	2.53	0.59	1.28	1.70	-0.52	0.76	-0.87	-2.05	-1.00	-2.91	-1.19	-2.78	-1.70	-3.68	-1.85	-3.70
EMMD161	105	discordant breccia	-0.25	-1.45	2.01	-1.51	2.02	0.22	-0.71	-0.11	-2.19	-0.75	-2.08	-3.38	-1.80	-3.49	-1.64	-3.22	-2.16	-4.14	-2.17	-3.94
EMDT203	102.8	marble	-3.67	1.75	0.48	-0.06	-2.50	-0.50	3.14	3.00	0.23	1.02	-1.25	-1.07	-1.14	-3.55	-2.02	-3.86	-2.89	-4.91	-3.28	-5.68
EMM018	175.5	marble	-2.20	-0.37	0.53	0.25	0.57	-1.62	1.27	1.22	-1.49	-0.54	-2.80	-2.99	-2.58	-4.79	-3.09	-4.70	-3.60	-5.39	-3.44	-5.26
EMMD001	117.5	marble	-1.01	-0.39	1.76	-1.09	0.38	-0.09	3.21	3.23	0.70	1.77	-0.17	-0.78	-0.33	-2.69	-1.37	-3.40	-2.84	-4.99	-3.42	-5.44
EMMD001	207.9	marble	-2.72	2.08	0.10	1.67	-1.20	-0.82	1.73	1.70	-1.00	-0.12	-2.25	-1.79	-2.12	-4.11	-2.28	-3.94	-2.92	-4.95	-3.19	-5.42
EMMD007	110.2	marble	-2.75	1.39	0.13	-1.06	-0.54	-1.68	2.03	1.78	-1.02	-0.32	-2.56	-1.87	-2.65	-4.87	-3.29	-4.83	-4.01	-5.67	-3.88	-6.04
EMMD013	101.6	marble	-2.81	1.00	0.26	1.08	-0.71	-0.87	2.15	2.13	-0.57	0.30	-1.94	-1.54	-1.97	-4.21	-2.59	-4.26	-3.18	-5.15	-3.39	-5.53
EMMD0136	170	marble	-2.03	-0.07	1.62	-0.76	0.52	-0.89	0.66	0.85	-1.66	-0.60	-2.41	-3.08	-2.36	-4.25	-2.49	-4.12	-3.05	-4.86	-3.06	-4.92
EMMD0136	362.2	marble	-1.30	-0.53	1.42	-0.86	1.17	0.03	1.29	1.60	-0.82	0.40	-1.52	-2.78	-1.50	-3.39	-1.66	-3.22	-2.31	-4.21	-2.35	-4.25
EMMD018	60.9	marble	-2.85	1.33	1.02	-0.13	-0.68	0.10	2.80	2.80	0.13	0.99	-1.24	-0.64	-1.27	-3.28	-1.63	-3.36	-2.38	-4.51	-2.95	-5.16
EMMD043	116.9	marble	-3.36	-0.06	0.18	-0.45	-1.05	-0.79	2.03	1.97	-0.75	0.08	-2.20	-1.85	-2.13	-4.33	-2.71	-4.36	-3.29	-5.23	-3.50	-5.62
EMMD052	314.5	marble	-3.22	-0.78	-0.04	-1.99	-0.49	0.22	1.81	1.86	-0.67	0.47	-1.20	-1.37	-1.02	-3.10	-1.63	-3.46	-2.70	-4.93	-3.30	-5.52
EMMD060	150.5	marble	-2.10	0.60	1.15	-0.10	0.30	-0.75	1.75	1.76	-0.87	0.12	-1.96	-2.20	-1.93	-4.07	-2.49	-4.11	-3.09	-5.06	-3.16	-5.06
EMMD066	100.5	marble	-2.53	0.84	0.43	-1.14	0.03	-0.69	2.01	1.90	-0.80	0.09	-2.01	-1.75	-1.96	-4.01	-2.30	-4.08	-3.06	-4.98	-3.20	-5.22
EMMD075	192.5	marble	-2.83	1.64	0.66	-1.01	-0.87	-0.94	1.97	1.85	-0.91	-0.04	-2.21	-1.70	-2.30	-4.32	-2.64	-4.35	-3.28	-5.17	-3.46	-5.54

Table B-3: Whole-rock data with CLR transform (unitless)

Hole ID	Depth	Lithology	Total C	Total S	Mo	Cu	Pb	Zn	Ag	Ni	Co	Mn	As	Au	Sb	Bi	Cr	Tl	Be	Li
EMM018	87	carbonaceous schist	6.08	6.25	-1.88	0.64	-0.13	2.45	-4.23	-0.12	-1.06	0.97	-0.08	-17.28	-2.62	-4.18	-1.95	-4.56	-4.27	-0.60
EMM019	126.8	carbonaceous schist	6.51	6.11	-3.11	0.57	-0.77	0.95	-5.48	-0.32	-1.11	3.75	-1.95	-17.11	-4.50	-4.36	-0.68	-4.02	-4.30	-0.86
EMMD097	269	carbonaceous schist	6.33	2.35	-3.19	1.91	-2.34	-0.30	-5.43	-0.23	-0.80	4.19	-0.21	-16.29	-3.39	-6.57	0.01	-5.25	-4.27	-1.85
EMMD117	140.8	carbonaceous schist	6.22	0.87	-2.47	-0.35	-2.24	-1.42	-5.76	-1.32	-2.09	2.08	-0.89	-19.16	-4.94	-6.26	-1.14	-6.04	-3.56	-1.85
EMMD167	105.7	carbonaceous schist	5.43	6.89	-2.86	1.20	-0.88	2.08	-3.32	0.57	-0.88	3.24	0.52	-16.44	-2.30	-2.59	-0.80	-4.52	-4.34	-0.60
EMMD167	127	carbonaceous schist	6.21	6.66	-1.17	2.57	-1.52	-1.69	-3.12	-0.03	-1.45	2.84	-0.55	-19.76	-3.68	-2.99	-2.30	-5.41	-4.00	-1.78
EMM008	93.1	diorite	4.38	3.06	-3.57	1.02	-1.90	0.53	-5.52	0.40	-0.01	3.81	-2.19	-14.68	-4.36	-6.44	1.38	-7.54	-4.54	-0.73
EMMD077	37.65	diorite	5.57	4.26	-3.71	1.41	-3.09	-0.34	-6.52	0.29	0.25	3.43	-2.07	-16.95	-5.57	-6.13	0.36	-7.51	-3.42	-0.13
EMMD008	60.5	discordant breccia	6.22	4.80	-2.74	0.67	-2.71	0.51	-5.75	0.41	0.27	3.21	-1.78	-16.48	-5.03	-4.41	0.71	-6.06	-3.98	0.15
EMMD013	151	discordant breccia	6.92	5.27	-1.58	2.48	-2.21	-1.50	-4.90	0.05	-0.21	3.74	0.58	-14.49	-4.98	-3.91	0.11	-5.07	-3.82	-1.25
EMMD153	306.5	discordant breccia	6.92	6.17	0.64	2.94	-2.09	-1.14	-5.04	-0.55	1.28	4.56	0.26	-14.48	-4.05	-3.13	-1.24	-4.79	-5.32	-1.08
EMMD030	96.2	discordant breccia	7.73	4.29	-4.23	2.30	-2.16	-3.53	-6.19	-0.20	-0.26	4.37	-2.03	-16.03	-5.84	-5.28	0.45	-7.22	-4.92	-2.62
EMMD077	290	discordant breccia	6.46	5.28	0.18	3.30	-2.65	-1.82	-5.45	-0.22	0.08	4.10	-1.32	-14.45	-4.69	-3.76	-0.75	-7.79	-5.48	-2.12
EMMD078	89	discordant breccia	5.02	3.10	-3.89	1.88	-2.93	0.36	-6.85	0.73	-0.44	3.47	-1.78	-19.23	-4.22	-7.03	0.73	-7.72	-3.63	-0.07
EMMD085	56	discordant breccia	8.21	1.45	-4.07	-0.57	-2.79	-1.72	-6.73	-0.26	-1.58	5.20	-1.39	-18.58	-5.68	-5.68	-0.14	-7.06	-5.45	-1.76
EMMD085	87.3	discordant breccia	6.48	3.79	-4.16	0.01	-2.70	-0.38	-6.56	0.36	-0.21	3.91	-0.24	-17.34	-6.01	-6.01	0.41	-7.62	-2.92	0.81
EMMD085	147.3	discordant breccia	6.38	2.47	-4.39	-1.22	-3.53	-0.62	-6.41	0.74	-0.64	3.82	-1.84	-16.55	-5.24	-6.75	0.60	-7.44	-2.74	-0.01
EMMD085	161	discordant breccia	6.33	4.46	-1.43	-1.14	-3.32	-0.82	-6.89	0.50	0.21	3.65	-0.86	-14.36	-5.10	-5.79	1.01	-7.58	-3.67	-0.76
EMMD085	295	discordant breccia	4.36	7.46	0.08	2.17	-1.27	-1.16	-3.11	0.16	2.44	2.12	1.27	-12.63	-2.77	-1.74	-0.90	-5.36	-4.15	-0.62
EMMD085	386.2	discordant breccia	5.76	6.23	-2.17	-0.85	-2.72	0.00	-5.35	0.50	0.73	3.55	-0.26	-14.67	-5.71	-3.22	0.23	-7.90	-3.30	0.31
EMMD085	393.2	discordant breccia	6.07	4.59	0.13	0.52	-2.49	-1.06	-5.76	-0.80	0.10	3.29	-1.06	-15.18	-4.74	-3.91	-0.87	-6.08	-3.78	-0.81
EMMD114	198.4	discordant breccia	4.93	1.10	-3.06	-0.22	-2.35	-1.35	-7.16	-0.80	-1.62	2.79	-2.81	-16.22	-4.42	-6.72	0.00	-7.42	-3.32	-2.55
EMMD161	105	discordant breccia	6.92	1.24	-2.75	0.50	-2.29	-0.30	-5.42	0.47	-0.52	3.79	-1.88	-14.84	-5.48	-5.89	1.03	-5.67	-3.87	-0.02
EMDT203	102.8	marble	4.57	7.73	1.97	6.21	0.28	-2.23	-1.74	-0.81	1.61	2.11	1.59	-11.36	-1.88	-0.20	-3.38	-7.07	-5.17	-2.53
EMM018	175.5	marble	6.29	6.93	-0.15	2.57	-0.89	-0.73	-2.56	-1.12	1.47	4.89	1.42	-12.99	-2.96	-0.40	-1.14	-3.86	-4.12	-1.44
EMMD001	117.5	marble	5.16	3.21	0.72	2.08	-1.55	0.39	-3.53	-1.08	-1.30	2.97	0.41	-13.60	-1.36	-3.36	-2.09	-7.39	-4.39	-0.92
EMMD001	207.9	marble	2.97	7.27	2.00	6.19	0.92	-0.16	-0.61	-0.96	2.13	1.51	2.04	-10.43	-0.85	0.13	-3.44	-6.84	-4.95	-2.70
EMMD007	110.2	marble	6.61	7.17	0.88	5.42	0.58	-0.14	-2.49	-1.43	1.79	5.27	2.23	-11.98	-1.89	-1.12	-3.22	-5.05	-3.53	-3.45
EMMD013	101.6	marble	5.93	6.57	0.83	5.31	0.47	1.39	-2.11	-1.46	1.38	4.52	1.80	-12.00	-2.26	-0.34	-2.84	-6.18	-4.33	-4.20
EMMD0136	170	marble	5.99	6.80	0.05	4.51	-1.44	-1.22	-4.14	-0.13	1.95	4.15	1.18	-12.63	-3.18	-2.40	-1.61	-5.23	-4.23	-1.45
EMMD0136	362.2	marble	6.41	7.13	-1.01	3.41	-2.30	-1.55	-4.60	0.34	1.91	4.18	1.70	-12.87	-4.58	-3.06	-3.16	-6.76	-5.15	-1.88
EMMD018	60.9	marble	7.19	1.75	-0.71	3.53	0.46	1.15	-3.28	-1.37	1.11	4.87	0.93	-11.64	-1.67	-1.91	-1.76	-7.46	-3.21	-1.60
EMMD043	116.9	marble	6.08	6.62	0.30	4.78	-0.76	0.78	-1.62	-1.37	1.42	5.11	-0.20	-12.60	-2.51	-1.17	-2.14	-4.08	-4.15	-0.79
EMMD052	314.5	marble	8.97	6.68	-1.10	4.01	-0.16	0.96	-4.25	0.13	0.70	6.91	-0.06	-13.85	-3.07	-2.67	-3.03	-6.44	-3.73	-1.39
EMMD060	150.5	marble	3.89	7.29	0.70	4.62	-0.81	-1.51	-3.92	-0.72	2.06	2.02	1.71	-12.50	-2.92	-1.72	-2.08	-6.04	-4.32	-1.18
EMMD066	100.5	marble	6.08	6.49	0.98	5.40	-0.13	-0.73	-2.45	-0.61	1.96	3.79	1.37	-11.87	-2.88	-1.31	-2.09	-5.22	-4.64	-0.84
EMMD075	192.5	marble	5.59	7.08	1.73	6.15	0.03	-0.68	-2.37	-0.67	2.18	4.37	1.84	-10.98	-2.58	-0.99	-2.83	-5.87	-3.83	-0.92

Table B-3: Whole-rock data with CLR transform (unitless)

Hole ID	Depth	Lithology	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃ *	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	Ba	F	Sc	Cs	Ga	Hf	Nb	Rb	Sn	Sr	Ta
EMMD075	205.3	marble	6.59	5.41	8.66	5.35	7.78	3.47	3.83	3.04	4.61	7.28	6.92	-3.17	-4.27	-3.21	-4.38	-1.77	-2.28	0.63	2.74	-3.87
EMMD077	174	marble	6.97	6.01	9.47	5.65	6.28	2.59	4.01	3.60	5.12	4.06	4.71	-3.00	-6.40	-2.18	-4.20	-1.59	-1.91	0.51	-0.28	-5.30
EMMD077	225.4	marble	7.26	6.23	9.21	5.32	7.63	3.89	4.33	3.50	4.28	7.47	6.67	-1.86	-6.93	-2.04	-4.16	-2.37	-1.20	0.74	3.23	-5.14
EMMD085	231.7	marble	10.31	8.80	7.71	7.25	8.92	7.26	7.95	5.69	4.28	3.56	3.59	-0.32	-4.42	-0.21	-1.53	-0.60	1.78	-2.12	1.15	-3.32
EMMD085	310.5	marble	7.37	6.23	9.05	5.16	7.28	1.21	4.99	3.77	4.78	7.35	6.58	-2.70	-6.39	-2.44	-3.91	-1.69	-0.96	0.24	3.18	-4.78
EMMD097	226.15	marble	7.87	7.37	8.38	6.29	7.05	3.35	5.85	4.95	3.76	6.27	5.11	-1.57	-2.55	-1.67	-2.98	-2.17	0.47	-0.23	1.61	-4.70
EMMD136	361.85	marble	9.80	8.30	8.27	6.30	7.57	3.60	7.24	4.78	4.20	4.22	4.60	-1.01	-3.63	-0.34	-1.58	-0.92	1.09	-0.23	-0.40	-3.92
EMMD182	239.75	marble	8.25	6.86	8.64	7.17	8.00	2.48	5.73	4.52	5.18	3.74	4.16	-2.31	-3.58	-1.81	-3.38	-2.17	0.07	-1.02	0.15	-5.12
EMM017	154.3	metaandesite	10.20	8.92	8.60	7.42	6.65	7.64	6.68	6.64	4.46	4.96	3.76	0.22	-2.45	-0.04	-1.32	-0.75	0.90	-2.35	0.93	-3.14
EMM018	133	metaandesite	9.79	8.75	9.03	7.67	7.32	4.31	6.72	6.47	4.19	5.09	3.81	0.03	-2.50	-0.15	-1.45	-0.45	0.84	-2.50	0.47	-3.41
EMM019	338	metaandesite	10.38	9.10	8.77	6.92	8.29	7.95	7.00	6.82	4.53	5.08	3.91	0.52	-2.78	0.19	-1.19	0.00	0.92	-1.17	1.35	-3.00
EMM022	74.6	metaandesite	10.66	9.22	8.70	6.65	6.62	8.12	7.16	6.97	4.86	4.28	4.55	0.30	-2.29	0.27	-0.95	-0.38	1.59	-1.59	0.67	-2.91
EMMD002	120.5	metaandesite	9.29	8.12	8.73	6.84	6.15	3.38	6.85	6.26	4.23	4.78	4.86	-0.53	-2.38	-0.66	-1.66	-1.02	1.44	-0.94	-0.42	-3.53
EMMD008	126	metaandesite	9.66	8.39	8.20	7.09	6.67	7.41	6.39	6.06	3.79	2.89	4.55	-0.34	-2.24	-0.58	-1.70	-0.33	0.94	-1.57	0.49	-3.63
EMMD018	101	metaandesite	9.84	8.60	8.38	7.22	6.96	7.68	6.77	6.25	4.12	3.02	4.75	-0.10	-2.22	-0.37	-1.60	-0.24	1.48	-1.94	0.68	-3.55
EMMD041	154.75	metaandesite	10.14	8.90	9.33	7.59	6.12	8.05	6.13	6.27	3.74	1.48	3.96	-0.11	-2.69	-0.06	-1.70	-1.56	0.72	-1.85	-0.14	-3.86
EMMD042	171.2	metaandesite	9.99	8.70	8.59	7.09	7.38	7.77	6.50	6.40	4.09	3.47	4.16	0.06	-1.55	-0.26	-1.61	-0.71	1.33	-2.46	1.09	-3.67
EMMD043	169.9	metaandesite	10.13	9.12	8.33	6.67	8.23	7.81	7.34	6.51	4.29	4.79	4.22	0.14	-2.61	0.07	-1.59	-0.54	1.71	-1.85	0.78	-3.46
EMMD064	150	metaandesite	10.00	8.87	8.23	7.21	7.14	7.85	6.69	6.38	3.72	3.25	3.90	-0.25	-1.97	-0.09	-1.47	-0.90	1.30	-2.50	1.16	-3.42
EMMD066	40	metaandesite	9.88	8.92	8.75	7.05	5.01	7.54	6.81	6.48	4.37	6.09	4.90	-0.28	-2.76	-0.20	-1.45	-0.79	0.92	-0.74	0.45	-3.33
EMMD066	123.6	metaandesite	9.83	8.50	8.40	6.53	6.99	7.46	6.36	6.59	4.45	4.18	4.00	-0.12	-3.04	-0.26	-1.32	-0.71	0.47	-1.99	1.34	-3.19
EMMD066	176	metaandesite	10.08	8.87	8.51	6.65	7.93	6.99	7.44	6.53	4.20	5.45	4.33	0.25	-2.78	0.00	-1.42	-0.85	1.68	-1.66	0.38	-3.40
EMMD067	187	metaandesite	9.97	8.85	8.55	6.81	7.08	7.60	6.94	6.74	4.69	4.48	4.21	0.01	-3.08	0.00	-1.07	-0.55	1.35	-0.97	0.11	-3.08
EMMD074	195	metaandesite	10.76	9.25	7.30	5.90	8.03	5.86	9.03	5.31	3.96	4.91	3.11	-1.90	-3.80	-0.51	-0.49	-0.18	2.39	-1.90	1.26	-2.95
EMMD075	116.2	metaandesite	9.28	8.27	8.73	6.22	4.95	3.49	6.60	6.40	4.32	4.84	4.29	-0.31	-3.28	-0.54	-1.57	-0.97	0.68	-2.07	-0.24	-3.50
EMMD077	81.7	metaandesite	9.27	8.25	8.75	6.70	6.83	5.42	7.17	5.94	3.72	5.21	5.06	-0.33	-2.92	-0.62	-2.03	-1.45	1.35	-0.66	-0.21	-3.88
EMMD077	162.4	metaandesite	9.88	8.95	10.11	7.34	5.72	7.67	6.98	6.80	4.66	5.10	4.99	0.30	-3.53	0.08	-1.26	-0.69	0.89	-0.75	0.42	-3.34
EMMD085	366.8	metaandesite	9.34	7.77	8.35	5.93	6.86	2.62	6.65	4.84	5.21	4.52	4.42	-1.83	-4.98	-1.27	-2.49	-1.27	0.39	-0.31	-0.45	-4.13
EMMD086	167.9	metaandesite	8.64	8.19	8.84	6.82	6.10	3.72	7.00	6.29	4.23	6.59	5.53	-0.62	-2.08	-0.49	-1.61	-1.03	1.35	0.44	0.48	-3.47
EMMD097	74.14	metaandesite	9.77	8.08	9.41	7.07	7.29	3.32	1.38	5.25	4.51	1.57	3.57	-1.03	-4.84	-1.12	-2.40	-1.75	-4.43	0.07	0.84	-4.43
EMMD097	174.1	metaandesite	10.12	8.86	8.10	6.85	7.21	7.86	6.24	6.58	4.68	3.73	3.41	0.16	-3.24	-0.03	-1.32	-0.68	0.47	-1.75	0.94	-3.24
EMMD114	71	metaandesite	10.18	9.00	7.67	6.14	7.28	8.14	6.28	6.55	4.50	3.66	4.34	-0.54	-3.79	-0.28	-1.31	-0.70	0.61	-1.71	1.23	-3.10
EMMD118	143.8	metaandesite	10.25	8.99	8.87	7.55	6.74	7.41	6.23	6.51	3.84	4.69	3.84	0.17	-3.32	0.29	-1.56	-0.96	0.43	-1.87	0.01	-3.66
EMMD119	174.9	metaandesite	10.35	8.64	8.47	7.82	8.40	3.81	8.01	5.52	4.13	3.68	4.13	-0.67	-4.08	-0.07	-1.44	-0.73	1.59	-1.77	0.94	-2.98
EMMD126	104	metaandesite	10.13	8.95	8.71	7.51	7.80	7.78	5.81	6.59	4.33	2.43	3.82	0.10	-3.09	-0.04	-1.28	-0.70	0.09	-2.29	1.53	-3.21
EMMD129	155	metaandesite	10.18	8.93	8.10	6.79	7.36	7.86	6.49	6.52	4.99	3.48	3.83	-0.19	-2.90	-0.36	-1.40	-0.81	0.84	-1.98	1.04	-3.31
EMMD136	71.9	metaandesite	9.88	8.74	7.74	6.37	7.42	7.66	6.60	6.28	4.68	3.65	4.05	-0.44	-2.86	-0.27	-1.59	-0.98	0.95	-2.23	1.23	-3.55

Table B-3: Whole-rock data with CLR transform (unitless)

Hole ID	Depth	Lithology	Th	U	V	W	Zr	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
EMMD075	205.3	marble	-2.99	1.23	0.25	1.36	-1.25	-1.03	2.54	2.42	-0.37	0.46	-1.93	-1.32	-1.87	-4.21	-2.55	-4.20	-3.18	-5.05	-3.27	-5.38
EMMD077	174	marble	-2.43	1.73	1.10	-0.82	-0.58	-0.39	2.67	2.73	0.25	1.33	-0.68	-1.30	-0.75	-3.10	-1.70	-3.64	-2.85	-4.92	-3.18	-5.37
EMMD077	225.4	marble	-2.81	0.26	1.09	1.82	-0.80	-0.91	1.49	1.41	-1.23	-0.33	-2.36	-2.14	-2.27	-4.31	-2.59	-4.09	-3.01	-5.14	-3.17	-5.11
EMMD085	231.7	marble	-0.24	-1.20	1.71	-1.93	2.06	0.48	0.34	1.00	-1.18	0.12	-1.44	-3.03	-1.39	-3.12	-1.31	-2.93	-1.85	-3.68	-1.88	-3.83
EMMD085	310.5	marble	-2.40	1.42	1.20	-0.33	-0.39	-0.79	1.62	1.60	-1.09	-0.18	-2.19	-1.99	-2.19	-4.12	-2.38	-3.91	-3.01	-4.93	-3.15	-5.20
EMMD097	226.15	marble	-2.00	-0.53	0.95	0.24	0.59	-1.22	1.64	1.55	-1.10	-0.18	-2.33	-2.32	-2.32	-4.53	-2.83	-4.40	-3.30	-5.19	-3.25	-5.17
EMMD136	361.85	marble	-1.30	-0.14	0.38	0.02	2.18	-0.42	0.32	0.65	-1.68	-0.53	-2.17	-3.27	-2.14	-3.99	-2.24	-3.82	-2.64	-4.43	-2.38	-4.00
EMMD182	239.75	marble	-1.43	-0.67	1.19	-1.17	0.36	-0.22	1.24	1.46	-0.96	0.21	-1.73	-2.88	-1.72	-3.61	-1.91	-3.45	-2.46	-4.39	-2.57	-4.49
EMM017	154.3	metaandesite	-0.47	-1.79	2.58	-2.12	2.34	0.44	0.31	0.96	-1.13	0.20	-1.37	-2.85	-1.27	-3.07	-1.29	-2.91	-1.80	-3.75	-1.93	-3.84
EMM018	133	metaandesite	-0.63	-1.71	2.32	-0.05	2.15	0.08	0.44	1.00	-1.16	0.20	-1.41	-2.92	-1.58	-3.37	-1.58	-3.06	-1.96	-3.82	-1.96	-3.84
EMM019	338	metaandesite	-0.52	-1.13	2.55	-1.21	2.38	0.27	-1.04	-0.54	-2.69	-1.34	-2.57	-4.05	-2.16	-3.62	-1.59	-3.02	-1.86	-3.67	-1.78	-3.70
EMM022	74.6	metaandesite	-0.16	-1.31	2.55	-1.56	2.64	0.61	-1.90	-1.21	-3.20	-1.59	-2.62	-3.90	-1.94	-3.24	-1.20	-2.63	-1.53	-3.45	-1.62	-3.54
EMMD002	120.5	metaandesite	-1.04	-0.93	1.91	-0.33	1.94	-0.15	-0.14	0.13	-2.23	-0.97	-2.55	-3.56	-2.36	-3.96	-2.03	-3.38	-2.20	-4.03	-2.17	-4.13
EMMD008	126	metaandesite	-0.98	-2.42	1.89	-1.13	1.85	0.06	1.60	1.87	-0.53	0.65	-0.96	-1.84	-0.91	-2.67	-1.09	-3.09	-2.36	-4.39	-2.53	-4.28
EMMD018	101	metaandesite	-0.86	-2.13	2.17	-1.41	2.01	0.20	0.76	1.24	-0.96	0.31	-1.19	-2.47	-1.26	-3.11	-1.44	-3.10	-2.02	-3.92	-2.01	-3.94
EMMD041	154.75	metaandesite	-0.99	-1.95	2.16	-2.61	1.86	-0.25	0.56	1.06	-1.18	0.12	-1.60	-3.43	-1.69	-3.68	-2.00	-3.62	-2.58	-4.51	-2.56	-4.38
EMMD042	171.2	metaandesite	-0.83	-2.03	2.32	-2.32	2.00	0.10	0.15	0.76	-1.42	-0.05	-1.58	-3.00	-1.63	-3.41	-1.66	-3.24	-2.17	-4.10	-2.20	-4.15
EMMD043	169.9	metaandesite	-1.02	-1.34	2.39	-0.93	1.99	0.22	-1.02	-0.33	-2.43	-0.95	-2.16	-3.28	-1.88	-3.35	-1.48	-3.00	-1.92	-3.84	-1.98	-3.87
EMMD064	150	metaandesite	-0.57	-1.88	2.00	-2.09	2.14	0.10	0.34	0.90	-1.23	0.07	-1.53	-2.83	-1.53	-3.33	-1.53	-3.13	-2.14	-4.06	-2.18	-4.04
EMMD066	40	metaandesite	-0.52	0.22	1.98	0.04	2.17	-0.12	-0.23	0.09	-2.29	-1.10	-2.53	-3.54	-2.34	-3.94	-1.96	-3.45	-2.29	-4.15	-2.24	-4.07
EMMD066	123.6	metaandesite	-0.50	-1.65	2.25	-1.60	2.30	0.30	0.44	1.10	-1.02	0.31	-1.25	-2.78	-1.31	-3.07	-1.34	-2.92	-1.87	-3.75	-1.87	-3.79
EMMD066	176	metaandesite	-0.72	-1.88	2.41	-1.03	2.14	0.12	0.45	1.00	-1.20	0.13	-1.49	-2.85	-1.51	-3.39	-1.62	-3.22	-2.08	-3.94	-2.04	-3.87
EMMD067	187	metaandesite	-0.31	-1.08	2.41	-1.00	2.49	0.22	0.55	1.04	-1.17	0.11	-1.47	-2.71	-1.47	-3.33	-1.55	-3.12	-1.91	-3.77	-1.88	-3.73
EMMD074	195	metaandesite	0.25	-0.42	-1.21	-0.60	3.27	0.32	-0.31	0.26	-1.95	-0.54	-2.03	-3.48	-1.86	-3.46	-1.56	-2.98	-1.82	-3.61	-1.63	-3.46
EMMD075	116.2	metaandesite	-0.81	-1.04	2.08	-0.05	2.06	0.13	0.17	0.70	-1.47	-0.12	-1.66	-2.84	-1.58	-3.37	-1.59	-3.17	-2.08	-3.98	-2.12	-4.02
EMMD077	81.7	metaandesite	-1.22	-1.15	1.89	-1.42	1.54	-0.46	1.46	1.73	-0.62	0.57	-1.18	-2.18	-1.33	-3.45	-1.96	-3.82	-2.73	-4.58	-2.63	-4.48
EMMD077	162.4	metaandesite	-0.54	-0.81	3.02	0.65	2.37	-0.25	-1.13	-0.98	-3.26	-1.92	-3.20	-3.51	-2.59	-4.14	-2.12	-3.55	-2.27	-4.18	-2.12	-3.94
EMMD085	366.8	metaandesite	-1.15	0.37	0.68	-0.03	1.13	-0.34	0.72	1.03	-1.38	-0.19	-2.00	-3.29	-2.00	-3.86	-2.08	-3.68	-2.56	-4.45	-2.54	-4.39
EMMD086	167.9	metaandesite	-0.92	-0.91	1.99	0.07	1.98	-0.61	1.13	1.09	-1.55	-0.57	-2.50	-3.01	-2.32	-4.25	-2.42	-3.83	-2.53	-4.25	-2.32	-4.11
EMMD097	74.14	metaandesite	-1.47	-0.16	1.40	0.60	1.15	-0.79	0.98	1.16	-1.51	-0.51	-2.43	-2.77	-2.44	-4.34	-2.58	-4.10	-2.97	-4.89	-3.02	-4.79
EMMD097	174.1	metaandesite	-0.51	-1.66	2.44	-1.43	2.29	0.23	0.37	1.00	-1.12	0.24	-1.32	-2.81	-1.34	-3.23	-1.50	-3.09	-1.98	-3.85	-1.98	-3.85
EMMD114	71	metaandesite	-0.43	-1.67	2.00	-0.97	2.30	0.07	1.60	2.08	-0.22	0.99	-0.74	-1.81	-0.97	-3.00	-1.48	-3.23	-2.16	-4.04	-2.09	-3.97
EMMD118	143.8	metaandesite	-0.67	-1.40	2.61	-0.48	2.11	-0.07	-0.20	0.27	-1.98	-0.68	-2.21	-3.48	-2.05	-3.72	-1.83	-3.34	-2.17	-4.04	-2.24	-4.02
EMMD119	174.9	metaandesite	-0.54	-1.59	1.52	-1.92	2.18	-0.01	0.64	1.31	-0.89	0.38	-1.35	-2.92	-1.50	-3.37	-1.70	-3.38	-2.41	-4.22	-2.45	-4.34
EMMD126	104	metaandesite	-0.48	-1.71	2.39	-1.89	2.37	0.47	0.43	1.06	-1.09	0.28	-1.26	-2.64	-1.25	-3.04	-1.29	-2.87	-1.86	-3.70	-1.85	-3.72
EMMD129	155	metaandesite	-0.48	-1.75	2.02	-2.39	2.24	0.20	0.71	1.28	-0.97	0.32	-1.35	-2.56	-1.39	-3.31	-1.51	-3.09	-1.99	-3.86	-1.93	-3.78
EMMD136	71.9	metaandesite	-0.70	-1.76	1.86	-1.66	2.04	0.04	1.27	1.68	-0.61	0.60	-1.06	-2.08	-1.18	-3.17	-1.56	-3.25	-2.24	-4.15	-2.22	-4.02

Table B-3: Whole-rock data with CLR transform (unitless)

Hole ID	Depth	Lithology	Total C	Total S	Mo	Cu	Pb	Zn	Ag	Ni	Co	Mn	As	Au	Sb	Bi	Cr	Tl	Be	Li
EMMD075	205.3	marble	5.51	6.70	1.31	5.64	-0.28	-1.86	-2.13	-1.46	1.21	4.80	1.03	-12.12	-2.79	-0.54	-3.28	-7.27	-4.63	-2.86
EMMD077	174	marble	3.73	6.88	2.09	5.68	0.28	-1.89	-2.70	-0.30	2.00	1.59	1.33	-12.81	-2.31	-1.52	-2.87	-5.33	-4.45	-1.65
EMMD077	225.4	marble	5.19	6.83	0.67	5.10	-0.50	-0.55	-1.75	-1.27	1.07	3.20	0.64	-12.33	-1.99	-1.26	-3.02	-6.35	-3.94	-1.62
EMMD085	231.7	marble	7.41	2.49	-5.47	-0.73	-3.29	-1.00	-6.58	0.90	0.45	4.56	-2.40	-15.43	-6.03	-7.41	1.00	-7.41	-3.50	0.02
EMMD085	310.5	marble	4.01	7.06	1.54	6.08	-0.73	-1.89	-2.66	-0.92	1.75	1.87	2.17	-11.51	-2.78	-2.09	-2.61	-5.70	-3.91	-1.56
EMMD097	226.15	marble	5.93	5.17	1.11	3.00	-1.76	0.10	-3.50	-1.06	0.07	4.31	-0.46	-14.29	-2.96	-2.41	-0.36	-4.26	-4.70	-0.68
EMMD136	361.85	marble	6.05	7.13	-2.61	0.05	-1.23	-1.50	-4.50	-0.83	1.84	3.24	1.02	-13.13	-3.19	-2.24	-3.31	-6.22	-5.71	-1.18
EMMD182	239.75	marble	6.98	6.88	-0.25	4.18	-1.70	-0.88	-4.53	-0.12	1.69	4.57	0.71	-12.88	-3.29	-2.48	-2.27	-5.26	-6.22	-1.46
EMM017	154.3	metaandesite	5.12	0.87	-3.79	0.25	-2.40	1.16	-6.86	0.45	-0.35	2.65	-3.26	-19.16	-4.03	-7.64	0.32	-4.43	-3.96	-0.13
EMM018	133	metaandesite	5.84	2.11	-3.46	0.55	-2.43	1.57	-6.57	0.17	-0.97	3.95	-2.36	-17.70	-4.06	-7.79	0.08	-6.41	-3.88	0.17
EMM019	338	metaandesite	6.83	1.13	-5.31	-0.80	-1.48	0.70	-6.35	0.49	-0.71	4.57	-2.68	-18.90	-3.15	-6.69	0.53	-5.59	-4.39	-0.49
EMM022	74.6	metaandesite	4.86	2.61	-2.18	-0.12	-1.56	-0.26	-5.79	0.06	-1.21	2.56	-2.10	-16.41	-4.41	-7.30	0.49	-6.60	-3.61	-0.76
EMMD002	120.5	metaandesite	4.36	4.53	0.40	3.69	-2.96	0.28	-4.92	-0.26	0.11	2.91	-0.79	-14.07	-4.92	-4.76	-1.35	-4.73	-4.40	-0.72
EMMD008	126	metaandesite	5.07	2.69	-3.42	0.90	-2.48	1.02	-6.40	0.43	-0.94	2.65	-2.36	-18.25	-4.76	-7.43	0.48	-4.00	-2.99	-1.13
EMMD018	101	metaandesite	5.44	2.38	-2.21	-0.90	-2.77	-0.55	-6.57	0.57	-0.73	2.91	-2.22	-16.67	-5.44	-7.93	0.68	-3.83	-3.83	-0.96
EMMD041	154.75	metaandesite	4.70	6.09	-2.93	2.82	-2.60	-0.25	-6.05	0.70	1.22	2.82	0.06	-15.89	-4.72	-3.92	-2.25	-5.16	-3.30	-0.57
EMMD042	171.2	metaandesite	6.33	0.75	-2.97	0.25	-2.27	0.62	-6.38	0.53	-0.67	4.28	-2.69	-16.57	-4.67	-6.38	0.39	-3.87	-4.07	-0.52
EMMD043	169.9	metaandesite	6.79	3.04	-2.18	-0.92	-2.72	-0.76	-6.72	-0.53	-0.88	4.63	-1.73	-17.28	-4.56	-5.76	-0.12	-5.76	-3.64	-0.79
EMMD064	150	metaandesite	5.56	2.11	-4.71	1.84	-1.67	0.63	-6.49	0.16	-0.09	3.55	-2.13	-16.31	-4.71	-6.70	-0.45	-4.46	-3.89	-0.79
EMMD066	40	metaandesite	3.86	2.47	-2.22	1.87	-2.26	0.49	-6.08	0.25	-0.50	2.97	-1.72	-16.17	-4.05	-6.22	-0.51	-5.44	-4.15	0.07
EMMD066	123.6	metaandesite	5.51	1.92	-2.50	1.21	-2.13	0.13	-6.64	-0.08	-1.49	3.12	-2.01	-16.93	-3.27	-7.98	-0.78	-4.94	-4.29	-1.30
EMMD066	176	metaandesite	6.80	3.35	-3.42	3.16	-2.82	-1.54	-5.68	-0.43	-2.40	4.72	-6.04	-15.80	-4.65	-7.65	-0.49	-5.86	-3.56	-2.30
EMMD067	187	metaandesite	6.05	2.53	-1.97	0.99	-2.55	-1.07	-7.51	0.16	-1.31	3.97	-3.53	-16.72	-5.29	-7.78	-0.44	-6.68	-4.38	-1.43
EMMD074	195	metaandesite	6.56	5.38	-2.02	0.24	-1.95	-0.53	-5.76	-2.06	0.17	4.02	-1.31	-15.67	-5.12	-4.56	-2.12	-7.20	-4.90	-1.72
EMMD075	116.2	metaandesite	5.84	3.23	-1.73	1.94	-2.73	-0.41	-5.87	-0.20	0.63	4.61	-0.76	-15.55	-3.40	-5.20	-1.14	-5.65	-3.79	-0.62
EMMD077	81.7	metaandesite	5.38	4.66	-1.38	-0.15	-3.26	-0.50	-6.63	0.01	-0.32	3.51	-0.65	-16.56	-4.12	-5.62	-0.58	-4.60	-4.02	-0.72
EMMD077	162.4	metaandesite	2.46	2.87	0.03	0.25	-2.09	-0.67	-5.32	0.98	-1.29	2.73	-1.70	-15.69	-3.68	-4.67	0.44	-5.83	-4.44	-0.25
EMMD085	366.8	metaandesite	5.35	7.70	-1.43	3.09	-1.12	-1.22	-3.81	-0.26	1.87	2.85	1.22	-12.90	-3.86	-1.85	-2.78	-6.59	-4.69	-1.77
EMMD086	167.9	metaandesite	4.23	3.37	-0.17	3.09	-3.04	-0.46	-5.03	-1.03	-2.31	2.56	-2.47	-15.02	-3.42	-5.59	-1.59	-4.37	-3.98	0.17
EMMD097	74.14	metaandesite	6.32	2.99	-1.31	4.60	2.12	3.67	-3.68	-0.53	0.98	3.42	1.55	-12.60	-2.94	-2.19	-0.91	-6.73	-3.23	-0.19
EMMD097	174.1	metaandesite	5.62	2.56	-4.06	1.70	-2.63	0.14	-7.00	-0.06	-0.35	2.97	-1.51	-16.26	-4.53	-7.05	0.34	-7.05	-4.06	-0.64
EMMD114	71	metaandesite	5.62	2.20	-3.40	0.51	-1.97	-0.98	-6.96	-0.29	-0.98	3.12	-2.84	-16.00	-4.76	-6.32	-0.36	-7.01	-4.30	-1.69
EMMD118	143.8	metaandesite	5.17	3.72	-2.90	0.07	-2.97	0.53	-5.43	0.94	-0.06	3.58	-1.26	-13.68	-5.78	-5.78	0.41	-7.57	-3.66	-0.18
EMMD119	174.9	metaandesite	6.84	4.95	-4.11	-0.88	-3.32	-0.75	-6.60	0.41	-0.18	4.18	-0.01	-16.35	-5.68	-5.87	0.62	-7.48	-3.23	0.25
EMMD126	104	metaandesite	6.42	0.93	-2.33	-1.73	-2.95	0.73	-7.25	0.90	-0.32	4.46	-2.65	-19.10	-4.60	-7.59	0.97	-5.51	-3.90	0.23
EMMD129	155	metaandesite	5.76	3.31	-3.90	3.26	-2.68	-0.69	-5.91	0.12	-0.67	3.57	-3.31	-15.67	-5.61	-6.30	-0.46	-6.99	-4.69	-1.00
EMMD136	71.9	metaandesite	5.79	2.37	-2.00	2.20	-1.05	-0.14	-6.74	-0.20	-0.91	3.33	-2.41	-16.88	-5.16	-6.32	-0.87	-5.74	-4.94	-1.49

Table B-3: Whole-rock data with CLR transform (unitless)

Hole ID	Depth	Lithology	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃ *	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	Ba	F	Sc	Cs	Ga	Hf	Nb	Rb	Sn	Sr	Ta
EMMD136	124	metaandesite	10.02	8.82	8.21	6.28	7.68	8.08	5.72	6.29	4.71	3.04	4.22	-0.67	-4.36	-0.43	-1.55	-0.93	0.08	-2.06	0.89	-3.51
EMMD136	215	metaandesite	9.97	8.78	8.03	6.92	8.27	7.67	6.97	6.44	4.22	4.37	4.40	0.20	-2.76	-0.16	-1.53	-0.97	1.44	-1.71	0.63	-3.61
EMMD136	267.5	metaandesite	10.48	8.20	9.59	6.01	6.22	3.55	7.15	4.85	3.70	5.58	4.70	-1.24	-2.38	-0.37	-3.07	-1.01	1.22	0.91	-1.09	-5.15
EMMD136	321	metaandesite	10.85	9.59	9.11	6.27	7.39	8.30	8.01	7.03	4.57	5.41	4.74	0.66	-3.12	0.56	-1.04	-0.39	2.20	-1.04	0.40	-3.12
EMMD167	180.3	metaandesite	10.35	9.25	8.25	7.06	7.88	8.43	6.55	6.79	4.57	3.84	3.74	0.19	-2.55	-0.04	-1.24	-0.69	1.02	-1.71	0.77	-3.50
EMMD167	234	metaandesite	10.02	8.93	8.94	7.73	7.45	7.28	5.99	6.39	2.66	3.03	3.64	-0.15	-3.40	0.09	-1.43	-0.92	0.57	-2.35	0.26	-3.40
EMMD167	279.7	metaandesite	9.91	8.65	8.44	7.25	7.16	7.22	6.28	6.15	4.55	2.85	4.04	-0.44	-3.49	-0.36	-1.72	-1.08	0.57	-1.66	0.23	-3.63
EMMD182	91.7	metaandesite	10.51	9.39	8.19	5.93	6.91	8.61	6.76	6.79	4.73	3.90	3.92	-0.37	-3.28	-0.25	-1.08	-0.63	1.27	-2.07	1.21	-3.12
EMMD184	50	metaandesite	9.71	8.65	8.31	7.19	7.71	7.24	7.08	6.19	3.85	3.86	4.32	-0.49	-1.06	-0.21	-1.78	-1.12	1.75	-2.63	0.94	-3.68
EMMD184	150.1	metaandesite	10.11	8.96	8.97	6.84	6.84	7.77	6.95	6.67	4.29	5.08	3.88	0.41	-2.28	0.02	-1.44	-0.95	1.37	-1.64	0.17	-3.72
EMMD196	27.5	metaandesite	10.24	9.12	7.61	5.58	8.44	8.34	6.54	6.75	4.63	3.78	3.30	-0.02	-2.73	-0.34	-1.17	-0.60	0.87	-2.22	1.76	-3.14
EMMD196	162	metaandesite	10.09	8.79	8.82	6.39	7.61	7.50	7.10	6.54	4.26	3.59	3.95	0.20	-2.47	-0.13	-1.51	-1.02	1.62	-1.96	-0.07	-3.57
EMM023	153.1	metasiltstone	6.84	5.54	9.81	6.37	7.78	0.31	4.62	2.62	5.12	3.56	5.35	-2.90	-3.50	-2.40	-4.51	-1.12	-0.81	-0.51	1.61	-5.90
EMMD008	93.5	metasiltstone	8.26	5.89	9.42	5.25	6.70	0.32	0.32	2.40	4.82	8.46	4.41	-2.49	-5.89	-2.76	-4.10	-2.64	-6.59	1.23	3.53	-3.59
EMMD009	131.9	metasiltstone	9.87	8.30	7.95	7.55	7.19	7.00	6.61	5.44	5.40	2.87	4.32	-1.07	-3.60	-0.63	-1.96	-0.89	0.60	-3.37	-0.21	-3.60
EMMD009	182.3	metasiltstone	9.71	8.38	7.45	6.78	7.13	6.37	7.42	5.34	4.49	3.68	4.11	-0.91	-2.26	-0.40	-2.00	-0.52	1.71	-2.85	0.58	-3.45
EMMD0113	97.6	metasiltstone	9.17	5.89	9.80	6.62	7.13	2.00	4.19	3.38	5.33	4.14	4.19	-2.20	-4.00	-1.76	-4.51	-2.39	-0.92	-0.60	0.85	-6.30
EMMD086	105.9	metasiltstone	9.34	8.18	8.80	6.77	4.99	6.24	5.93	6.29	4.41	4.87	4.08	-0.53	-4.36	-0.50	-1.68	-1.04	-0.03	-1.10	-0.42	-3.48
EMMD086	194.9	metasiltstone	10.13	8.98	8.09	6.59	8.27	7.57	7.28	6.63	4.30	4.66	4.59	0.17	-3.12	0.10	-1.38	-0.88	1.87	-0.81	0.58	-3.23
EMMD097	128.5	metasiltstone	10.17	9.07	8.85	7.71	7.00	8.03	6.01	6.77	4.59	3.64	4.04	0.08	-2.22	-0.01	-1.17	-0.52	0.71	-2.96	1.01	-3.07
EMMD184	125.9	metasiltstone	9.07	7.65	8.34	5.23	6.87	3.76	6.11	5.26	4.78	6.07	4.12	-1.05	-3.01	-0.92	-2.69	-1.54	0.41	0.29	1.00	-4.58
EMMD018	139	metatuff	10.13	8.70	8.48	7.48	7.47	7.43	6.46	6.41	3.81	3.17	3.99	0.12	-2.69	-0.15	-1.66	-1.08	0.72	-2.40	0.04	-3.61
EMMD066	53.6	metatuff	9.33	5.50	8.84	4.51	6.18	3.99	3.33	2.85	4.83	3.97	3.48	-2.74	-4.75	-3.00	-4.75	-1.70	-2.03	0.96	0.07	-6.83
EMMD075	166	metatuff	9.54	8.61	8.84	7.08	5.72	6.63	7.33	6.72	4.57	5.42	5.26	-0.04	-2.13	-0.09	-1.20	-0.56	1.77	-0.61	0.65	-3.04
EMMD076	107	metatuff	9.70	8.47	8.31	7.17	7.82	7.66	6.08	6.20	3.84	3.64	4.74	-0.24	-1.79	-0.74	-1.85	-1.42	0.82	-2.23	0.93	-4.03
EMMD085	288.75	metatuff	8.85	7.92	8.90	6.82	6.68	4.51	6.68	5.49	4.43	4.15	4.46	-0.95	-3.04	-0.92	-2.37	-1.52	0.74	0.11	-0.30	-4.48
EMMD067	76	metavolcanic breccia	8.81	7.94	8.86	6.69	5.10	3.99	6.01	5.97	4.19	5.65	4.13	-0.99	-3.35	-0.90	-1.97	-1.32	0.01	-0.38	-0.30	-3.88
EMMD067	127.1	metavolcanic breccia	8.82	7.75	8.72	5.68	5.05	5.18	6.35	5.27	4.46	5.78	4.48	-1.31	-2.98	-1.15	-2.60	-1.87	0.50	-0.30	-0.04	-4.71
EMMD074	105.5	metavolcanic breccia	8.76	7.85	9.89	6.62	6.21	5.50	6.28	5.62	5.41	3.27	4.87	-1.23	-3.53	-0.42	-2.64	-1.67	0.09	-1.23	0.07	-4.12
EMMD075	39.4	metavolcanic breccia	9.30	8.65	9.39	6.72	5.17	6.47	7.14	6.19	4.70	5.43	4.89	-0.46	-3.40	-0.40	-1.73	-1.04	1.19	-0.14	-0.70	-3.63
EMMD077	201.5	metavolcanic breccia	8.62	7.19	8.55	5.34	6.05	2.34	6.07	4.81	4.13	6.62	5.42	-1.81	-4.72	-1.80	-3.14	-1.98	-0.16	-0.15	2.97	-4.03
EMMD077	250.2	metavolcanic breccia	9.34	8.03	8.64	6.01	6.74	4.35	6.84	5.79	4.07	5.59	4.50	-0.67	-3.82	-0.53	-2.33	-1.56	0.74	-0.32	-0.56	-4.63
EMMD085	344.1	metavolcanic breccia	7.79	6.37	8.92	5.31	7.23	1.19	5.24	3.93	4.64	7.29	6.51	-2.50	-5.72	-2.04	-4.11	-2.07	-0.81	-0.06	3.20	-4.33
EMMD086	48.4	metavolcanic breccia	9.07	8.08	8.51	6.51	5.09	3.56	6.69	5.69	4.03	5.28	4.95	-0.99	-2.62	-1.05	-2.17	-1.48	0.95	-0.83	-0.03	-3.98
EMMD086	125	metavolcanic breccia	8.80	7.60	8.57	6.43	5.29	3.00	6.55	5.65	3.95	5.02	4.81	-1.00	-2.20	-1.28	-2.30	-1.57	1.20	-0.72	-0.62	-4.19
EMM022	167.1	psammite	7.87	6.95	8.50	6.10	6.79	2.75	4.01	4.51	4.26	4.90	5.92	-1.85	-5.18	-2.00	-3.39	-1.73	-1.77	0.48	0.80	-5.41
EMMD013	170.9	psammite	10.63	9.18	7.75	7.37	8.38	8.50	6.33	5.84	4.66	3.31	4.59	-0.35	-2.88	0.26	-1.20	-0.66	1.23	-2.66	1.16	-2.88

Table B-3: Whole-rock data with CLR transform (unitless)

Hole ID	Depth	Lithology	Th	U	V	W	Zr	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
EMMD136	124	metaandesite	-0.59	-1.75	1.75	-1.07	2.06	0.20	1.41	1.77	-0.53	0.74	-0.91	-1.86	-0.94	-2.93	-1.42	-3.20	-2.18	-4.03	-2.23	-4.03
EMMD136	215	metaandesite	-0.80	-2.10	2.35	-1.53	2.08	0.50	0.34	0.87	-1.28	0.04	-1.48	-2.67	-1.38	-3.16	-1.29	-2.84	-1.80	-3.75	-1.94	-3.85
EMMD136	267.5	metaandesite	-1.72	-0.71	1.88	-0.37	0.61	-1.49	0.21	0.19	-2.29	-1.18	-2.89	-3.76	-2.76	-4.74	-2.98	-4.89	-3.82	-5.66	-3.96	-5.84
EMMD136	321	metaandesite	-0.42	-0.97	2.96	-0.30	2.54	0.26	-1.15	-0.65	-2.79	-1.37	-2.64	-3.70	-2.10	-3.60	-1.57	-3.05	-1.89	-3.78	-1.74	-3.60
EMMD167	180.3	metaandesite	-0.49	-1.33	2.45	-1.45	2.38	0.42	-0.06	0.41	-1.73	-0.32	-1.85	-2.88	-1.57	-3.29	-1.42	-3.00	-1.87	-3.73	-1.87	-3.68
EMMD167	234	metaandesite	-0.67	-1.59	2.25	-1.63	2.12	0.27	0.49	1.11	-1.09	0.23	-1.48	-2.79	-1.51	-3.33	-1.55	-3.11	-1.96	-3.91	-2.05	-3.89
EMMD167	279.7	metaandesite	-0.76	-2.40	1.95	-1.32	1.87	0.32	1.43	1.86	-0.35	0.93	-0.65	-1.78	-0.74	-2.76	-1.25	-2.98	-2.11	-4.14	-2.30	-4.24
EMMD182	91.7	metaandesite	-0.27	-1.46	1.95	-0.33	2.52	0.83	0.79	1.22	-1.03	0.26	-1.32	-2.55	-1.30	-2.97	-1.03	-2.52	-1.45	-3.40	-1.67	-3.52
EMMD184	50	metaandesite	-0.82	-2.02	1.97	-3.14	1.90	-0.10	0.20	0.87	-1.34	-0.08	-1.81	-3.00	-1.76	-3.60	-1.83	-3.43	-2.33	-4.27	-2.40	-4.32
EMMD184	150.1	metaandesite	-0.81	-1.44	2.55	-1.17	2.13	0.02	0.50	1.02	-1.17	0.20	-1.40	-2.66	-1.42	-3.31	-1.64	-3.33	-2.19	-4.17	-2.27	-4.08
EMMD196	27.5	metaandesite	-0.25	-1.63	2.20	-2.22	2.46	0.42	1.08	1.63	-0.52	0.81	-1.01	-2.38	-1.04	-2.96	-1.24	-2.84	-1.80	-3.69	-1.80	-3.71
EMMD196	162	metaandesite	-0.72	-2.18	2.44	-2.14	2.13	0.40	0.34	1.01	-1.14	0.19	-1.32	-2.65	-1.28	-3.05	-1.30	-2.96	-1.93	-3.88	-2.03	-3.90
EMM023	153.1	metasiltstone	-2.96	0.21	0.16	-1.74	-0.86	-0.89	2.29	2.28	-0.41	0.55	-1.43	-1.41	-1.45	-3.68	-2.23	-4.06	-3.48	-5.49	-3.77	-6.26
EMMD008	93.5	metasiltstone	-3.33	1.64	0.84	1.79	-1.94	-1.06	3.06	2.90	0.14	0.96	-1.39	-2.04	-1.22	-3.79	-2.43	-4.14	-3.28	-5.11	-3.43	-5.56
EMMD009	131.9	metasiltstone	-0.75	-0.80	1.86	-0.93	1.58	-0.44	-0.10	0.51	-1.66	-0.39	-1.97	-3.79	-1.96	-3.84	-2.12	-3.76	-2.82	-4.76	-2.94	-4.89
EMMD009	182.3	metasiltstone	-0.84	-1.17	1.66	-1.82	1.61	-0.32	0.14	0.82	-1.33	-0.05	-1.75	-3.71	-1.87	-3.77	-2.03	-3.70	-2.62	-4.49	-2.65	-4.57
EMMD0113	97.6	metasiltstone	-3.53	0.79	1.22	0.48	-0.72	-0.64	0.43	0.43	-2.13	-1.03	-2.69	-2.20	-2.28	-4.00	-2.16	-3.88	-3.06	-5.34	-3.55	-5.61
EMMD086	105.9	metasiltstone	-0.88	-0.79	2.04	-0.46	1.95	-0.22	0.52	0.89	-1.45	-0.23	-1.88	-3.00	-1.87	-3.61	-1.84	-3.42	-2.35	-4.14	-2.28	-4.17
EMMD086	194.9	metasiltstone	-0.74	-1.40	2.31	-0.54	2.24	0.09	-0.19	0.27	-2.02	-0.73	-2.15	-3.07	-1.95	-3.55	-1.65	-3.16	-2.05	-3.88	-1.99	-3.88
EMMD097	128.5	metasiltstone	-0.32	-1.53	2.45	-2.22	2.47	0.47	-0.66	0.09	-2.02	-0.64	-2.01	-3.47	-1.75	-3.29	-1.32	-2.79	-1.71	-3.66	-1.75	-3.64
EMMD184	125.9	metasiltstone	-1.35	-0.13	1.20	-0.64	0.95	0.00	1.42	1.67	-0.81	0.33	-1.54	-2.42	-1.53	-3.48	-1.76	-3.28	-2.29	-4.24	-2.49	-4.60
EMMD018	139	metatuff	-0.83	-1.93	2.36	-2.00	1.98	0.06	0.20	0.85	-1.30	0.04	-1.53	-2.80	-1.58	-3.33	-1.61	-3.19	-2.10	-4.04	-2.18	-4.04
EMMD066	53.6	metatuff	-2.92	0.68	0.49	-1.26	-1.24	-0.26	2.41	2.36	-0.29	0.63	-1.41	-1.31	-1.37	-3.49	-1.91	-3.69	-2.90	-5.04	-3.30	-5.40
EMMD075	166	metatuff	-0.44	-0.94	2.45	-0.79	2.41	-0.29	0.67	0.97	-1.35	-0.08	-1.79	-2.85	-1.80	-3.77	-2.03	-3.55	-2.27	-4.00	-2.06	-3.90
EMMD076	107	metatuff	-1.14	-1.95	2.09	-1.74	1.74	-0.06	-0.30	0.16	-2.07	-0.74	-2.34	-3.32	-2.05	-3.73	-1.91	-3.37	-2.34	-4.23	-2.40	-4.28
EMMD085	288.75	metatuff	-1.57	-0.38	1.50	0.42	1.25	-0.66	0.47	0.64	-1.81	-0.67	-2.47	-3.19	-2.35	-4.20	-2.41	-4.05	-2.97	-4.86	-2.99	-4.78
EMMD067	76	metavolcanic breccia	-1.17	-0.64	1.75	-0.25	1.66	-0.37	0.00	0.16	-2.28	-1.06	-2.78	-3.17	-2.52	-4.22	-2.27	-3.75	-2.56	-4.44	-2.58	-4.49
EMMD067	127.1	metavolcanic breccia	-1.51	-0.48	1.39	-1.31	0.99	-0.58	0.58	0.79	-1.68	-0.52	-2.35	-3.05	-2.26	-4.21	-2.42	-3.96	-2.84	-4.71	-2.85	-4.67
EMMD074	105.5	metavolcanic breccia	-1.00	-2.20	2.92	-1.92	0.94	-0.06	1.01	1.40	-0.99	0.23	-1.63	-3.53	-1.58	-3.55	-1.87	-3.45	-2.37	-4.32	-2.44	-4.34
EMMD075	39.4	metavolcanic breccia	-0.70	-0.26	2.24	0.10	1.84	-0.31	-0.88	-0.40	-2.63	-1.25	-2.71	-3.27	-2.41	-4.10	-2.16	-3.70	-2.45	-4.40	-2.47	-4.34
EMMD077	201.5	metavolcanic breccia	-1.87	0.43	1.04	1.09	0.49	-0.67	1.47	1.45	-1.14	-0.13	-2.10	-2.26	-2.11	-4.11	-2.38	-3.89	-2.79	-4.64	-2.72	-4.64
EMMD077	250.2	metavolcanic breccia	-1.73	-0.10	1.62	-0.03	1.32	-0.72	0.85	0.99	-1.48	-0.33	-2.15	-2.61	-2.15	-4.04	-2.35	-4.02	-2.97	-4.95	-3.00	-4.95
EMMD085	344.1	metavolcanic breccia	-2.37	0.86	0.96	0.31	-0.26	-0.83	1.75	1.72	-0.93	0.05	-2.06	-2.04	-2.02	-4.14	-2.45	-4.10	-2.97	-4.95	-3.14	-5.13
EMMD086	48.4	metavolcanic breccia	-1.25	0.01	1.42	-0.32	1.43	-0.38	0.34	0.58	-1.81	-0.71	-2.39	-3.12	-2.21	-4.00	-2.18	-3.80	-2.72	-4.61	-2.72	-4.61
EMMD086	125	metavolcanic breccia	-1.40	-0.25	1.43	-1.84	1.30	-0.55	0.91	1.01	-1.47	-0.33	-2.11	-2.66	-2.12	-3.98	-2.25	-3.83	-2.80	-4.69	-2.82	-4.69
EMM022	167.1	psammite	-2.30	0.29	0.67	-1.78	0.22	-0.95	1.94	1.93	-0.70	0.18	-2.04	-1.92	-2.14	-4.29	-2.56	-4.18	-3.16	-5.05	-3.31	-5.31
EMMD013	170.9	psammite	-0.02	-1.78	1.37	-2.25	2.37	-0.40	-0.47	0.04	-2.09	-0.67	-2.18	-3.06	-1.96	-3.83	-2.10	-3.74	-2.63	-4.62	-2.61	-4.43

Table B-3: Whole-rock data with CLR transform (unitless)

Hole ID	Depth	Lithology	Total C	Total S	Mo	Cu	Pb	Zn	Ag	Ni	Co	Mn	As	Au	Sb	Bi	Cr	Tl	Be	Li
EMMD136	124	metaandesite	6.34	4.16	-3.96	3.94	-2.49	-0.88	-5.24	-0.50	-0.94	4.12	-2.42	-15.13	-4.99	-6.38	-0.40	-7.76	-6.15	-2.16
EMMD136	215	metaandesite	7.10	1.51	-3.42	1.97	-2.91	-1.19	-6.51	-0.40	-1.41	4.82	-1.59	-16.73	-5.40	-6.60	-0.59	-5.91	-4.70	-1.93
EMMD136	267.5	metaandesite	4.80	6.66	1.67	3.88	-1.98	-1.97	-3.68	0.05	2.76	2.52	1.51	-11.23	-3.11	-0.37	-1.57	-5.66	-4.46	-1.57
EMMD136	321	metaandesite	5.76	1.48	-3.60	2.22	-2.80	-1.96	-6.20	-0.48	-2.65	3.41	-2.79	-15.50	-4.64	-7.04	0.79	-7.04	-4.04	-1.74
EMMD167	180.3	metaandesite	6.81	1.10	-3.56	0.66	-2.64	-0.77	-6.25	0.04	-0.73	4.84	-3.32	-16.16	-5.22	-6.32	0.53	-7.41	-4.01	-1.68
EMMD167	234	metaandesite	5.99	3.76	-4.82	3.47	-3.13	0.94	-5.79	0.79	0.68	4.07	-1.59	-15.73	-5.57	-6.04	-0.52	-7.65	-6.04	-0.06
EMMD167	279.7	metaandesite	5.60	3.41	-4.93	1.93	-3.51	-0.04	-6.65	0.50	-0.40	3.63	-1.26	-15.10	-5.31	-6.27	-0.63	-7.88	-3.78	-0.79
EMMD182	91.7	metaandesite	5.62	1.14	-1.72	0.20	-2.20	-1.93	-6.34	-1.43	-2.59	3.59	-3.28	-16.32	-5.07	-5.99	0.00	-6.68	-3.97	-3.12
EMMD184	50	metaandesite	6.20	2.89	-5.85	2.78	-2.53	1.14	-5.78	0.21	-0.01	3.91	-2.33	-15.47	-4.71	-6.14	-0.78	-3.59	-4.24	-0.23
EMMD184	150.1	metaandesite	5.81	0.89	-4.86	0.73	-2.95	0.06	-6.64	0.45	-0.58	4.01	-3.25	-17.07	-4.41	-6.53	0.99	-5.43	-4.23	-0.66
EMMD196	27.5	metaandesite	6.89	1.00	-3.39	-0.69	-1.82	-0.55	-7.05	-0.65	-1.50	4.32	-2.51	-17.09	-4.12	-6.83	-0.12	-6.42	-5.91	-1.78
EMMD196	162	metaandesite	6.46	0.86	-3.04	1.11	-2.43	-1.67	-6.67	0.30	-0.47	4.33	-0.95	-16.47	-4.37	-6.56	0.00	-6.05	-4.26	-1.89
EMM023	153.1	metasiltstone	6.70	6.99	1.10	4.56	-0.30	0.51	-1.94	-0.11	1.80	5.32	1.54	-12.59	-1.54	-0.52	-3.33	-3.51	-5.90	-2.03
EMMD008	93.5	metasiltstone	4.93	7.60	0.22	6.04	1.62	0.63	-1.13	-1.12	1.96	3.83	2.12	-11.32	-2.47	-1.12	-3.50	-6.81	-4.28	-2.76
EMMD009	131.9	metasiltstone	5.66	6.73	-1.06	0.81	-2.09	-1.43	-4.67	0.89	0.69	2.55	1.69	-14.36	-4.68	-2.67	0.37	-7.98	-4.07	-0.20
EMMD009	182.3	metasiltstone	5.77	5.73	-2.04	2.25	-2.58	-0.93	-4.63	0.14	-0.16	3.30	1.19	-17.87	-4.18	-5.38	0.10	-4.82	-3.45	-0.78
EMMD0113	97.6	metasiltstone	7.39	6.80	1.08	6.41	0.58	-0.66	-2.72	0.29	2.33	5.36	0.99	-11.19	-4.22	-2.02	-2.97	-4.82	-2.77	-0.42
EMMD086	105.9	metasiltstone	5.00	4.81	-0.95	3.26	-2.91	-0.68	-5.39	-0.25	0.52	4.18	0.34	-14.21	-4.77	-4.03	-1.13	-8.27	-4.36	-0.71
EMMD086	194.9	metasiltstone	6.76	3.67	-3.05	3.41	-3.30	-1.20	-6.03	-1.02	-1.85	4.25	-3.23	-15.52	-5.42	-6.92	-0.37	-6.52	-4.62	-1.42
EMMD097	128.5	metasiltstone	5.38	0.95	-3.29	-0.79	-2.59	1.76	-7.04	0.61	0.18	2.70	-2.96	-15.53	-3.68	-7.57	0.71	-4.86	-4.57	0.16
EMMD184	125.9	metasiltstone	6.06	2.66	-2.67	4.21	-2.21	-1.89	-6.46	-0.64	0.76	6.68	-0.14	-15.96	-3.78	-2.99	-1.33	-5.36	-5.50	-1.59
EMMD018	139	metatuff	6.02	3.12	-3.87	2.07	-2.75	0.04	-4.16	0.70	0.10	3.73	-2.63	-15.09	-6.09	-7.70	0.23	-5.40	-3.61	-0.55
EMMD066	53.6	metatuff	5.93	6.74	0.54	6.15	0.35	-1.03	-1.48	-0.76	2.23	5.23	1.84	-11.60	-2.43	-0.78	-2.64	-5.04	-4.35	-1.73
EMMD075	166	metatuff	3.47	1.86	-3.03	1.55	-3.07	-0.54	-6.42	-0.13	-1.16	1.86	-2.41	-16.73	-4.13	-6.66	-0.81	-4.41	-4.36	0.06
EMMD076	107	metatuff	6.74	4.36	-2.71	1.12	-3.06	0.38	-5.99	0.65	-0.27	5.00	-1.51	-16.32	-4.28	-4.68	0.03	-4.15	-3.69	-0.71
EMMD085	288.75	metatuff	6.37	6.21	0.11	2.35	-2.40	-0.78	-4.42	-0.32	1.69	3.02	0.31	-13.84	-3.72	-2.70	-1.66	-6.45	-3.79	-1.06
EMMD067	76	metavolcanic breccia	5.68	5.45	0.60	2.82	-2.41	0.05	-4.74	-0.28	1.51	5.21	1.29	-14.44	-4.90	-2.13	-1.77	-6.08	-4.39	-0.73
EMMD067	127.1	metavolcanic breccia	4.93	5.81	0.01	4.26	-2.42	-1.40	-4.45	-0.57	1.57	4.14	1.18	-12.96	-4.14	-2.99	-1.05	-4.56	-4.12	-0.67
EMMD074	105.5	metavolcanic breccia	2.56	7.46	-2.93	2.80	-2.35	-0.67	-5.31	0.70	1.08	2.96	0.94	-15.23	-4.27	-2.65	-1.22	-5.83	-4.34	-0.52
EMMD075	39.4	metavolcanic breccia	1.90	5.93	0.08	0.65	-2.73	-1.19	-5.12	0.25	1.51	1.96	0.71	-14.01	-3.65	-3.60	-0.42	-6.22	-4.61	-0.88
EMMD077	201.5	metavolcanic breccia	2.48	6.50	0.40	4.03	-1.28	-1.95	-3.54	-0.88	1.31	1.30	1.20	-12.99	-2.42	-1.00	-1.58	-6.18	-4.57	-1.68
EMMD077	250.2	metavolcanic breccia	5.17	6.13	-0.33	0.21	-2.20	-2.44	-4.55	-0.37	1.22	2.71	1.27	-13.08	-3.03	-1.68	-0.18	-6.24	-4.92	-1.11
EMMD085	344.1	metavolcanic breccia	4.16	7.25	0.95	5.57	-1.00	-1.72	-3.29	-1.02	1.67	1.89	1.12	-11.79	-2.72	-1.62	-2.54	-5.82	-3.84	-1.55
EMMD086	48.4	metavolcanic breccia	5.18	4.93	-0.45	4.14	-1.62	-0.74	-5.07	-0.18	1.23	2.90	0.13	-13.09	-4.63	-3.16	-1.76	-4.93	-4.79	-0.30
EMMD086	125	metavolcanic breccia	4.07	6.02	0.34	3.74	-2.14	-0.97	-4.55	-0.49	1.65	3.35	1.27	-13.37	-3.70	-2.83	-1.92	-4.35	-5.29	-0.68
EMM022	167.1	psammite	4.59	6.04	1.35	4.74	-0.47	1.45	-2.43	-0.53	1.28	3.46	0.88	-12.80	-3.01	-1.57	-0.95	-5.73	-3.75	-0.64
EMMD013	170.9	psammite	6.87	4.15	-2.99	0.98	-2.22	-1.03	-5.83	0.71	-0.16	3.42	-1.59	-15.01	-4.96	-5.18	1.32	-5.47	-5.65	-0.87

Appendix C
Microprobe and Mineral Liberation Analysis Data

Data Summary

The complete tables of WDS analyses of carbonates (Table C-1), feldspars (Table C-2) and biotites (Table C-3) are shown below. Following this, modal mineralogy tables of each MLA samples are shown in Table C-4. Grain size estimates are based on MLA measurements of the long axes of grains. The tables correspond to the pie charts shown in Chapter 2, but with trace phases included.

Table C-1: WDS Data - Carbonates

Sample (EMMD)	052_6	052_6	052_6	052_6	153_14	153_14	153_14	153_14	055_11	055_11	055_11	153_13	153_13	153_13	153_13	075_205
Point	S1	S2	S3	S4	S2	S3	S4	S5	S1	S2	S3	S13	S14	S15	S16	S1
FeO ¹	0.90	1.04	1.24	0.94	21.60	20.70	18.65	21.10	50.57	1.25	1.17	12.25	1.92	1.09	11.40	12.14
MnO	2.19	1.15	1.82	1.81	1.56	1.29	1.77	3.00	9.81	0.12	0.04	0.97	0.63	0.85	0.89	7.23
MgO	0.30	0.59	0.44	0.35	6.70	6.53	8.50	5.23	0.08	0.08	0.03	13.36	0.95	0.45	14.30	9.26
CaO	55.22	54.18	55.85	53.49	25.63	26.21	26.23	25.91	1.75	55.41	54.83	27.54	56.81	55.82	27.96	25.93
Total	58.60	56.95	59.36	56.60	55.48	54.73	55.15	55.23	62.21	56.86	56.07	54.12	60.30	58.22	54.56	54.56
Fe ²⁺	0.012	0.015	0.017	0.013	0.301	0.288	0.260	0.294	0.704	0.017	0.016	0.171	0.027	0.015	0.159	0.169
Mn	0.031	0.016	0.026	0.026	0.022	0.018	0.025	0.042	0.138	0.002	0.000	0.014	0.009	0.012	0.013	0.102
Mg	0.007	0.015	0.011	0.009	0.166	0.162	0.211	0.130	0.002	0.002	0.001	0.331	0.024	0.011	0.355	0.230
Ca	0.985	0.966	0.996	0.954	0.457	0.467	0.468	0.462	0.031	0.988	0.978	0.491	1.013	0.995	0.499	0.462
Total	1.035	1.011	1.050	1.001	0.946	0.936	0.963	0.928	0.875	1.009	0.995	1.007	1.072	1.034	1.025	0.963
Ca/(Ca+Mg+Fe+Mn)	95.11	95.53	94.87	95.26	48.32	49.96	48.57	49.80	3.57	97.91	98.23	48.78	94.48	96.29	48.67	48.02
Fe/(Ca+Mg+Fe+Mn)	1.20	1.43	1.64	1.31	31.80	30.79	26.95	31.65	80.41	1.73	1.64	16.94	2.49	1.47	15.49	17.55
Mn/(Ca+Mg+Fe+Mn)	2.98	1.60	2.45	2.55	2.32	1.95	2.59	4.56	15.79	0.17	0.05	1.36	0.83	1.16	1.22	10.58
Mg/(Ca+Mg+Fe+Mn)	0.71	1.44	1.04	0.88	17.56	17.31	21.89	13.99	0.23	0.19	0.08	32.92	2.20	1.09	34.62	23.85

General formula: (Ca, Fe, Mn, Mg) CO₃¹ All Fe reported as Fe²⁺

Table C-1: WDS Data - Carbonates

Sample (EMMD)	075_205	075_205	075_227	075_227	075_227	075_227	153_7	153_7	153_7	153_7
Point	S2	S3	S3	S4	S5	S6	S7	S8	S9	S10
FeO [†]	11.39	11.41	10.27	9.98	14.94	12.64	46.10	45.81	42.42	45.05
MnO	9.89	11.65	0.78	1.70	2.23	1.04	15.27	15.05	16.10	16.31
MgO	8.38	6.96	14.67	8.83	11.34	13.42	0.24	0.21	0.17	0.20
CaO	26.09	26.34	27.02	17.50	26.99	27.84	1.53	1.54	2.49	1.83
Total	55.74	56.36	52.74	38.01	55.51	54.94	63.14	62.61	61.18	63.39
Fe ²⁺	0.159	0.159	0.143	0.139	0.208	0.176	0.642	0.638	0.590	0.627
Mn	0.139	0.164	0.011	0.024	0.031	0.015	0.215	0.212	0.227	0.230
Mg	0.208	0.173	0.364	0.219	0.281	0.333	0.006	0.005	0.004	0.005
Ca	0.465	0.470	0.482	0.312	0.481	0.496	0.027	0.028	0.044	0.033
Total	0.971	0.965	1.000	0.694	1.002	1.020	0.890	0.882	0.866	0.895
Ca/(Ca+Mg+Fe+Mn)	47.92	48.66	48.20	44.96	48.03	48.68	3.07	3.12	5.12	3.66
Fe/(Ca+Mg+Fe+Mn)	16.33	16.45	14.29	20.03	20.75	17.25	72.08	72.25	68.17	70.08
Mn/(Ca+Mg+Fe+Mn)	14.36	17.01	1.10	3.46	3.14	1.44	24.18	24.05	26.21	25.70
Mg/(Ca+Mg+Fe+Mn)	21.40	17.88	36.41	31.55	28.07	32.63	0.68	0.58	0.49	0.56

Table C-2: WDS Data - Feldspars

Sample No.	001_5	001_5	153_7	153_7	153_7	153_1	153_1	153_1	146_215	146_215	008_1	008_1	008_1	007_3	001_1	001_1	001_1
Point No.	S1	S5	S1	S4B	S6	S8	S9	S10	S2	S4	S1	S9	10	S2	S2	S3	S4
SiO ₂	68.47	70.86	64.48	65.43	66.32	70.25	69.97	68.73	68.12	68.38	67.79	65.36	67.79	67.79	67.79	64.53	64.81
TiO ₂	0.05	0.01	0.00	0.01	0.00	0.03	0.00	0.04	0.06	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.02
Al ₂ O ₃	18.34	18.78	17.24	17.30	17.17	18.42	18.33	18.55	18.95	18.62	19.36	17.36	19.47	19.72	18.87	17.15	17.52
FeO ¹	0.60	0.17	0.87	0.64	0.81	0.21	0.15	0.15	0.41	0.05	0.06	0.26	0.31	0.45	0.06	0.02	0.06
MnO	0.00	0.00	0.09	0.10	0.07	0.01	0.00	0.03	0.02	0.00	0.00	0.00	0.02	0.00	0.00	0	0
MgO	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0
CaO	0.06	0.04	0.00	0.04	0.00	0.05	0.02	0.07	1.01	0.49	0.74	0.00	0.01	0.04	0.02	0	0.04
Na ₂ O	12.05	11.78	0.09	0.11	0.26	12.01	12.34	12.24	11.53	11.97	10.86	0.20	11.32	10.86	12.39	0.4	0.43
K ₂ O	0.04	0.02	17.13	16.36	15.62	0.05	0.01	0.00	0.08	0.09	0.12	16.51	0.04	0.03	0.07	16.84	16.09
Total	99.62	101.69	99.9	99.98	100.27	101.02	100.82	99.81	100.18	99.61	98.93	99.69	98.95	98.9	99.21	98.96	98.96
Cations on the basis of 8 O																	
Si	3.01	3.04	3.01	3.03	3.05	3.04	3.03	3.01	2.99	3.01	2.99	3.03	2.99	2.99	2.99	3.03	3.02
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0
Al	0.95	0.95	0.95	0.94	0.93	0.94	0.94	0.96	0.98	0.97	1.01	0.95	1.01	1.03	0.98	0.95	0.96
Fe ²⁺	0.02	0.01	0.03	0.02	0.03	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.02	0.00	0	0
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.02	0.03	0.00	0.00	0.00	0.00	0	0
Na	1.03	0.98	0.01	0.01	0.02	1.01	1.04	1.04	0.98	1.02	0.93	0.02	0.97	0.93	1.06	0.04	0.04
K	0.00	0.00	1.02	0.97	0.92	0.00	0.00	0.00	0.00	0.00	0.01	0.98	0.00	0.00	0.00	1.01	0.96
Total	5.02	4.98	5.03	4.98	4.95	5	5.02	5.03	5.01	5.02	4.97	4.99	4.99	4.96	5.05	5.02	4.99
Ca+Na+K+other-1	0.06	0.01	0.07	0.01	0.03	0.02	0.04	0.05	0.05	0.05	0.03	0.01	0.02	0.05	0.07	0.05	0
4-(Si+Al)	0.03	0.01	0.04	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.00	0.02	0.00	0.01	0.02	0.02	0.01
Al-(2Ca+K+Na)	-0.08	-0.04	-0.08	-0.04	-0.01	-0.08	-0.10	-0.09	-0.10	-0.11	0.00	-0.05	0.04	0.09	-0.08	-0.1	-0.04
Or	0.21	0.12	95.74	96.03	94.02	0.25	0.08	0.02	0.44	0.46	0.70	97.23	0.20	0.19	0.37	96.4	95.71
Ab	97.42	98.92	0.74	0.95	2.39	98.75	99.31	99.06	93.52	97.12	95.46	1.76	98.53	97.88	99.28	3.47	3.85
An	2.37	0.95	3.53	3.02	3.59	1	0.61	0.92	6.04	2.42	3.83	1.01	1.27	1.92	0.36	0.13	0.43

General formula: (K, Na, Ca) (Al, Si)₄O₈¹All Fe reported as Fe²⁺

Table C-3: WDS Data - Biotite

Sample (EMMD)	008-1	008-1	008-1	008-1	153-13	153-13	153-13	153-13	182-94-5	182-94-5	182-94-5	182-94-5	182-94-5	182-249-6	182-249-6
Spot	S5	S6	S7	S8	S18	S19	S20	S21	S6	S7	S8	S9	S10	S1	S2
SiO ₂	40.29	39.03	39.56	39.03	25.29	36.00	35.09	66.09	35.10	35.83	36.93	35.72	36.67	36.64	36.30
TiO ₂	2.08	1.92	2.60	2.40	0.03	1.73	3.06	0.00	1.36	1.63	1.68	1.67	1.77	0.87	0.84
Al ₂ O ₃	13.32	13.54	13.15	13.59	22.66	16.94	16.80	20.95	15.87	15.71	15.93	15.97	17.24	14.17	14.15
FeO ¹	11.59	12.73	14.30	12.42	29.86	15.79	16.98	0.20	26.77	25.13	21.89	24.48	20.89	15.28	15.93
MnO	0.04	0.08	0.07	0.07	0.24	0.04	0.04	0.00	0.08	0.08	0.08	0.05	0.04	0.04	0.05
MgO	18.41	17.06	15.90	17.31	10.88	10.08	8.46	0.08	6.83	8.15	9.77	8.21	9.23	13.46	13.13
CaO	0.00	0.00	0.03	0.02	0.05	0.03	0.11	1.58	0.04	0.02	0.05	0.00	0.00	0.01	0.03
Na ₂ O	0.05	0.06	0.01	0.04	0.12	0.10	0.19	10.02	0.06	0.10	0.09	0.08	0.07	0.09	0.09
K ₂ O	9.99	10.34	10.04	9.90	0.01	7.27	6.79	0.28	9.42	9.59	9.83	9.74	9.76	7.74	7.59
F	0.91	0.42	0.61	0.40	0.00	1.34	1.43	0.00	0.49	0.94	0.93	0.80	0.98	3.03	3.16
Cl	0.51	0.71	0.57	0.52	0.13	0.13	0.27	0.05	2.08	1.37	0.45	1.11	0.17	0.97	1.16
Total	97.20	95.91	96.84	95.71	89.27	89.45	89.22	99.25	98.11	98.55	97.63	97.82	96.83	92.30	92.43
Cations on the basis of 24 total O															
C_H ₂ O	3.55	3.64	3.61	3.72	3.57	3.08	2.96	4.92	3.03	3.06	3.37	3.19	3.42	2.07	1.94
O-F-Cl	0.50	0.34	0.39	0.29	0.03	0.59	0.66	0.01	0.68	0.71	0.49	0.59	0.45	1.49	1.59
T-Si	5.88	5.81	5.86	5.79	4.21	5.76	5.68	error	5.55	5.58	5.65	5.56	5.60	5.86	5.84
T-Al	2.12	2.19	2.14	2.21	3.79	2.24	2.32	-0.03	2.45	2.42	2.35	2.44	2.40	2.14	2.16
T-Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sum_T	8.00	8.00	8.00	8.00	8.00	8.00	8.00	-0.03	8.00	8.00	8.00	8.00	8.00	8.00	8.00
M-Al	0.17	0.19	0.16	0.17	0.65	0.95	0.88	3.03	0.51	0.46	0.52	0.50	0.70	0.53	0.52
M-Ti	0.23	0.22	0.29	0.27	0.00	0.21	0.37	0.00	0.16	0.19	0.19	0.20	0.20	0.10	0.10
M-Fe ²⁺	1.41	1.59	1.77	1.54	4.15	2.11	2.30	0.02	3.54	3.27	2.80	3.19	2.67	2.04	2.14
M-Mn	0.01	0.01	0.01	0.01	0.03	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.01
M-Mg	4.00	3.79	3.51	3.83	2.70	2.40	2.04	0.02	1.61	1.89	2.23	1.91	2.10	3.21	3.15
Sum_M	5.81	5.79	5.74	5.81	7.54	5.68	5.60	3.06	5.84	5.82	5.75	5.79	5.68	5.89	5.92
I-Ca	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.21	0.01	0.00	0.01	0.00	0.00	0.00	0.00
I-Na	0.02	0.02	0.00	0.01	0.04	0.03	0.06	2.36	0.02	0.03	0.03	0.02	0.02	0.03	0.03
I_K	1.86	1.97	1.90	1.87	0.00	1.48	1.40	0.04	1.90	1.90	1.92	1.94	1.90	1.58	1.56
sum_I	1.87	1.98	1.91	1.89	0.05	1.52	1.48	2.61	1.93	1.94	1.95	1.96	1.92	1.61	1.59
A_F	0.42	0.20	0.29	0.19	0.00	0.68	0.73	0.00	0.25	0.46	0.45	0.40	0.47	1.53	1.61
A_Cl	0.13	0.18	0.14	0.13	0.04	0.03	0.07	0.01	0.56	0.36	0.12	0.29	0.04	0.26	0.32
A_OH	3.45	3.62	3.57	3.68	3.96	3.29	3.20	3.99	3.20	3.17	3.43	3.31	3.48	2.20	2.08
sum_A	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Fe/(Fe+Mg)	0.26	0.30	0.34	0.29	0.61	0.47	0.53	0.57	0.69	0.63	0.56	0.63	0.56	0.39	0.41
Endmembers (%)															
Phlogopite	74	70	66	71	39	53	47	43	31	37	44	37	44	61	59
Annite	26	30	34	29	61	47	53	57	69	63	56	63	56	39	41

General formula: I₂ M₄ T₈ O₂₀ A₄¹All Fe reported as Fe²⁺C_H₂O = calculated H₂O

Table C-3: WDS Data - Biotite

Sample (EMMD)	182-249-6	182-249-6	001-14	001-14	001-14	001-14	008-15	008-15	008-15	008-15	055-15	055-15	055-10	055-10	055-10
Spot	S3	S4	S2	S3	S4	S5	S1	S2	S3	S4	S1	S2	S1	S2	S3
SiO ₂	35.92	36.43	38.76	37.79	38.04	39.37	37.97	38.93	38.01	38.12	38.05	36.80	38.51	37.48	36.68
TiO ₂	1.13	0.86	0.54	0.63	0.58	0.63	2.28	1.70	1.69	1.96	0.79	1.01	0.86	1.03	1.07
Al ₂ O ₃	13.80	14.48	14.47	14.25	14.54	13.94	16.29	14.85	15.46	16.40	13.42	14.28	14.47	15.09	15.16
FeO ¹	16.92	14.77	9.65	10.31	9.99	9.13	16.03	16.66	15.84	15.59	16.07	12.46	12.79	13.81	12.86
MnO	0.08	0.06	0.19	0.19	0.12	0.18	0.12	0.10	0.13	0.12	0.10	0.15	0.05	0.10	0.08
MgO	12.49	13.76	17.72	17.91	17.79	19.28	12.45	12.80	13.21	12.88	14.38	15.38	15.41	14.93	14.71
CaO	0.00	0.00	0.06	0.07	0.02	0.03	0.00	0.01	0.00	0.00	0.00	0.03	0.00	0.00	0.00
Na ₂ O	0.09	0.10	0.24	0.26	0.25	0.22	0.05	0.12	0.05	0.06	0.07	0.28	0.37	0.33	0.29
K ₂ O	7.57	7.47	8.71	8.46	8.66	9.50	9.72	9.07	9.70	10.00	9.31	7.82	8.01	8.35	8.09
F	2.87	3.03	3.74	4.02	3.61	3.75	0.47	0.86	0.95	0.62	3.42	3.65	3.08	3.43	3.60
Cl	1.04	0.64	0.03	0.02	0.02	0.05	0.11	0.50	0.52	0.34	0.97	0.08	0.09	0.05	0.06
Total	91.90	91.60	94.11	93.90	93.62	96.07	95.48	95.60	95.57	96.09	96.59	91.93	93.65	94.61	92.59
Cations on the basis of 24 total O															
C_H ₂ O	2.07	2.15	2.15	1.99	2.19	2.22	3.74	3.44	3.37	3.63	2.00	2.04	2.42	2.25	2.09
O-F-Cl	1.44	1.42	1.58	1.70	1.52	1.59	0.22	0.47	0.52	0.34	1.66	1.55	1.32	1.46	1.53
T-Si	5.82	5.83	5.90	5.82	5.83	5.89	5.70	5.88	5.76	5.71	5.90	5.82	5.92	5.78	5.77
T-Al	2.18	2.17	2.10	2.18	2.17	2.11	2.30	2.12	2.24	2.29	2.10	2.18	2.08	2.22	2.23
T-Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sum_T	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
M-Al	0.46	0.56	0.50	0.40	0.46	0.34	0.59	0.52	0.52	0.60	0.35	0.48	0.54	0.52	0.58
M-Ti	0.14	0.10	0.06	0.07	0.07	0.07	0.26	0.19	0.19	0.22	0.09	0.12	0.10	0.12	0.13
M-Fe ²⁺	2.29	1.98	1.23	1.33	1.28	1.14	2.01	2.10	2.01	1.95	2.08	1.65	1.64	1.78	1.69
M-Mn	0.01	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.01	0.02	0.01	0.01	0.01
M-Mg	3.02	3.28	4.02	4.11	4.07	4.30	2.79	2.88	2.98	2.87	3.32	3.62	3.53	3.43	3.45
Sum_M	5.92	5.93	5.84	5.94	5.90	5.87	5.66	5.71	5.72	5.66	5.86	5.89	5.83	5.86	5.85
I-Ca	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-Na	0.03	0.03	0.07	0.08	0.08	0.06	0.01	0.03	0.02	0.02	0.02	0.09	0.11	0.10	0.09
I_K	1.57	1.52	1.69	1.66	1.69	1.81	1.86	1.75	1.88	1.91	1.84	1.58	1.57	1.64	1.62
sum_I	1.59	1.56	1.77	1.75	1.77	1.88	1.88	1.78	1.89	1.93	1.86	1.67	1.68	1.74	1.71
A_F	1.47	1.53	1.80	1.96	1.75	1.77	0.22	0.41	0.45	0.29	1.68	1.83	1.50	1.67	1.79
A_Cl	0.29	0.17	0.01	0.00	0.00	0.01	0.03	0.13	0.13	0.09	0.26	0.02	0.02	0.01	0.02
A_OH	2.24	2.29	2.19	2.04	2.24	2.21	3.75	3.46	3.41	3.62	2.07	2.15	2.48	2.31	2.19
sum_A	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Fe/(Fe+Mg)	0.43	0.38	0.23	0.24	0.24	0.21	0.42	0.42	0.40	0.40	0.39	0.31	0.32	0.34	0.33
Endmembers (%)															
Phlogopite	57	62	77	76	76	79	58	58	60	60	61	69	68	66	67
Annite	43	38	23	24	24	21	42	42	40	40	39	31	32	34	33

Table C-4: Modal Mineralogy of MLA Samples

EMMD153-7 (76.55m)						
Mineral	Wt.%	Area %	Area (μ^2)	Grain Count	Mean Grain Size	Max Grain Size
Magnetite	30.31	22.61	1009212	3113	14.0	512.9
Siderite-Mn-Ca	28.37	27.52	1228333	3838	20.1	300.0
Quartz	8.94	13.08	583818	1133	26.3	489.4
Fluorite	7.94	9.74	434850	2932	13.6	167.8
Siderite-Mn-Mg	5.58	5.41	241474	5135	7.3	66.9
Chalcopyrite	4.49	4.11	183442	382	22.8	312.3
Pyrite	2.84	2.18	97264	735	9.8	148.7
Calcite-Fe	2.78	3.94	175690	5886	5.4	42.5
Chlorite	2.36	3.08	137334	4287	5.5	121.6
Orthoclase	1.68	2.52	112396	595	16.4	136.7
Apatite	1.22	1.47	65454	545	11.1	66.0
Dolomite-Fe-Mn	1.19	1.61	71697	3567	4.0	35.5
Biotite-Ti-Cl	0.80	0.99	44024	1769	4.8	31.7
Muscovite-Ti	0.43	0.58	25803	671	6.0	61.8
Monazite	0.32	0.24	10715	24	24.9	89.2
Muscovite	0.18	0.24	10858	306	5.7	25.2
Paracelsian	0.17	0.19	8484	172	7.4	49.0
Calcite	0.13	0.19	8354	559	3.2	10.6
Bastnasite-(La)	0.08	0.06	2803	9	22.2	69.1
Ilmenite-Mn	0.05	0.04	1964	72	4.5	21.8
Brannerite	0.04	0.03	1272	35	6.3	15.6
Rutile-alt-Fe	0.03	0.03	1370	45	5.0	19.7
Rutile	0.03	0.02	1067	23	6.8	22.0
Molybdenite	0.02	0.01	656	20	5.7	15.8
Albite	0.01	0.01	656	42	3.5	8.7
Roentgenite-Synchysite	0.01	0.01	339	25	3.5	8.7
Scheelite	0.01	0.00	179	16	2.4	4.4
Unknown	0.00	0.07	3320	25	-	-
No_XRay	0.00	0.01	625	75	-	-
Total	100.00	100.00	4463513	36039	9.9	512.9

EMMD153-13 (311.7m)						
Mineral	Wt%	Area%	Area (μ^2)	Grain Count	Mean Grain Size	Max Grain Size
Dolomite-Fe-Mn	22.42	26.07	1317131	3945	11.5	712.6
Pyrite	16.77	11.09	560347	50	125.6	719.5
Magnetite	16.62	10.70	540284	130	57.1	563.5
Quartz	10.90	13.76	695176	661	34.9	370.1
Calcite	9.46	11.57	584544	2177	15.4	285.2
Chlorite	9.43	10.60	535422	1747	19.0	343.2
Biotite-Ti-Cl	4.56	4.87	246235	4984	5.9	265.3
Albite	4.42	5.59	282326	1136	10.7	386.5
Apatite	2.28	2.37	119647	76	24.2	390.4
Muscovite-Ti	0.93	1.10	55339	1033	7.8	108.9
Scheelite	0.80	0.44	22359	1431	3.7	19.8
Muscovite	0.35	0.41	20934	875	4.7	33.5
Ilmenite-Mn	0.33	0.23	11618	97	11.4	76.4
Roentgenite-Synchysite	0.16	0.14	6874	87	10.0	61.8
Orthoclase	0.12	0.15	7698	353	4.7	82.7
Paracelsian	0.11	0.11	5451	245	4.7	27.3
Calcite-Fe	0.09	0.11	5451	338	3.1	47.0
Rutile-alt-Fe	0.08	0.06	3152	60	7.7	42.0
Chalcopyrite	0.08	0.06	3071	42	10.3	53.3
Siderite-Mn-Ca	0.05	0.04	1934	88	4.7	23.1
Biotite-Ba	0.04	0.04	2253	128	3.6	62.8
Barite	0.01	0.00	251	4	10.5	14.5
Unknown	0.00	0.47	23618	214	-	-
Total	100.00	100.00	5051328	19915	17.8	719.5

Table C-4: Modal Mineralogy of MLA Samples
EMMD075-205.3m

Mineral	Wt%	Area%	Area (μ^2)	Grain Count	Mean Grain Size	Max Grain Size
Ankerite-Mg-Fe-Mn	14.98	20.36	1112808	10188	6.8	395.8
Biotite	0.36	0.45	24482	995	4.4	36.0
Muscovite	0.01	0.02	843	42	3.8	9.3
Quartz	0.95	1.41	77101	122	25.7	151.0
Albite	2.19	3.26	178421	335	24.0	263.2
Orthoclase	0.03	0.05	2606	59	6.1	36.2
Paracelsian	0.27	0.31	17012	765	4.2	21.9
Chlorite	2.14	2.84	155202	1224	12.2	111.9
Apatite	1.79	2.19	119769	674	13.7	93.7
Fluorite	12.42	15.5	847244	1344	25.5	357.5
Barite	24.91	21.72	1187075	979	37.4	518.3
Magnetite	29	21.99	1202141	649	45.4	466.6
Ilmenite-Mn	0.15	0.13	6917	357	3.7	15.6
Rutile	0.01	0.01	678	22	5.4	15.6
Pyrite	1.63	1.27	69461	359	11.2	155.4
Chalcopyrite	8.39	7.81	426670	704	25.8	334.7
Molybdenite	0.01	0.01	424	16	4.8	11.7
Monazite	0	0	22	1	-	4.4
Bastnasite-(La)	0.14	0.11	6167	24	21.7	109.9
Roentgenite-Synchysite	0.46	0.45	24808	1321	3.6	19.8
Scheelite	0.14	0.09	5092	212	4.2	21.9
Brannerite	0.01	0.01	379	15	4.0	15.6
Coffinite	0	0	170	6	5.4	9.1
Not measured	0	0	232	2	-	-
Total	100	100	5465728	20415	13.6	518.3

EMMD001-5 (59.9m)

Mineral	Wt%	Area%	Area (μ^2)	Grain Count	Mean Grain Size	Max Grain Size
Albite	31.23	34.55	1693364	3291	23.0	655.7
Muscovite-Ba	18.24	18.71	917067	7204	11.5	325.7
Chlorite	16.11	15.83	775940	6253	11.5	410.6
Quartz	9.61	10.62	520239	2577	13.8	367.8
Magnetite	8.63	4.86	238020	1188	14.8	133.0
Muscovite	8.30	8.51	417102	10027	6.2	98.8
Biotite-Ti-Cl	4.78	4.47	218907	9895	4.0	27.7
Rutile-alt-Fe	1.06	0.73	35536	611	8.0	62.8
Ilmenite-Mn	0.50	0.31	15218	451	5.6	27.8
Orthoclase	0.48	0.54	26468	1469	3.3	19.1
Rutile	0.45	0.31	15146	160	11.1	65.3
Apatite	0.35	0.32	15704	188	9.8	51.4
Paracelsian	0.24	0.21	10179	503	3.9	21.1
Biotite-Ba	0.01	0.01	455	31	2.8	4.4
Siderite-Mn-Ca	0.00	0.00	31	2	2.4	2.4
Unknown	0.00	0.03	1281	10	-	-
Total	100.00	100.00	4900657	43860	8.8	655.7

Table C-4: Modal Mineralogy of MLA Samples
EMMD055-14 (155.35m)

Mineral	Wt%	Area%	Area (μ^2)	Grain Count	Mean Grain Size	Max Grain Size
Magnetite	33.97	24.68	1328502	1763	30.5	223.1
Chlorite	19.22	24.38	1312570	3154	18.9	829.1
Fluorite	15.07	18.02	970074	1673	22.3	455.1
Chalcopyrite	11.38	10.14	545743	367	43.5	546.5
Siderite-Mn-Mg	4.09	3.86	207808	3306	8.5	208.0
Quartz	3.80	5.41	291327	152	46.3	465.2
Apatite	2.55	2.99	160718	491	18.1	185.5
Pyrite	1.89	1.41	76039	297	12.2	149.8
Calcite-Fe	1.79	2.47	132706	5421	4.5	53.1
Barite	1.62	1.36	73036	202	23.9	596.8
Biotite-Ba	1.55	1.88	100932	356	16.8	359.7
Biotite-Ti-Cl	0.77	0.92	49768	2092	4.2	41.2
Dolomite-Fe-Mn	0.62	0.82	44051	2018	4.0	42.3
Siderite-Mn-Ca	0.52	0.49	26593	1224	3.9	25.0
Roentgenite-Synchysite	0.32	0.30	16329	75	16.4	72.5
Rutile	0.22	0.20	10626	103	9.9	61.3
Rutile-alt-Fe	0.16	0.14	7765	265	4.8	29.9
Coffinite	0.12	0.09	4695	61	10.4	38.4
Calcite	0.10	0.14	7792	269	4.8	23.2
Albite	0.06	0.08	4414	266	3.5	19.7
Molybdenite	0.05	0.04	1897	33	8.9	40.6
Muscovite-Ba	0.05	0.06	3409	57	8.4	45.8
Muscovite	0.02	0.03	1522	30	6.8	32.7
Ilmenite-Mn	0.02	0.02	826	46	3.1	12.8
Paracelsian	0.01	0.01	696	23	5.1	25.0
Brannerite	0.01	0.01	361	13	5.2	9.8
Unknown	0.00	0.04	2325	14	-	-
Total	100.00	100.00	5382718	23781	13.3	829.1

EMMD182-94.5m

Mineral	Wt%	Area%	Area (μ^2)	Grain Count	Mean Grain Size	Max Grain Size
Biotite-Ti-Cl	41.74	39.69	2129307	5767	8.7	1320.8
Muscovite-Ti	18.68	19.49	1045498	12097	9.0	705.8
Dolomite-Fe-Mn	12.24	12.66	678949	1592	17.4	463.5
Muscovite	10.04	10.48	562098	8561	7.7	200.2
Albite	8.84	9.94	533551	1189	19.2	660.8
Chlorite	4.54	4.54	243442	1243	14.8	492.0
Ilmenite-Mn	2.37	1.49	79766	337	19.1	98.6
Orthoclase	0.57	0.66	35505	745	6.8	64.7
Calcite	0.36	0.39	21091	187	9.2	186.7
Rutile-alt-Fe	0.26	0.18	9858	246	6.1	42.8
Quartz	0.25	0.28	14963	86	14.4	106.0
Apatite	0.07	0.07	3579	17	17.3	95.2
Paracelsian	0.02	0.02	928	50	3.5	9.4
Rutile	0.01	0.01	357	7	7.2	13.2
Unknown	0.00	0.11	5730	45	-	-
Total	100.00	100.00	5365050	32187	11.5	1320.8

Table C-4: Modal Mineralogy of MLA Samples

EMMD146-215m						
Mineral	Wt%	Area%	Area (μ^2)	Grain Count	Mean Grain Size	Max Grain Size
Albite	55.88	61.16	3310354	672	35.4	1364.1
Chlorite	15.04	14.62	791568	3003	15.8	488.3
Magnetite	10.50	5.85	316402	469	29.7	143.4
Calcite	9.99	10.57	572251	705	32.6	328.4
Muscovite-Ba	1.74	1.77	95635	3070	4.7	56.0
Quartz	1.46	1.60	86460	513	12.0	139.6
Biotite-Ti-Cl	1.30	1.20	64936	3441	3.7	26.8
Rutile-alt-Fe	1.12	0.76	40900	751	7.1	104.5
Rutile	0.75	0.51	27369	269	11.2	80.8
Muscovite	0.53	0.54	29168	975	4.7	38.7
Dolomite-Fe-Mn	0.52	0.53	28548	1459	3.8	26.1
Ilmenite-Mn	0.47	0.28	15392	385	6.2	65.1
Apatite	0.33	0.30	16128	71	19.3	72.8
Paracelsian	0.33	0.28	15280	752	3.8	26.1
Orthoclase	0.02	0.02	1330	69	3.3	10.6
Calcite-Fe	0.01	0.01	424	26	3.4	4.4
Siderite-Mn-Ca	0.01	0.00	201	14	-	-
Total	100.00	100.00	5412591	16658	12.3	1364.1

EMMD167-105m						
Mineral	Wt%	Area%	Area (μ^2)	Grain Count	Mean Grain Size	Max Grain Size
Muscovite-Sericite	51.37	50.05	2712889	6852	12.8	1368.6
Quartz	39.60	41.52	2250701	7776	12.2	1330.6
Biotite	4.07	3.61	195643	6018	5.4	61.1
Dolomite-Fe-Mn	2.56	2.48	134219	1314	10.1	110.4
Chlorite	1.73	1.61	87401	871	10.3	139.4
Apatite	0.27	0.23	12478	126	11.1	90.6
Paracelsian	0.27	0.22	11844	500	4.1	19.0
Rutile	0.06	0.04	2280	40	7.1	31.4
Rutile-alt-Fe	0.04	0.03	1473	63	4.1	18.5
Albite	0.02	0.02	1200	8	21.8	38.7
Titanite	0.02	0.01	652	31	3.9	11.4
Calcite	0.00	0.00	45	2	3.3	4.3
Coffinite	0.00	0.00	13	1	-	2.4
Unknown	0.00	0.18	9497	81	-	-
Total	100.00	100.00	5420333	23683	8.8	1368.6

EMMD085-112m						
Mineral	Wt%	Area%	Area (μ^2)	Grain Count	Mean Grain Size	Max Grain Size
Muscovite-Sericite	45.05	47.33	2586493	1007	16.2	1368.9
Actinolite	23.32	22.77	1244528	2962	11.7	923.5
Biotite	17.01	16.29	890032	15727	6.7	327.8
Clinozoisite-Pumpellyite	5.55	4.92	268964	1570	11.7	251.4
Chlorite	5.32	5.36	292706	4101	7.8	217.4
Titanite	2.78	2.37	129720	283	13.4	426.3
Calcite	0.35	0.38	20698	263	9.7	66.9
Apatite	0.18	0.17	9037	4	49.5	136.0
Albite	0.16	0.18	9666	124	7.7	85.6
Magnetite	0.12	0.07	3780	43	10.9	53.2
Quartz	0.07	0.08	4168	80	6.9	30.1
Dolomite-Fe-Mn	0.06	0.07	3677	139	4.1	17.4
Rutile-alt-Fe	0.01	0.01	375	10	6.3	22.2
Total	100.00	100.00	5464933	26339	12.5	1368.9

Table C-4: Modal Mineralogy of MLA Samples
EMMD085-310.5m

Mineral	Wt%	Area%	Area (μ^2)	Grain Count	Mean Grain Size	Max Grain Size
Magnetite	18.66	12.46	855317	1384	25.4	412.8
Barite	15.76	12.10	830291	1281	27.8	374.4
Quartz	15.43	20.21	1387190	906	38.4	595.8
Muscovite-Sericite	11.04	13.44	922556	5164	12.6	237.7
Calcite	9.35	11.87	814421	4370	10.7	536.3
Fluorite	8.80	9.67	663539	1449	19.6	593.6
Chalcopyrite	8.20	6.71	460836	604	29.7	302.1
Biotite	4.21	4.67	320423	7621	6.5	103.6
Pyrite	3.28	2.25	154564	418	18.1	180.7
Chlorite	2.68	3.12	214332	4124	7.3	123.1
Apatite	1.54	1.67	114289	142	28.5	204.3
Dolomite-Fe-Mn	0.28	0.34	23175	599	6.4	33.7
Albite	0.20	0.26	17699	993	3.5	13.1
Siderite-Mn	0.14	0.12	8060	372	3.9	14.5
Paracelsian	0.10	0.10	6868	370	3.5	14.8
Roentgenite-Synchysite	0.09	0.08	5391	160	4.6	52.2
Titanite	0.07	0.07	4882	249	3.7	20.5
Rutile-alt-Fe	0.05	0.04	2646	77	5.5	19.8
Ilmenite-Mn	0.04	0.03	2031	75	4.9	30.3
Rutile	0.03	0.02	1589	43	6.3	17.3
Molybdenite	0.02	0.01	884	9	11.3	42.4
Brannerite	0.02	0.01	772	19	6.0	23.5
Coffinite	0.01	0.00	281	7	6.7	14.3
Unknown	0.00	0.74	51004	472	-	-
Total	100.00	100.00	6863271	30914	12.7	595.8

EMMD167-180m

Mineral	Wt%	Area%	Area (μ^2)	Grain Count	Mean Grain Size	Max Grain Size
Albite	72.35	74.77	4038508	392	32.9	1368.6
Dolomite-Fe-Mn	12.14	11.53	623018	188	40.4	639.6
Muscovite-Sericite	5.54	5.31	286784	7898	5.5	53.1
Chlorite	4.79	4.40	237538	1299	15.6	214.9
Ilmenite-Mn	2.22	1.28	69104	577	13.2	55.5
Biotite	1.17	1.02	55002	2395	4.3	31.2
Calcite	0.93	0.93	50250	385	11.3	325.5
Paracelsian	0.24	0.19	10532	491	3.8	17.4
Apatite	0.22	0.19	10219	89	11.4	41.7
Rutile-alt-Fe	0.16	0.11	5676	184	5.6	29.9
Quartz	0.15	0.15	8323	199	5.3	61.7
Titanite	0.06	0.05	2588	126	3.7	12.1
Rutile	0.01	0.01	361	13	4.2	16.3
Unknown	0.00	0.06	3316	32	-	-
Total	100.00	100.00	5401367	14272	12.1	1368.6

Appendix D
Monazite U-Pb LA-ICP-MS Data

Table D-1: Processed LA-ICP-MS U-Pb Monazite data, sample EMD033-79.5m

Spot ID	Measured Isotope Ratios									Age Estimate					
Analysis	$^{238}\text{U}/^{206}\text{Pb}$	Err 1 σ	Err 2 σ	$^{207}\text{Pb}/^{206}\text{Pb}$	Err 1 σ	Err 2 σ	$^{206}\text{Pb}/^{238}\text{U}$	Err 1 σ	Err 2 σ	$^{207}\text{Pb}/^{235}\text{U}$	Err 1 σ	Err 2 σ	$^{207}\text{Pb}/^{206}\text{Pb}$	Err 1 σ	Err 2 σ
79-5_D_mnz23b*	4.5535	0.0674	0.1348	0.0822	0.0026	0.0052	0.2196	0.0033	0.0065	2.4885	0.0773	0.1546	1249	60	120
79-5_B_mnz14*	4.4179	0.0732	0.1464	0.1033	0.0037	0.0073	0.2264	0.0038	0.0075	3.2232	0.1119	0.2238	1683	63	127
79-5_C_mnz9*	4.4105	0.0741	0.1482	0.0864	0.0034	0.0068	0.2267	0.0038	0.0076	2.7022	0.1041	0.2083	1347	73	147
79-5_D_mnz25	4.4016	0.0849	0.1697	0.0993	0.0048	0.0095	0.2272	0.0044	0.0088	3.1113	0.1453	0.2907	1611	86	173
79-5_D_mnz23*	4.3571	0.0687	0.1374	0.0866	0.0030	0.0061	0.2295	0.0036	0.0072	2.7405	0.0948	0.1896	1351	66	132
79-5_B_mnz11b	4.3256	0.0653	0.1306	0.0908	0.0028	0.0056	0.2312	0.0035	0.0070	2.8954	0.0886	0.1771	1443	57	115
79-5_B_mnz20b*	4.2240	0.0689	0.1377	0.0823	0.0032	0.0063	0.2367	0.0039	0.0077	2.6862	0.1012	0.2024	1252	73	146
79-5_B_mnz12*	4.2205	0.0866	0.1731	0.0928	0.0049	0.0098	0.2369	0.0049	0.0097	3.0315	0.1563	0.3127	1483	97	194
79-5_B_mnz17	4.2109	0.0695	0.1390	0.0904	0.0034	0.0068	0.2375	0.0039	0.0078	2.9613	0.1091	0.2182	1434	69	139
79-5_B_mnz18	4.1843	0.0660	0.1320	0.0931	0.0032	0.0063	0.2390	0.0038	0.0075	3.0674	0.1023	0.2046	1489	62	125
79-5_C_mnz1	4.1225	0.0811	0.1621	0.0926	0.0046	0.0092	0.2426	0.0048	0.0095	3.0966	0.1504	0.3007	1479	91	183
79-5_C_mnz10	4.0581	0.0649	0.1298	0.0932	0.0031	0.0063	0.2464	0.0039	0.0079	3.1666	0.1053	0.2107	1491	62	124
79-5_C_mnz7	4.0253	0.0682	0.1364	0.0888	0.0035	0.0070	0.2484	0.0042	0.0084	3.0418	0.1180	0.2359	1399	73	147
79-5_B_mnz11	4.0093	0.0757	0.1514	0.0916	0.0042	0.0085	0.2494	0.0047	0.0094	3.1506	0.1424	0.2848	1459	85	171
79-5_C_mnz8	3.8746	0.0704	0.1408	0.0842	0.0038	0.0076	0.2581	0.0047	0.0094	2.9978	0.1325	0.2650	1298	85	170
79-5_B_mnz15*	3.8476	0.0767	0.1534	0.0980	0.0048	0.0096	0.2599	0.0052	0.0104	3.5122	0.1673	0.3346	1586	88	177
79-5_C_mnz5	3.8251	0.0632	0.1264	0.0912	0.0033	0.0066	0.2614	0.0043	0.0086	3.2869	0.1171	0.2342	1450	67	134

*rejected prior to generating concordia and weighted averages due to anomalously high or low age

Spreadsheet template provided by Rob Holm

Table D-1: Processed LA-ICP-MS U-Pb Monazite data, sample EMD033-79.5m

Spot ID	Age Estimate						Conventional Concordia					Age Estimate	
Analysis	$^{206}\text{Pb}/^{238}\text{U}$	Err 1 σ	Err 2 σ	$^{207}\text{Pb}/^{235}\text{U}$	Err 1 σ	Err 2 σ	$^{207}\text{Pb}/^{235}\text{U}$	Err 2 σ	$^{206}\text{Pb}/^{238}\text{U}$	Err 2 σ	Error Correlation (ρ)	$^{207}\text{Pb}/^{206}\text{U}$ Age	Err 2 σ
79-5_D_mnz23b*	1279	17	34	1268	22	45	2.4885	0.1546	0.2196	0.0065	0.4763	1249	120
79-5_B_mnz14*	1315	19	39	1462	26	53	3.2232	0.2238	0.2264	0.0075	0.4773	1683	127
79-5_C_mnz9*	1317	20	40	1329	28	57	2.7022	0.2083	0.2267	0.0076	0.4361	1347	147
79-5_D_mnz25	1319	23	46	1435	35	71	3.1113	0.2907	0.2272	0.0088	0.4127	1611	173
79-5_D_mnz23*	1331	19	38	1339	25	51	2.7405	0.1896	0.2295	0.0072	0.4559	1351	132
79-5_B_mnz11b	1340	18	36	1380	23	46	2.8954	0.1771	0.2312	0.0070	0.4936	1443	115
79-5_B_mnz20b*	1369	20	40	1324	27	55	2.6862	0.2024	0.2367	0.0077	0.4328	1252	146
79-5_B_mnz12*	1370	25	50	1415	39	78	3.0315	0.3127	0.2369	0.0097	0.3977	1483	194
79-5_B_mnz17	1373	20	40	1397	28	55	2.9613	0.2182	0.2375	0.0078	0.4480	1434	139
79-5_B_mnz18	1381	19	39	1424	25	51	3.0674	0.2046	0.2390	0.0075	0.4729	1489	125
79-5_C_mnz1	1400	24	49	1431	37	74	3.0966	0.3007	0.2426	0.0095	0.4050	1479	183
79-5_C_mnz10	1420	20	40	1449	25	51	3.1666	0.2107	0.2464	0.0079	0.4806	1491	124
79-5_C_mnz7	1430	21	43	1418	29	59	3.0418	0.2359	0.2484	0.0084	0.4370	1399	147
79-5_B_mnz11	1435	24	48	1445	34	69	3.1506	0.2848	0.2494	0.0094	0.4178	1459	171
79-5_C_mnz8	1480	24	48	1407	33	67	2.9978	0.2650	0.2581	0.0094	0.4111	1298	170
79-5_B_mnz15*	1489	26	53	1530	37	75	3.5122	0.3346	0.2599	0.0104	0.4184	1586	177
79-5_C_mnz5	1497	22	44	1478	27	55	3.2869	0.2342	0.2614	0.0086	0.4638	1450	134

Table D-2: Raw LA-ICP-MS U-Pb Monazite Data

Date: 23 June 2015		Isotope Ratios				Isotope Ratios Error σ_1			
Type	Analysis_#	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{208}\text{Pb}/^{232}\text{Th}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{208}\text{Pb}/^{232}\text{Th}$
Standard	NIST610-001	0.89737	0.25136	31.10315	0.51842	0.0091	0.00315	0.38146	0.00572
Standard	NIST610-002	0.89066	0.2627	32.26317	0.53437	0.00905	0.00322	0.38674	0.00585
Standard	ElkMtn-01	0.08942	0.33683	4.15304	0.06728	0.0009	0.00417	0.05096	0.00074
Standard	ElkMtn-02	0.08946	0.30742	3.79219	0.06579	0.0009	0.00382	0.04665	0.00072
Standard	ElkMtn-03	0.08924	0.27928	3.43599	0.06797	0.00089	0.00336	0.04066	0.00073
Standard	ManangMZ1	0.05857	0.09046	0.73054	0.02773	0.00065	0.00111	0.0095	0.0003
Standard	ManangMZ2	0.05831	0.08901	0.7156	0.0271	0.00065	0.00111	0.00941	0.0003
Standard	ManangMZ3	0.05747	0.0899	0.71238	0.02738	0.00065	0.00112	0.0095	0.0003
Standard	ElkMtn-04	0.08825	0.24707	3.00588	0.07349	0.00088	0.00298	0.03574	0.00079
Standard	ElkMtn-05	0.08869	0.24909	3.04561	0.07362	0.00088	0.00301	0.03628	0.00079
Standard	ElkMtn-06	0.08795	0.24566	2.97847	0.07245	0.00087	0.00297	0.03544	0.00078
Standard	ElkMtn-07	0.08957	0.23894	2.9504	0.06798	0.00089	0.00289	0.03509	0.00073
Standard	ElkMtn-08	0.08856	0.23377	2.85386	0.07189	0.00088	0.00282	0.03392	0.00077
Standard	ElkMtn-09	0.08828	0.23848	2.90231	0.07236	0.00088	0.00287	0.03443	0.00078
Standard	ManangMZ4	0.05739	0.08161	0.64585	0.02515	0.00069	0.00102	0.00891	0.00028
Standard	ManangMZ5	0.05888	0.08334	0.67653	0.02632	0.00066	0.00102	0.00875	0.00029
Standard	ManangMZ6	0.05898	0.08992	0.73135	0.02686	0.0007	0.00112	0.01007	0.0003
Standard	ManangMZ7	0.0587	0.08913	0.72142	0.02784	0.00067	0.00109	0.00949	0.00031
Standard	ManangMZ8	0.05921	0.08789	0.71764	0.02745	0.00069	0.00107	0.00951	0.0003
Standard	ManangMZ9	0.05861	0.08754	0.70741	0.0266	0.00064	0.00107	0.00903	0.00029
Unkown	79-5_C_mnz1	0.09258	0.24257	3.09664	0.06869	0.0046	0.00477	0.15036	0.00077
Unkown	79-5_C_mnz1b	0.10503	0.31105	4.50483	0.06519	0.00592	0.00705	0.24734	0.00074
Unkown	79-5_C_mnz2	0.12427	1.01315	17.36007	0.05881	0.00341	0.01727	0.4888	0.00068
Unkown	79-5_C_mnz3	0.10509	0.2495	3.61511	0.05013	0.00501	0.00503	0.16788	0.00057
Unkown	79-5_C_mnz4	0.11242	0.38436	5.95803	0.02612	0.00152	0.0047	0.0869	0.00028
Unkown	79-5_C_mnz4b	0.11206	0.05733	0.88579	0.04862	0.00186	0.00073	0.01533	0.00053
Unkown	79-5_C_mnz5	0.09118	0.26143	3.28693	0.06309	0.00329	0.00432	0.11711	0.00071
Unkown	79-5_C_mnz6	0.12102	0.17342	2.89382	0.024	0.00148	0.00221	0.04059	0.00027
Unkown	79-5_C_mnz7	0.0888	0.24843	3.04179	0.06694	0.0035	0.00421	0.11795	0.00077

Table D-2: Raw LA-ICP-MS U-Pb Monazite Data

Date: 23 June 2015		Age Estimates				Age Estimates Error σ 1			
Type	Analysis _#	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{208}\text{Pb}/^{232}\text{Th}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{208}\text{Pb}/^{232}\text{Th}$
Standard	NIST610-001	5085	1446	3522	8442	14	16	12	76
Standard	NIST610-002	5074	1504	3558	8653	14	16	12	77
Standard	ElkMtn-01	1413	1871	1665	1316	19	20	10	14
Standard	ElkMtn-02	1414	1728	1591	1288	19	19	10	14
Standard	ElkMtn-03	1409	1588	1513	1329	19	17	9	14
Standard	ManangMZ1	551	558	557	553	24	7	6	6
Standard	ManangMZ2	541	550	548	540	25	7	6	6
Standard	ManangMZ3	509	555	546	546	25	7	6	6
Standard	ElkMtn-04	1388	1423	1409	1433	19	15	9	15
Standard	ElkMtn-05	1398	1434	1419	1436	19	16	9	15
Standard	ElkMtn-06	1381	1416	1402	1414	19	15	9	15
Standard	ElkMtn-07	1416	1381	1395	1329	19	15	9	14
Standard	ElkMtn-08	1395	1354	1370	1403	19	15	9	15
Standard	ElkMtn-09	1389	1379	1383	1412	19	15	9	15
Standard	ManangMZ4	506	506	506	502	26	6	6	5
Standard	ManangMZ5	563	516	525	525	24	6	5	6
Standard	ManangMZ6	567	555	557	536	26	7	6	6
Standard	ManangMZ7	556	550	552	555	25	6	6	6
Standard	ManangMZ8	575	543	549	547	25	6	6	6
Standard	ManangMZ9	553	541	543	531	24	6	5	6
Unkown	79-5_C_mnz1	1479	1400	1432	1343	91	25	37	14
Unkown	79-5_C_mnz1b	1715	1746	1732	1277	100	35	46	14
Unkown	79-5_C_mnz2	2018	4511	2955	1155	48	55	27	13
Unkown	79-5_C_mnz3	1716	1436	1553	989	85	26	37	11
Unkown	79-5_C_mnz4	1839	2097	1970	521	24	22	13	6
Unkown	79-5_C_mnz4b	1833	359	644	960	30	4	8	10
Unkown	79-5_C_mnz5	1450	1497	1478	1237	67	22	28	13
Unkown	79-5_C_mnz6	1971	1031	1380	479	22	12	11	5
Unkown	79-5_C_mnz7	1400	1430	1418	1310	74	22	30	15

Table D-2: Raw LA-ICP-MS U-Pb Monazite Data

Date: 23 June 2015		Isotope Ratios				Isotope Ratios Error σ 1			
Type	Analysis_#	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{208}\text{Pb}/^{232}\text{Th}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{208}\text{Pb}/^{232}\text{Th}$
Unkown	79-5_C_mnz6b	0.11747	0.19288	3.12419	0.03292	0.00151	0.00237	0.04405	0.00036
Unkown	79-5_C_mnz8	0.08424	0.25809	2.99776	0.06727	0.00379	0.00469	0.13251	0.00075
Unkown	79-5_C_mnz10	0.0932	0.24642	3.16659	0.01951	0.00314	0.00394	0.10534	0.00023
Unkown	79-5_C_mnz9	0.08643	0.22673	2.70222	0.06328	0.00339	0.00381	0.10413	0.00071
Standard	ManangMZ10	0.05803	0.0893	0.71452	0.02757	0.00068	0.00109	0.00955	0.00031
Standard	ManangMZ11	0.0588	0.08838	0.71656	0.02714	0.00068	0.00108	0.00951	0.0003
Standard	ManangMZ12	0.05958	0.08491	0.69752	0.02695	0.0007	0.00102	0.0092	0.0003
Standard	ElkMtn-10	0.09051	0.35504	4.43056	0.06814	0.0009	0.00422	0.05204	0.00074
Standard	ElkMtn-11	0.08914	0.30192	3.71046	0.06765	0.00089	0.0036	0.04356	0.00074
Standard	ElkMtn-12	0.0887	0.24503	2.99637	0.0706	0.00088	0.00288	0.03484	0.00076
Standard	ElkMtn-13	0.08872	0.29417	3.59816	0.06965	0.00088	0.00348	0.04202	0.00076
Standard	ElkMtn-14	0.09224	0.60976	7.75457	0.06928	0.00092	0.00717	0.08992	0.00075
Standard	ElkMtn-15	0.08998	0.38603	4.78919	0.06645	0.0009	0.00454	0.05566	0.00072
Unkown	79-5_B_mnz11	0.09161	0.24942	3.15056	0.05174	0.00423	0.00471	0.14239	0.00076
Unkown	79-5_B_mnz11b	0.09083	0.23118	2.89541	0.06011	0.00281	0.00349	0.08856	0.00068
Unkown	79-5_B_mnz12	0.0928	0.23694	3.03145	0.06598	0.00491	0.00486	0.15633	0.00076
Unkown	79-5_B_mnz12b	0.11089	0.57325	8.76492	0.06865	0.00331	0.00927	0.26143	0.00077
Unkown	79-5_B_mnz13	0.08846	0.02011	0.24534	0.0553	0.00353	0.00033	0.00955	0.00064
Unkown	79-5_B_mnz14	0.10328	0.22635	3.2232	0.06641	0.00365	0.00375	0.11189	0.00076
Unkown	79-5_B_mnz14b	0.11596	0.01076	0.17209	0.02258	0.00449	0.00018	0.00642	0.00025
Unkown	79-5_B_mnz14c	0.10524	0.1621	2.35225	0.01749	0.00205	0.00216	0.04708	0.0002
Unkown	79-5_B_mnz15	0.09801	0.2599	3.51224	0.06672	0.00479	0.00518	0.1673	0.00076
Unkown	79-5_B_mnz16	0.14009	0.01271	0.24561	0.03439	0.00489	0.00021	0.00823	0.00039
Unkown	79-5_B_mnz17	0.09043	0.23748	2.96131	0.06939	0.00339	0.00392	0.1091	0.00096
Unkown	79-5_B_mnz18	0.09308	0.23899	3.06735	0.06987	0.00315	0.00377	0.10231	0.00079
Standard	ElkMtn-16	0.08855	0.2839	3.46602	0.07371	0.00089	0.00333	0.04043	0.0008
Standard	ElkMtn-17	0.09252	0.77951	9.94304	0.06107	0.00095	0.00886	0.11398	0.00063
Standard	ElkMtn-18	0.08842	0.2604	3.17438	0.06924	0.00092	0.00301	0.03724	0.00073
Standard	ElkMtn-19	0.08857	0.2433	2.97099	0.07172	0.00089	0.00282	0.03419	0.00078

Table D-2: Raw LA-ICP-MS U-Pb Monazite Data

Type	Analysis_#	Age Estimates				Age Estimates Error $\sigma 1$			
		$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{208}\text{Pb}/^{232}\text{Th}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{208}\text{Pb}/^{232}\text{Th}$
Unkown	79-5_C_mnz6b	1918	1137	1439	655	23	13	11	7
Unkown	79-5_C_mnz8	1298	1480	1407	1316	85	24	34	14
Unkown	79-5_C_mnz10	1492	1420	1449	391	62	20	26	5
Unkown	79-5_C_mnz9	1348	1317	1329	1240	74	20	29	13
Standard	ManangMZ10	530	551	547	550	26	6	6	6
Standard	ManangMZ11	560	546	549	541	25	6	6	6
Standard	ManangMZ12	588	525	537	538	25	6	6	6
Standard	ElkMtn-10	1436	1959	1718	1333	19	20	10	14
Standard	ElkMtn-11	1407	1701	1574	1323	19	18	9	14
Standard	ElkMtn-12	1398	1413	1407	1379	19	15	9	14
Standard	ElkMtn-13	1398	1662	1549	1361	19	17	9	14
Standard	ElkMtn-14	1472	3069	2203	1354	19	29	10	14
Standard	ElkMtn-15	1425	2104	1783	1300	19	21	10	14
Unkown	79-5_B_mnz11	1459	1436	1445	1020	86	24	35	15
Unkown	79-5_B_mnz11b	1443	1341	1381	1180	58	18	23	13
Unkown	79-5_B_mnz12	1484	1371	1416	1292	97	25	39	14
Unkown	79-5_B_mnz12b	1814	2921	2314	1342	53	38	27	15
Unkown	79-5_B_mnz13	1393	128	223	1088	75	2	8	12
Unkown	79-5_B_mnz14	1684	1315	1463	1300	64	20	27	14
Unkown	79-5_B_mnz14b	1895	69	161	451	68	1	6	5
Unkown	79-5_B_mnz14c	1719	968	1228	351	35	12	14	4
Unkown	79-5_B_mnz15	1587	1489	1530	1306	89	26	38	14
Unkown	79-5_B_mnz16	2228	81	223	683	59	1	7	8
Unkown	79-5_B_mnz17	1435	1374	1398	1356	70	20	28	18
Unkown	79-5_B_mnz18	1490	1381	1425	1365	63	20	26	15
Standard	ElkMtn-16	1394	1611	1520	1437	19	17	9	15
Standard	ElkMtn-17	1478	3715	2430	1198	20	32	11	12
Standard	ElkMtn-18	1392	1492	1451	1353	20	15	9	14
Standard	ElkMtn-19	1395	1404	1400	1400	19	15	9	15

Table D-2: Raw LA-ICP-MS U-Pb Monazite Data

Date: 23 June 2015		Isotope Ratios				Isotope Ratios Error σ_1			
Type	Analysis_#	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{208}\text{Pb}/^{232}\text{Th}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{208}\text{Pb}/^{232}\text{Th}$
Standard	ElkMtn-20	0.08968	0.27946	3.45551	0.07016	0.00092	0.00323	0.04013	0.00075
Standard	ElkMtn-21	0.12477	3.60174	61.96347	0.07005	0.00129	0.04234	0.73564	0.00076
Standard	ManangMZ13	0.05826	0.08954	0.71935	0.02752	0.00064	0.00105	0.00895	0.0003
Standard	ManangMZ14	0.05891	0.08701	0.70673	0.02717	0.00068	0.00103	0.00911	0.0003
Standard	ManangMZ15	0.05892	0.08558	0.69527	0.02687	0.00068	0.00102	0.00902	0.0003
Unkown	79-5_B_mnz20	0.0989	0.25424	3.46689	0.06271	0.00401	0.00445	0.13761	0.00073
Unkown	79-5_B_mnz20b	0.08229	0.23674	2.68624	0.06166	0.00315	0.00386	0.1012	0.00071
Unkown	79-5_B_mnz19	0.12338	0.6608	11.24054	0.07349	0.00478	0.01291	0.43069	0.00084
Unkown	79-5_B_mnz22	0.08135	0.18567	2.0823	0.02185	0.0051	0.00401	0.12714	0.00027
Unkown	79-5_B_mnz22b	0.09412	0.19882	2.57992	0.03918	0.0041	0.00356	0.10956	0.00046
Unkown	79-5_D_mnz23	0.08661	0.22951	2.74053	0.06576	0.00304	0.00362	0.09481	0.00077
Unkown	79-5_D_mnz23b	0.08218	0.21961	2.48847	0.06105	0.00258	0.00325	0.07732	0.0007
Unkown	79-5_D_mnz24	0.54398	-1.07872	-80.87154	0.08476	0.24783	1.33594	102.07291	0.02406
Unkown	79-5_D_mnz25	0.09933	0.22719	3.11133	0.06649	0.00477	0.00438	0.14533	0.00077
Standard	ElkMtn-22	0.09228	0.64215	8.17134	0.06221	0.00093	0.00737	0.09308	0.00068
Standard	ElkMtn-23	0.08839	0.239	2.9129	0.07168	0.00089	0.00274	0.03324	0.00078
Standard	ElkMtn-24	0.08812	0.25458	3.09304	0.07252	0.00092	0.00294	0.0364	0.00078
Standard	ManangMZ16	0.05867	0.08722	0.70556	0.02746	0.00068	0.00103	0.00906	0.00031

Table D-2: Raw LA-ICP-MS U-Pb Monazite Data

Date: 23 June 2015		Age Estimates				Age Estimates Error $\sigma 1$			
Type	Analysis_#	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{208}\text{Pb}/^{232}\text{Th}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{208}\text{Pb}/^{232}\text{Th}$
Standard	ElkMtn-20	1419	1589	1517	1371	19	16	9	14
Standard	ElkMtn-21	2026	9840	4206	1368	18	59	12	14
Standard	ManangMZ13	539	553	550	549	25	6	5	6
Standard	ManangMZ14	564	538	543	542	25	6	5	6
Standard	ManangMZ15	564	529	536	536	25	6	5	6
Unkown	79-5_B_mnz20	1604	1460	1520	1229	74	23	31	14
Unkown	79-5_B_mnz20b	1253	1370	1325	1209	73	20	28	14
Unkown	79-5_B_mnz19	2006	3270	2543	1433	67	50	36	16
Unkown	79-5_B_mnz22	1230	1098	1143	437	118	22	42	5
Unkown	79-5_B_mnz22b	1511	1169	1295	777	80	19	31	9
Unkown	79-5_D_mnz23	1352	1332	1340	1287	66	19	26	15
Unkown	79-5_D_mnz23b	1250	1280	1269	1198	60	17	23	13
Unkown	79-5_D_mnz24	4365	-NaN	-NaN	1644	542	*****	*****	448
Unkown	79-5_D_mnz25	1612	1320	1436	1301	87	23	36	15
Standard	ElkMtn-22	1473	3198	2250	1220	19	29	10	13
Standard	ElkMtn-23	1391	1382	1385	1399	19	14	9	15
Standard	ElkMtn-24	1385	1462	1431	1415	20	15	9	15
Standard	ManangMZ16	555	539	542	548	25	6	5	6

Appendix E

Leapfrog Modeling Database

Data Summary

The geological and geochemical models developed in Leapfrog and discussed in Chapter 3 can be accessed digitally in the disc accompanying this volume. The Leapfrog modeling methodology is outlined below. The base lithology, alteration and structure codes used to log the diamond drill holes and build the geology database are shown in Table E-1. Drill core structural measurements are shown in Table E-2. All drill core measurements were made using a goniometer on oriented core. Dip and dip direction were calculated using GeoCalculator (developed by R. Holcombe). Following the structural data is a geologic map of the E1 North open pit, and then logs of the 23 physically-logged diamond holes. Lastly, summary statistics (Table E-3) and probability plots of elements modeled in Chapter 3 are shown. To model the E1 Group geology, the base rock type codes were grouped into simplified stratigraphic units. The base codes are classified solely on the rock type, and not on stratigraphic level; thus, many of the codes are included in multiple units. The groupings can be viewed visually in Leapfrog. The log database is available as a CSV file on the disc.

File names:

Appendix_E_logs_DIGITAL.csv

Appendix_E_probability_plots_DIGITAL.pdf

E1_Group_Geological_Model.lfview

Leapfrog Geological and Geochemical Modeling Methodology

Modeling Faults and Geological Boundary Surfaces

An idealized workflow for creating a geological model in Leapfrog Geo can be summarized as follows. First, the X, Y, and Z extents of model must be defined. Next, 3-D surfaces must be generated for every geological contact in the model, and these surfaces comprise the Surface Chronology. Thirdly, if faults are present, the model must be subdomained into faulted blocks in order to model offset. Each fault block inherits the same surface chronology surfaces, and their parameters, from the parent model, but is treated as structurally independent from the other fault blocks. Finally, if necessary, the surfaces in each fault block are individually adjusted to reflect structural trends

within that fault block. With the exception of surfaces forming a stratigraphic sequence, each geological boundary is modeled independently of other boundaries, which may result in intersecting surfaces. Once the modeled surfaces are activated and the user has specified their timing relationships, volumes between each surface are automatically generated and the cross-cutting relationships are honored.

Multiple types of surfaces may be modeled in Leapfrog, depending on the abstract nature of the contact being modeled, and include Intrusion, Deposit, Erosion, and Stratigraphic Sequence. For example, consider two conformable sedimentary (or volcanic) lithologies, A and B (A being older), which are intruded by granite. The contact surface between A and B can be modeled as a deposit by specifying B as the 'primary' lithology (deposited on top of A) and modeling all contacts with A that are below B. Such contacts are transformed into points which then define a surface. Intervals of A are 'avoided' by the software, which prevents the surface from crossing through the interval. Other contacts between lithology B and the younger granite are ignored, which permits the surface to intersect granite intervals. To model the granite intrusion, Leapfrog interpolates positive numerical values (increasing inward) for the interior of the intrusion, and negative values (becoming more negative outward) for the exterior. An intrusive contact surface is generated where the numerical values converge to zero. Interpolation of intrusions is similar to numerical (grade) interpolation (see next section) and can be adjusted with the same parameters (e.g. range). Both intrusive and deposit surfaces can be manually adjusted with polyline digitization if the initial modeled surface is not geologically reasonable. The A-B contact will intersect the intrusion surface, but the volume of the intrusion which overlaps with the volumes of lithologies A and B will be subtracted from the A and B volumes for the final model output. In the case of unconformable contacts, an 'Erosion' surface can be modeled in a similar manner to a depositional surface. However, lithologies older than the primary lithology will be truncated at the unconformity surface when the output volumes are generated. Systems characterized by continuous or partially-continuous layering can be modeled as a Stratigraphic Sequence. The surfaces of each stratigraphic unit are modeled in similar manner to Deposit surfaces, but the software maintains parallel topology between the surfaces and does not allow them to intersect. The Stratigraphic Sequence surface type is thus well-suited to folded systems if continuity is reasonable. As is the case for this study, lithologies can be grouped to reduce complexity. Fault

offset can be modeled by applying fault block boundary filters to surfaces such that they are not affected by data outside the fault block.

Modeling grade distribution

Leapfrog Geo utilizes Fast Radial Basis Functions (RBF) to interpolate numerical data for implicit modeling of element grade shells (Cowan et al., 2003). Stewart et al. (2014) have demonstrated that, although less statistically robust, Fast-RBF can produce comparable results to ordinary and dual kriging, but in far less computational time. Such speed enables further refinement of the model in reasonable timeframes (hours or days). The aim of this study was to gain insight into the structural geometry and alteration patterns of the E1 Group by modeling the spatial distribution of various elements in the hydrothermal system. The shells presented in this study were not used for resource estimation.

To interpolate using Fast-RBF, the user must specify the model drift (linear or constant), RBF interpolation type (linear or spheroidal), and trend (isotropic or anisotropic). The detailed nature of these parameters is discussed in Stewart et al. (2014). For most ore deposits, a spheroidal RBF is much more geologically realistic than a linear RBF, and as such a spheroidal model was used for all interpolants in this study, including the initial model. Once the interpolation has been computed, grade shells are generated as isosurfaces of user-specified value. Depending on the nature of ore deposit (i.e. timing relative to faulting), interpolated grade shells can be modeled either independently of or dependent on the geological model volumes and fault blocks. If modeled dependently, the interpolant is subdomained into each geological volume or fault block, allowing parameters to be individually specified in within each subdomain.

References

- Cowan, E., Beatson, R., Ross, H., Fright, W., McLennan, T., Evans, T. and Titley, M., (2003). Practical implicit geological modelling: *in*: Fifth International Mining Geology Conference Proceedings, Bendigo, VIC, Australia, Nov 17-19 2003, p.89–99. <https://www.ausimm.com.au/publications/publication.aspx?ID=188>.
- Stewart, M., de Lacey, J., Hodkiewicz, P.F. and Lane, R., (2014). Grade Estimation from Radial Basis Functions – How Does it Compare with Conventional Geostatistical Estimation?: *in* Ninth International Mining Geology Conference. Adelaide, Australia, p.129–139.

Table E-1: Leapfrog Modeling Codes

Lith Code	Description
HBREC	discordant breccia; polymict, red-altered, unfoliated clasts
PVOLC	porphyritic cohesive meta-andesite
CPVOLC	coarse porphyritic cohesive meta-andesite (phenocrysts >1.5cm)
SCPVOLC	heavily altered and sheared?/ brecciated CPVOLC
MVOLC	massive cohesive meta-andesite
QVOLC	massive meta-andesite? With wavy quartz veins
AVOLC	amygdaloidal cohesive meta-andesite
BVOLC	volcanic flow-top breccia/autobreccia?; defining characteristic is a "psuedo-breccia"-like appearance main difference between this and "BTUFF" - BTUFF has clear "islands" of material, representing clasts
PMSILT	porphyroblastic calcareous siliclastic rock (needle-like porphyroblasts)
DIOR	diorite
MDOL	metadolerite
PSAM	psammite
UBREC	silicified metavolcanic breccia?; unfoliated, variable alteration; red-carb-dark; subangular;
UNKN	indeterminant from core photos
VEIN	major carbonate vein
SVEIN	major silicate vein (feldspar or quartz)
VBREC	calcite infill breccia/vein
CBREC	carbonate-mtx subanular breccia (type interval 362-363m EMMD052)
FBREC	suspected fault breccia
AMPH	amphibolite (type interval in EMMD174)
SVOLC	sheared metavolcaniclastic rocks (defined by lenticular fabrics/banding, especially if amygdales present); marble may be intercalated
CBVOLC	relatively less-sheared or intact metavolcanic rocks with large-scale (> drill core width) "clasts" or "islands" forming a clast-supported breccia-like texture
SBVOLC	same as BVOLC, but in cases where shearing is less than "SVOLC" and breccia-like texture is still visible
USED	undifferentiated coarse-grained metasediments/volcaniclastics (defined by regular to sub-regular layering)
SHEAR	undifferentiated sheared metasediments/volcanics (used where no clasts visible, layering is discontinuous and protolith cannot be surmised)
MARB	undifferentiated marble; used if it has continuous layering and is whitish (indicating high carbonate content)
PMARB	porphyroblastic marble; used if porphyroblasts are visible
MSILT	undifferentiated fine-grained metasediments; dark brown; continuous layering
BSHAL	carbonaceous schist; dark grey - black; highly-deformed and interlaminated w/ qtz-py-rich layers
BTUFF	refers to the metavolcanic breccia/conglomeratic unit in E1 South and Central sandwiched between marble/seds; also present at E1 North
DAVOLC	heavily altered/deformed amygdaloidal metavolcanic basal unit below main marble horizon
SAVOLC	heavily sheared amygdaloidal? Meta-andesite; highly altered; type section EMMD032 and EMMD029
DSED	heavily deformed layered metasediment; possibly some kind of breccia? Zones variably oriented; localized unit - marker bed?

Table E-1: Leapfrog Modeling Codes

Alteration (not modelled in text due to paucity of data)	
red	Na-Ca or K - dominated
mag	magnetite-dominated
ore	mag-sulfide-dominated
redore	sulf-mag overprinting substantial red alteration
redint	intense widespread red alteration
carb	intense carbonate veining
weath	weathered zone
redsil	siliceous red-gray alteration
magred	red alteration overprinted by magnetite+sulfide
magapa	magnetite-pyrite-apatite
fspr	slightly pink-red fspr, but not fully hematite-stained
Faults/weathering	
minor	core breakage and minor weathering
high	more core breakage and high weathering, but intact
intense	core mostly disintegrated
extreme	core mostly altered to clay
complete	complete clay alteration and disintegration
Veins	
low	<5% area
moderate	5-10% area
high	10-20%
very high	>20

Table E-2: Drillcore measurements

Hole ID	Depth	Beta	Alpha	Hole dip	Hole azimuth	Feature dip	Feature dip direction	Feature	Comments	Confidence
EMMD118	256.7	32	45	57.9	99.3	73.7	302.2	carbvein		good
EMMD118	258.85	113	20	57.9	99.3	60.9	17.8	carbvein		good
EMMD118	260.2	215	50	57.9	99.3	21.7	183.2	carbvein		good
EMMD118	267.05	66	37	58.2	95.8	70.1	326.6	carbvein		good
EMMD118	268.95	65	40	58.2	95.8	67.9	324.3	carbvein		moderate
EMMD153	124.6	70	50	61	91.5	55.7	318.4	carbvein	parallel to S1?	good
EMMD153	131.3	235	42	60	94.5	37.5	181.2	carbvein		good
EMMD153	143.9	55	40	61	93	70	315	carbvein		good
EMMD153	147.15	30	50	61	93	66	294	carbvein	set	good
EMM014	66.74	355	45	74	93	61	269	F2		good
EMM014	116	139	20	74	94	58	48	F2		poor
EMM014	151.14	163	60	73	91	15	55	F2	microfold/kink?	moderate
EMMD118	275.43	285	60	58.2	95.8	48	235.3	F2		good
EMMD118	307.45	170	72	57.7	95.3	14.8	287.3	F2		good
EMMD118	327.7	210	55	58	95	17	188	F2		good
EMMD118	337.3	333	65	58	95	55	262	F2		moderate
EMMD118	340.05	80	60	58	95	46	318	F2		moderate
EMMD118	359.35	138	60	58.6	95.2	21.1	343.3	F2		moderate
EMMD118	364.65	300	55	58.6	95.2	56.6	238.7	F2		moderate
EMMD153	131.35	40	60	60	94.5	56	297.2	F2	fold axis?	moderate
EMMD153	133.6	40	42	60	94.5	72.8	304.4	F2		good
EMMD153	143.7	25	55	61	93	62	289	F2	fold axis?	good
EMMD153	144	58	60	61	93	51	306	F2	fold axis?	moderate
EMM014	97.74	310	75	74	93	28	248	microfault	carbonate infill	good
EMM014	104.69	55	65	74	94	36	310	microfault		good
EMM014	123	37	60	74	93	44	299	microfault	fault set	good
EMMD118	352.15	320	45	58.6	95.2	71.2	246.5	microfault	carbonate infill	good
EMMD118	361.1	182	42	58.6	95.2	16.6	100.3	microfault	carbonate infill	moderate
EMM014	72.9	345	60	74	93	46	263	S0		good
EMM014	78.8	340	45	74	93	60	257	S0		good
EMM014	92.7	315	32	74	93	70	233	S0		good
EMM014	97.1	330	40	74	93	64	248	S0		good
EMM014	97.71	331	42	74	93	62	249	S0		good
EMM014	104.58	348	15	74	94	89	82	S0		good
EMM014	111.3	122	32	74	94	51	26	S0		good
EMM014	117.6	350	50	74	94	56	266	S0		good
EMM014	139.6	328	27	74	93	77	244	S0		good

Table E-2: Drillcore measurements

Hole ID	Depth	Beta	Alpha	Hole dip	Hole azimuth	Feature dip	Feature dip direction	Feature	Comments	Confidence
EMM014	151.1	345	17	73	91	89	257 S0			moderate
EMMD118	272.45	340	32	58.2	95.8	88.2	258.9 S0			good
EMMD118	275.25	150	65	58.2	95.8	15.6	327.5 S0		limb of F1	good
EMMD118	275.4	326	15	58.2	95.8	78.3	62.3 S0		opposing limb	good
EMMD118	324.4	7	30	58	95	88	101 S0			good
EMMD118	328.1	153	20	58	95	43	56 S0			good
EMMD118	334.75	297	25	58	95	82	220 S0			good
EMMD118	341.8	180	60	58	95	2	275 S0			good
EMMD118	345.5	105	25	58	95	61	3 S0			moderate
EMMD118	352.1	240	20	58.6	95.2	57.5	169.8 S0			good
EMMD118	358.15	220	12	58.6	95.2	55.3	145 S0			good
EMMD118	359.37	160	15	58.6	95.2	46	67.8 S0			moderate
EMM014	85.3	130	35	74	93	46	32 S2		parallel to S0?	good
EMM014	191.4	325	30	73	90	74	239 S2		mica cleavage	good
EMM014	193.2	150	20	73	90	56	55 S2		mica cleavage	good
EMMD118	260.5	340	50	57.9	99.3	70.8	265.8 S2		fol. Volc	moderate
EMMD118	267.06	332	47	58.2	95.8	72.2	256.1 S2		layer-parallel foliation	moderate
EMMD118	347.6	28	55	58	95	65	292 S2		mica cleavage	moderate
EMMD153	147.25	35	62	61	93	54	292 S2		fol. Volc	good
EMMD009	156.12	258	55	60	270	40	29 carbvein		birds-wing veining	good
EMMD009	170.25	16	55	60	270	64	100 carbvein		vein set	good
EMMD011	294.9	50	85	60	270	33	97 F2			poor
EMMD087	157	275	68	58.7	93.5	39.1	237.2 F2			poor
EMMD153	161.1	45	65	61	93	50	296 F2		fold axis?	poor
EMMD153	188.05	108	80	61	93	27	294 F2		fold axis?	moderate
EMMD153	188.2	94	60	61	93	39	325 F2			moderate
EMMD153	216.2	298	65	60	93	47	242 F2		fold axis?	moderate
EMMD011	294.6	260	85	60	270	30	80 microfault		carbonate infill	good
EMM016	85.7	50	35	73	275	67	138 S0			good
EMM016	99.3	70	35	73	275	62	155 S0		contact	good
EMM016	137.2	315	25	73	274	77	53 S0			good
EMM016	173.2	275	30	73	274	63	18 S0			good
EMM016	182.5	352	35	73	273	72	86 S0			good
EMM016	195.35	224	35	73	272	44	327 S0			good
EMMD009	156.1	85	35	60	270	63	157 S0			good
EMMD009	195.5	322	65	60	270	52	71 S0			good
EMMD011	263.9	305	20	60	270	88	40 S0			good

Table E-2: Drillcore measurements

Hole ID	Depth	Beta	Alpha	Hole dip	Hole azimuth	Feature dip	Feature dip direction	Feature	Comments	Confidence
EMMD011	266.4	303	15	60	270	88	216 S0			good
EMMD011	280.9	124	20	60	270	56	200 S0			good
EMMD011	307	112	40	62.5	275	45.3	181.5 S0			good
EMMD072	159	190	45	70	91.5	25.4	108 S0			poor
EMMD077	285.4	115	15	62	86.5	65.1	11.7 S0	layered tuff		good
EMMD077	296	155	10	62	86.5	55	55.9 S0	layered tuff		good
EMMD087	214.8	295	20	58.5	93.2	85.1	214.4 S0			good
EMMD097	73.6	308	40	68	266.5	65.2	44.8 S0			good
EMMD097	85.5	294	40	68	266.5	61.3	33.6 S0			good
EMMD097	97.4	43	20	68	266.5	86.5	126.4 S0			good
EMMD141	245.2	108	35	64	270	51	178 S0			good
EMMD141	256.15	135	20	64	270	53	214 S0			good
EMMD153	158.7	126	35	61	93	43	15 S0			good
EMMD153	168	25	5	61	93	69	120 S0			good
EMMD153	182.8	326	25	61	93	90	243 S0			good
EMMD153	190.1	302	30	61	93	78	224 S0			good
EMMD153	198.6	244	15	61	93	64	167 S0			good
EMMD153	214	314	15	60	93	84	49 S0			good
EMMD153	216.1	90	20	60	93	73	353 S0			moderate
EMMD153	217	294	30	60	93	75	218 S0			good
EMM016	102	168	42	73	275	32	258 S2	fol. Volc		moderate
EMM016	137	310	20	73	274	81	47 S2	fabric		moderate
EMM016	195.3	276	25	73	272	68	15 S2	cleavage		moderate
EMMD011	306.5	126	50	62.5	275	31.3	182.9 S2	fol. Volc		good
EMMD069	33.1	65	40	62	90.7	65.4	320.4 S2	fabric; vesicule flattend		good
EMMD069	206.5	94	65	62	90.5	35.5	317 S2	fol. Volc		good
EMMD069	209.8	94	60	62	90.5	38.6	323.5 S2	fol. Volc		good
EMMD069	234.1	110	65	62	91.5	29.7	324.6 S2	fol. Volc		good
EMMD077	171.6	38	40	62	85.5	73.4	294.9 S2	fol. Volc		good
EMMD077	253.4	38	40	62	86.5	73.4	295.9 S2	fol. Volc		good
EMMD097	112.3	262	20	68	266.5	68.5	356.9 S2	fol. Volc		good
EMMD097	125.7	320	50	68	261.5	58.2	52.4 S2	fol. Volc		moderate
EMMD141	282.8	272	45	64	270	51	25 S2	fol. Volc		good
EMMD141	310.5	98	28	64	271.5	61.5	175.2 S2	cleavage		good
EMMD141	311.4	100	30	64	271.5	58.9	175.8 S2	cleavage		good
EMDT077	177.8	75	85	53	87	39	275 F2	layer-suparallel		moderate
EMMD016	131.8	335	75	77	86	27	252 F2			good

Table E-2: Drillcore measurements

Hole ID	Depth	Beta	Alpha	Hole dip	Hole azimuth	Feature dip	Feature dip direction	Feature	Comments	Confidence
EMMD016	133.2	300	75	77	86	24		233 F2		good
EMMD040	39	100	80	75	174	16		31 F2	parallel to S0?	poor
EMDT077	177.7	318	55	53	87	67		242 S0	layering	good
EMM014	148.6	340	30	73	91	76		253 S0	x-beds; younging?	good
EMMD011	248.5	118	17	60	270	61		196 S0		good
EMMD020	198.2	338	30	65	212	83		13 S0		good
EMMD040	38	105	85	75	174	15		14 S0		good
EMMD056	138.6	157	25	74	266.5	50.4		239.1 S0		good
EMMD061	223.2	73	60	90	0	30		253 S0		good
EMDT077	165.2	170	52	53	87	6		2 shearing	dextral shear indicator	good
EMDT077	175.9	330	35	53	87	88		243 S2	parallel to S0?	good
EMMD033	131.1	350	40	59	90.3	80.6		262.5 S2	fol. Volc	good
EMMD074	115.1	42	45	60	94.5	69.5		304.8 shearing	fol. Volc (sheared)	moderate
EMMD074	115.3	355	55	60	94.5	64.9		271.3 shearing	fol. Volc (sheared)	poor
EMMD074	135.6	334	40	60	94.5	77.7		254.4 S2	fol. Volc	good
EMMD074	140	342	35	60	94.5	83.8		259.7 S2	fol. Volc	good
EMMD074	176	359	42	60	94.5	77.9		273.7 shearing	shear zone (bottom to left)	poor
EMM008	56.6	309	50	62	265	61		50 shearing	sheared boudin	poor
EMM008	126	324	27	61	268	87		56 S0	in situ?	moderate
EMM008	143.5	290	30	62	268	72		29 S0	in situ?	moderate
EMM008	159.8	245	15	62	269	65		344 S0	sediments	moderate
EMM008	166.1	292	20	62	269	82		27 S0	cross-bedded	good
EMM008	166.8	288	25	62	269	76		26 S0		good
EMM008	187	280	20	62	270	77		18 S0		good
EMM008	199.5	294	20	62	270	83		30 S0		good
EMM008	246	284	27	62	273	73		28 S0		good
EMM008	252.4	278	30	62	273	67		25 S0		good
EMM008	297.7	160	22	62	275	42		247 shearing	up to right	moderate
EMM008	308.4	111	45	62	277	42		178 shearing	up to right	poor
EMM008	317.4	48	80	62	277	35		110 F2		moderate
EMM008	317.7	66	50	62	277	56		142 F2		poor
EMM008	317.8	45	40	62	277	72		132 F2		good
EMM008	319.5	62	45	62	277	62		142 S0		good
EMM008	320.3	278	25	62	277	72		26 contact	discordant red breccia	good
EMM008	322.6	32	50	62	277	65		119 shearing	shear fabric in red rock	good
EMM008	323.4	106	75	62	277	28		130 shearing	vein? Up to right	moderate
EMM008	324.5	61	87	62	277	30		102 S0	comp. layering	moderate

Table E-2: Drillcore measurements

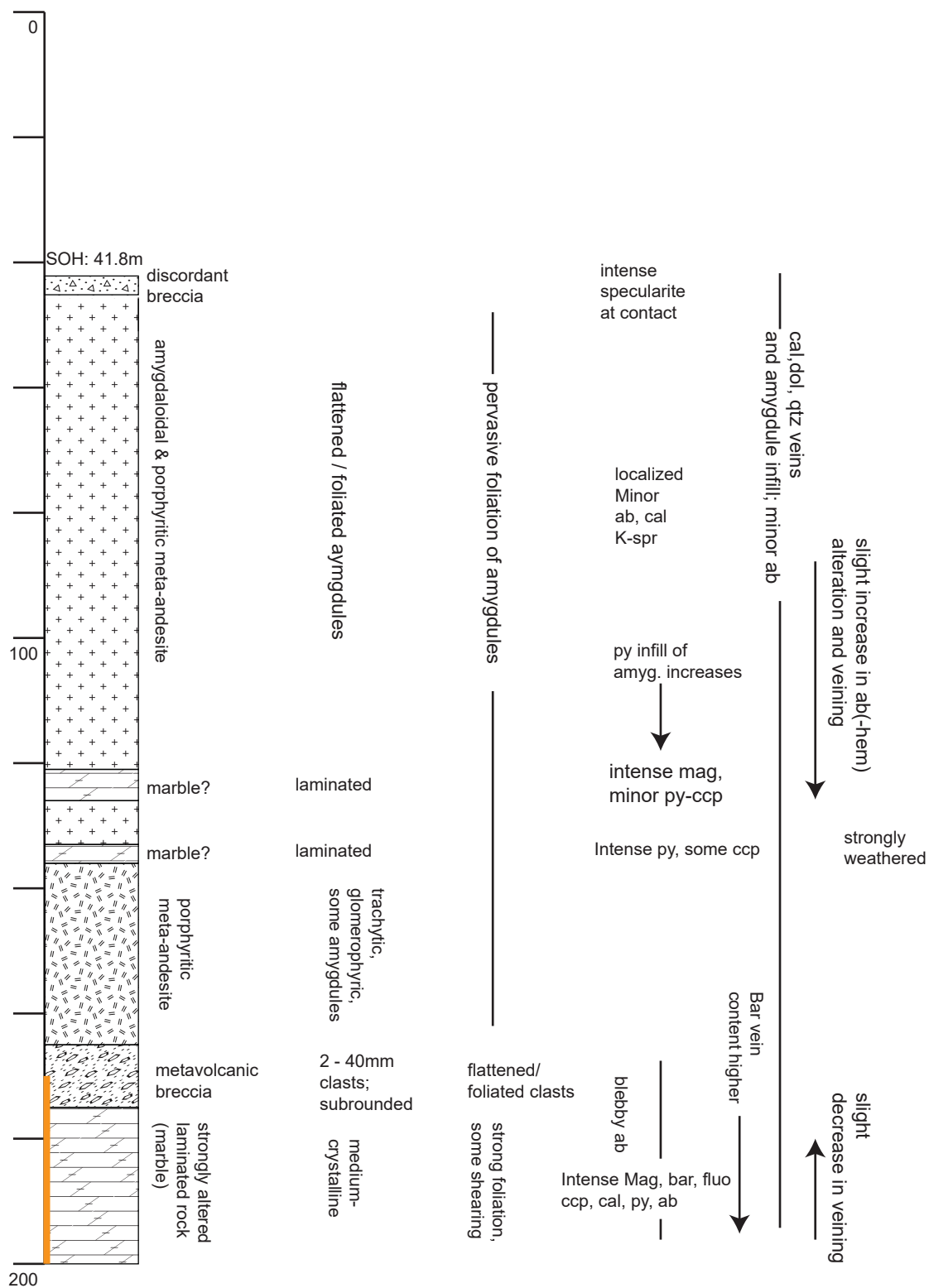
Hole ID	Depth	Beta	Alpha	Hole dip	Hole azimuth	Feature dip	Feature dip direction	Feature	Comments	Confidence
EMMD135	112	280	30	66	268	67	20 S0		marble	good
EMMD129	46.7	338	17	58	94	77	72 S0			good
EMMD192	138.1	336	30	61	275	87	74 S0			good
EMMD167	95.3	342	45	60	267	74	74 S0		shale	good
EMMD167	119.3	288	40	60	266	64	32 S0		shale	good
EMMD042	138	328	45	62	270	70	66 S0			good
EMM015	74.7	350	50	80	84	50	256 F2			moderate
EMM015	82	348	30	80	85	70	254 S2		mica cleavage	moderate
EMM015	104.8	198	15	80	88	66	107 S0		comp. layering	good
EMM015	109.7	20	35	80	89	64	287 S2		mica cleavage	moderate
EMM015	116.7	13	25	80	89	75	281 S2		mica cleavage	good
EMM015	128.7	90	15	80	90	75	357 S0			good
EMM015	137.3	15	25	80	90	75	284 S2		mica cleavage	good
EMM015	137	10	25	80	90	75	279 S2		mica cleavage	moderate
EMM015	139	140	50	80	90	33	40 F2			moderate
EMM015	143.3	100	65	80	91	25	349 F2		open fold	good
EMM015	148.2	150	15	80	91	66	59 S0			good
EMM015	148.4	120	30	80	91	55	25 F2		sheared	poor
EMM015	152.3	145	20	80	92	62	54 S0			good
EMM015	152.4	38	15	80	92	83	309 S2		mica cleavage	moderate
EMM015	158.7	124	50	80	92	35	25 F2		close fold	good
EMM015	164.7	340	65	80	94	35	259 F2		open asym. Fold	poor
EMM015	167.6	122	85	80	94	8	304 F2		open sym. Fold	moderate
EMM015	140.1	30	50	80	91	49	296 F2		recumbent close folds	good
EMM008	229.1	272	55	62	270	44	35 shearing		S0-parallel shearing	poor
EMM006	178.8	20	50	65	273	64	107 S2		fol. Volc.	good
EMM006	184.5	70	40	65	274	62	149 S2		volcanic layering (fol.?)	poor
EMM006	192.1	265	45	65	273	48	22 S2		volcanic layering (fol.?)	poor
EMM006	217	312	30	65	273	78	52 S2		fol. Volc.	good
EMM006	231.5	332	35	65	273	78	70 S2		fol. Volc.	good
EMM006	234.9	330	30	65	273	82	67 S2		fol. Volc.	good
EMM019	70.1	342	25	76	264	78	67 S0		comp. layering	moderate
EMM019	70.12	342	25	76	264	78	67 S2		S0-parallel fabric	moderate
EMM019	78	120	25	76	264	59	197 S0			good
EMM019	86.5	300	35	75	263	63	30 S0		comp. layering	good
EMM019	93.6	72	45	75	263	51	143 S0		comp. layering	good
EMM019	93.5	170	55	75	263	20	246 S2		fabric	good

Table E-2: Drillcore measurements

Hole ID	Depth	Beta	Alpha	Hole dip	Hole azimuth	Feature dip	Feature dip direction	Feature	Comments	Confidence
EMM019	138.3	338	40	75	260	64		61 S2	S0-parallel fabric	poor
EMM019	143	258	85	75	259	15		59 S2	fabric/microfolds	moderate
EMM019	136.6	350	40	75	260	65		72 shearing	fabric of deformed qtz sulf-carb	poor
EMM019	159.4	350	32	75	259	73		70 shearing	S0-parallel shearing	good
EMM019	170	98	27	75	257	62		167 shearing	S0-parallel shearing	good
EMM019	171.4	358	27	75	257	78		75 S2	fabric	good
EMM019	178.7	200	55	75	257	21		289 F2	asym. Fold hinges	poor
EMM019	179.5	242	50	75	257	35		338 shearing	sheared boudin	good
EMM019	185.4	280	50	75	256	45		12 S0		moderate
EMM019	185.8	252	85	75	256	14		56 S2	oblique to S0	moderate
EMM019	173.5	280	55	75	257	40		16 F2	Z-fold hinges	poor
EMMD087	105.6	340	50	59	94	70		260 S2	fol. Volcanics	good
EMMD087	202.5	270	15	59	93	77		191 shearing	So? Shearing	good
EMMD087	202.52	304	50	59	93	62		236 S2	kinks	good

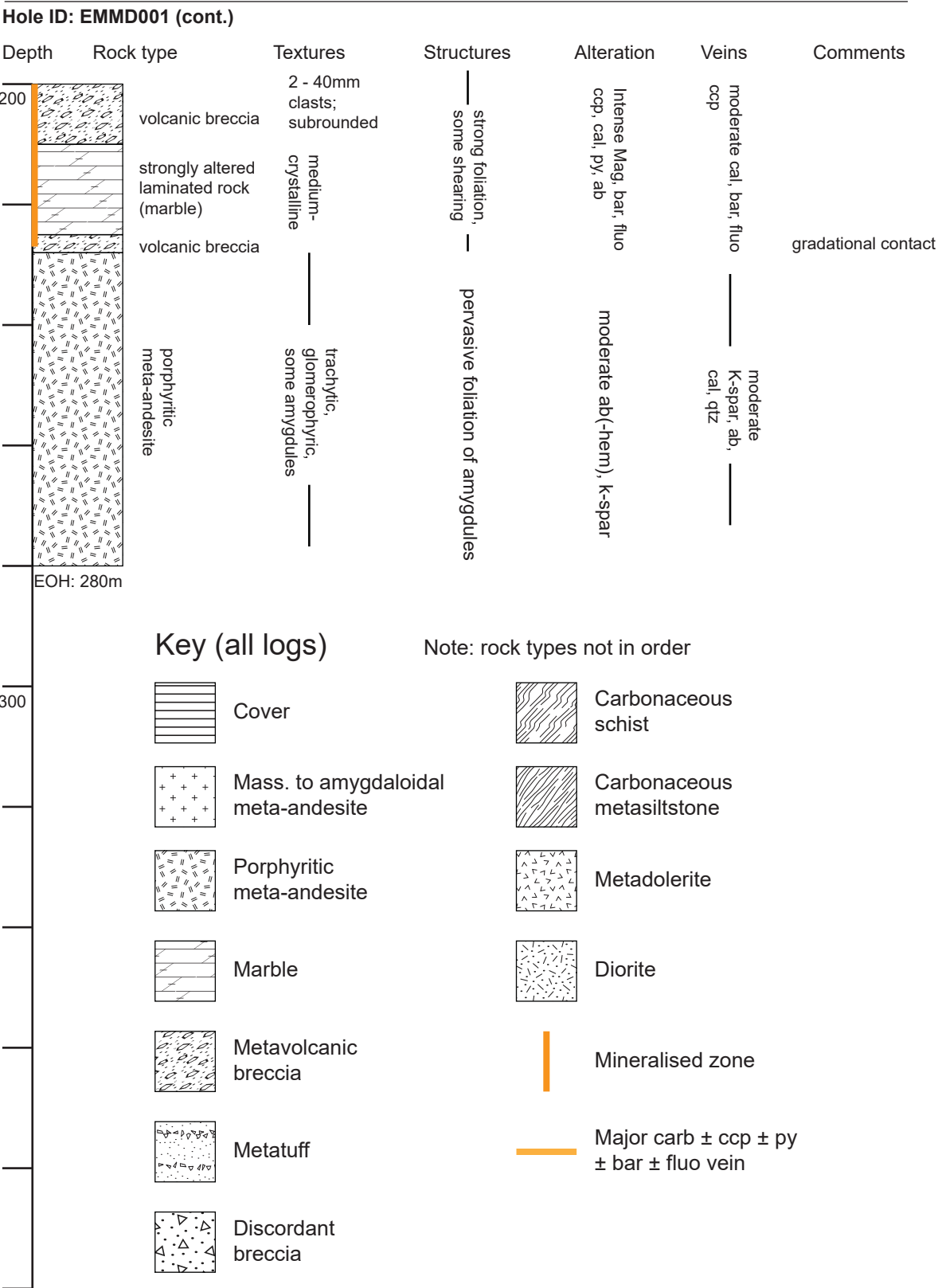
Hole ID: EMMD001 Site: E1N Total Depth: 280m E/N (m): 477571/ 7739614 A/I(°): 090 / -60

Depth Rock type Textures Structures Alteration Veins Comments



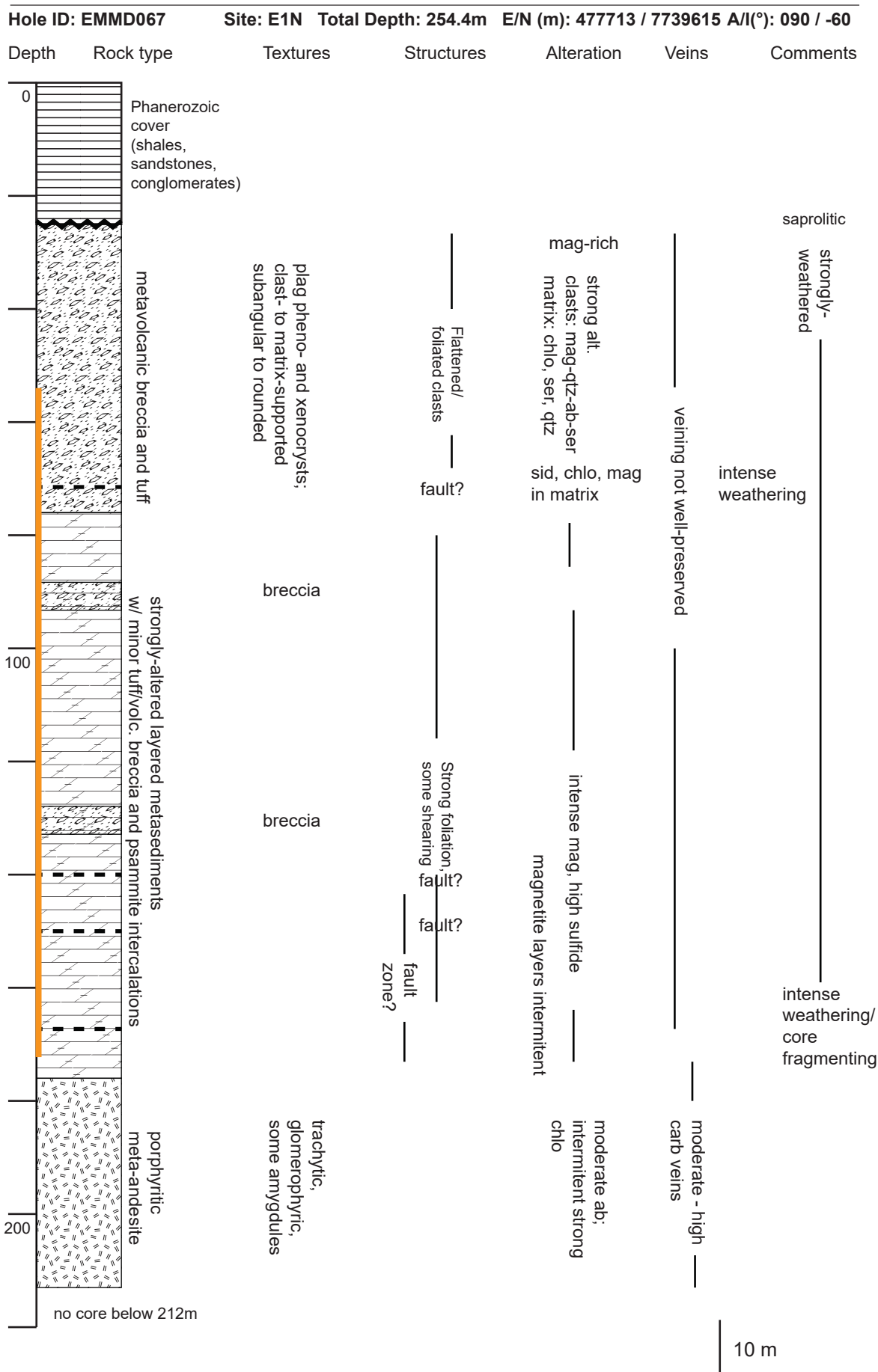
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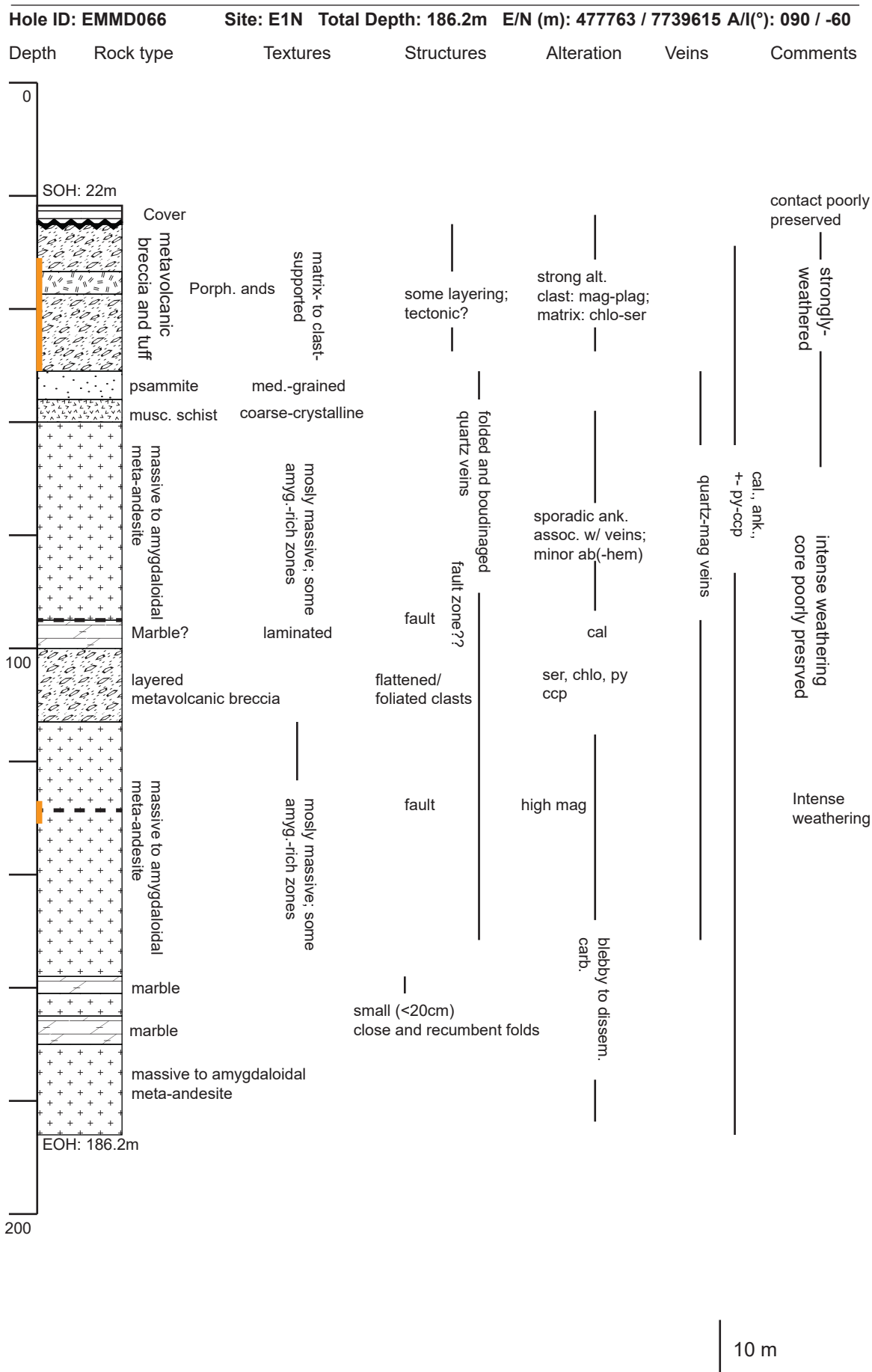
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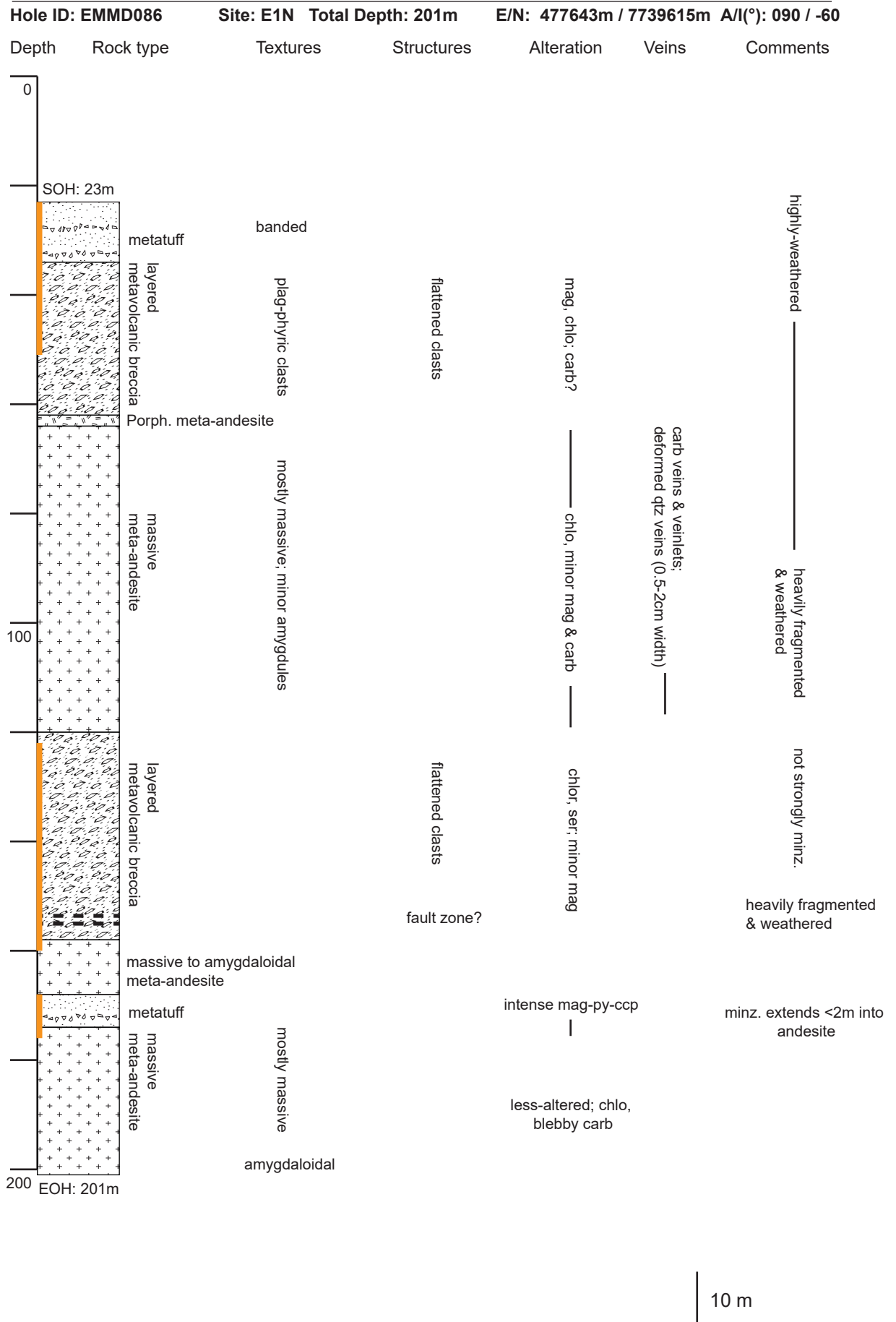


Mineral abbreviations: E/N, easting/northing; A/I, azimuth/inclination (design); dol, dolomite; sid, siderite; cal, calcite; carb, carbonate; mag, magnetite; chlo, chlorite; fluo, fluorite; ccp, chalcopryrite; py, pyrite; bar, barite; qtz, quartz; K-spr, K-feldspar; ab, albite; bt, biotite; ser, sericite; hem, hematite.

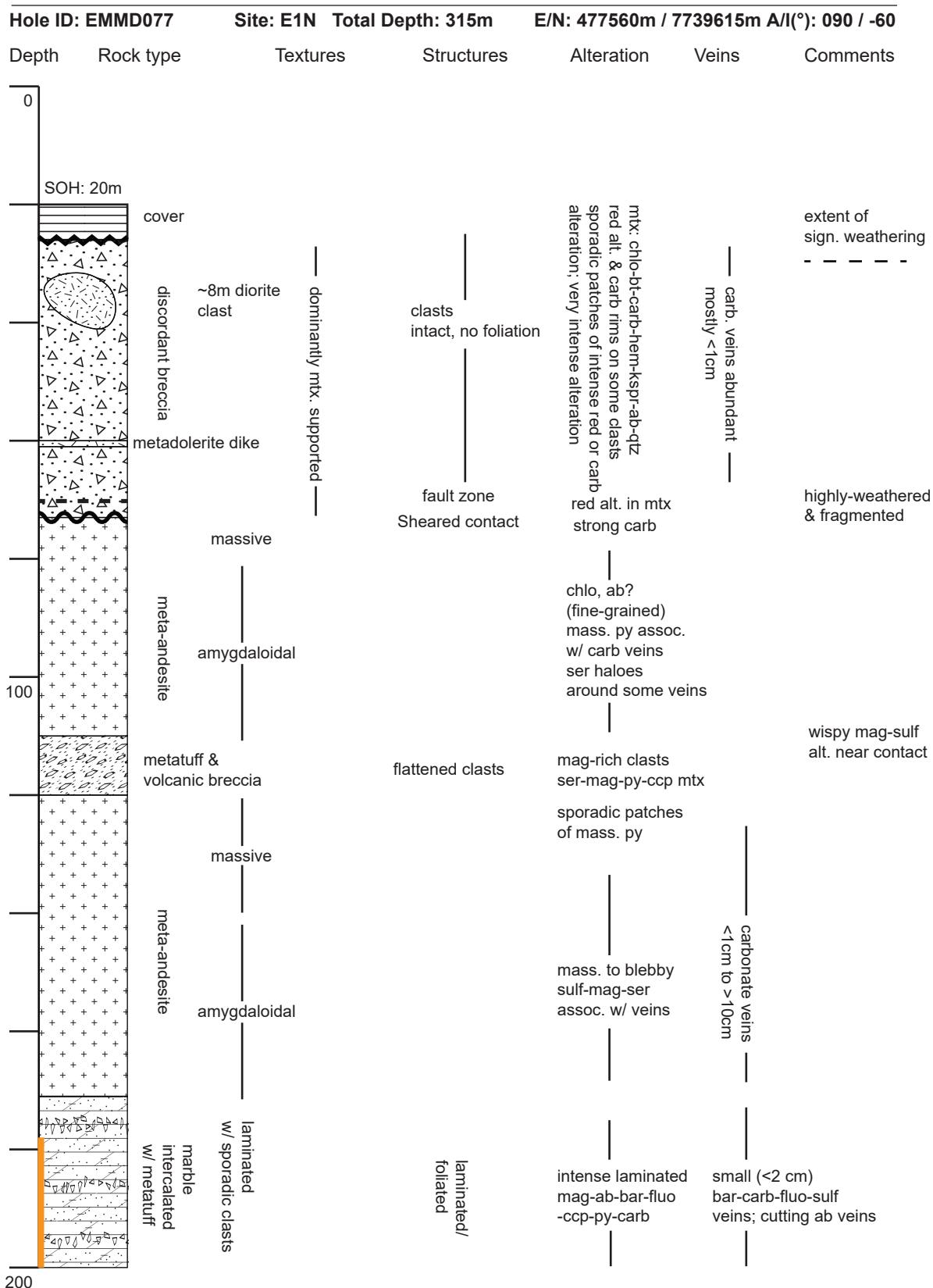
10 m







Hole ID: EMD075		Site: E1N Total Depth: 231m		E/N: 477603m / 7739615m A/I(°): 090 / -60		
Depth	Rock type	Textures	Structures	Alteration	Veins	Comments
0						
SOH: 23m						
	metavolcanic breccia		flattened clasts	strong al. clasts: qtz-ser mtx: mag-chlo, dissem. - wispy		highly - weathered & fragmented
	amygdaloidal meta-andesite	autobrec.? amygdaloidal		mtx. rich in chlo-qtz; qtz-mag-rich 'clasts'	mag-qtz infill of amygdaloids & veinlets	
	metavolcanic breccia		flattened clasts			
	psammite intercalated w/ metatuff?			qtz-ser-mag-py-ccp-chlo-Fe-carb		weathered & fragmented
100	metavolcanic brecc.		flattened clasts			
	meta-and. intercalated w/ metatuff & psammite		flattened clasts			
	massive meta-andesite			very fine-grained; chlo, ser	moderate carb veining	
		autobrec.?				
	metavolcanic breccia		flattened clasts	wispy mag-chlo-bt		
200	marble intercalated w/ psammite			intense mass. mag; dissem py-ccp		carb-rich aurozone
	metavolcanic breccia		flattened clasts	intense laminated mag-bar-fluo-sulfides-dol(-Fe)		
	amygdaloidal meta-andesite			chlo, ab	abund. carb veins	
EOH: 231m						10 m



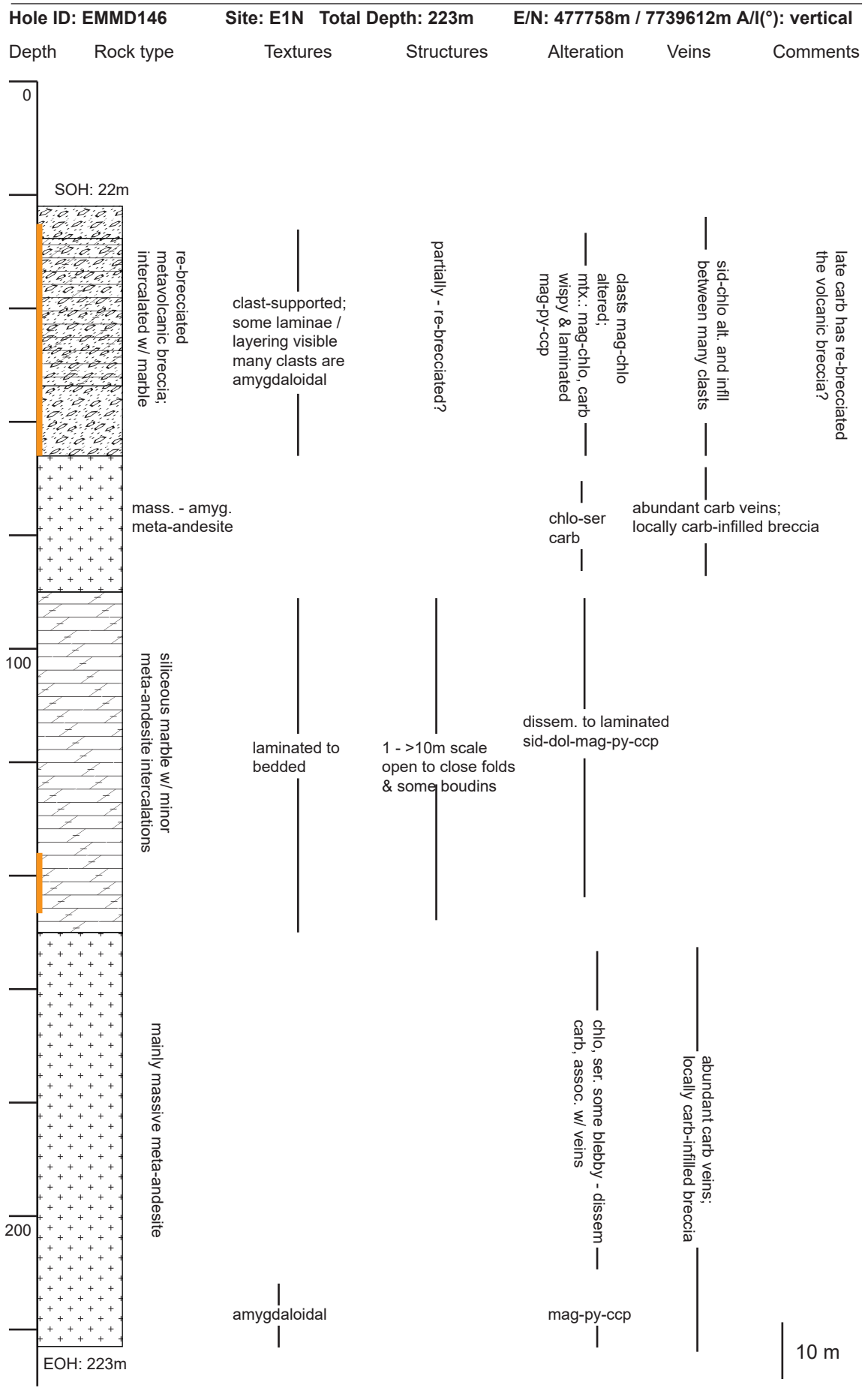
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10 m

Hole ID: EMMD077 (cont.)

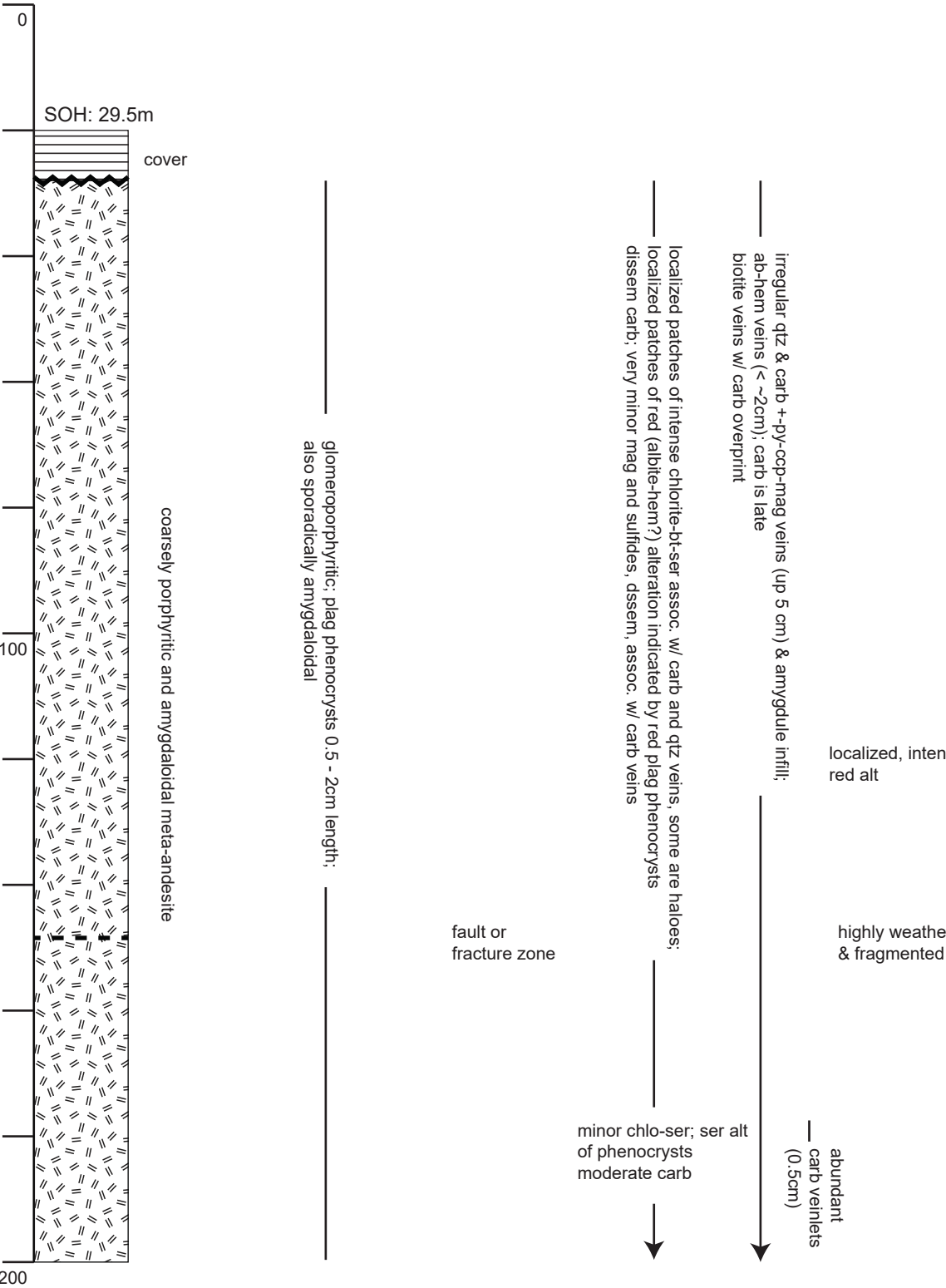
Depth	Rock type	Textures	Structures	Alteration	Veins	Comments
200	metavolcanic breccia			intense laminated mag-ab-bar-fluo -ccp-py-carb	small (<2 cm) bar-carb-fluo-sulf veins; cutting ab veins	
	marble					
	metavolcanic breccia	sporadic amygdaloidal clasts throughout	laminated; clasts are foliated	intense to mod. mag-ccpy-py (decreases downhole) mainly chlo-ser carb alt.	carb veins dominant	
300						
	EOH: 315n					

10 m



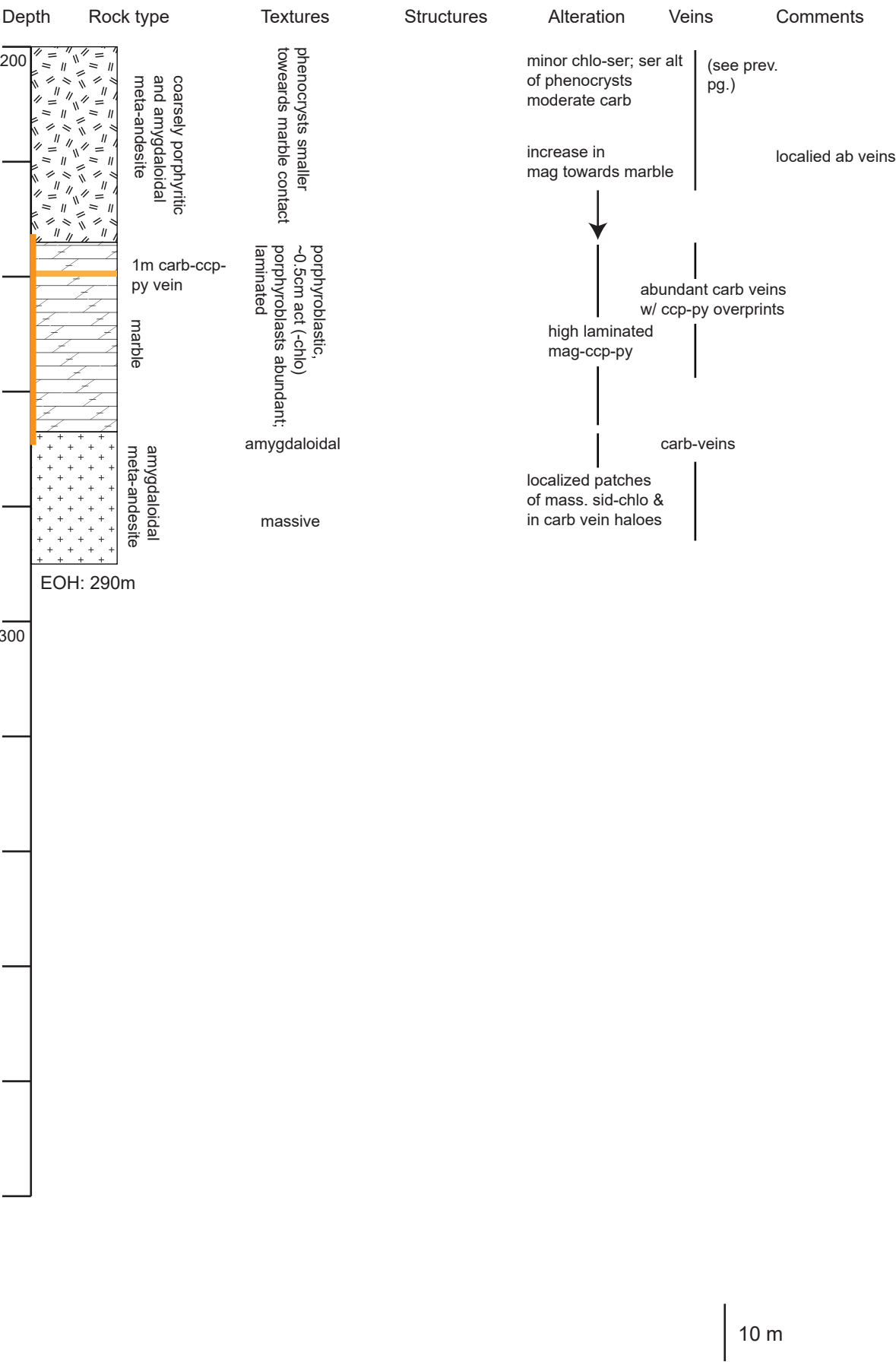
Hole ID: EMD182 Site: E1N Total Depth: 289m E/N (m): 477934 / 7739626 A/I(°): 270 / -60

Depth Rock type Textures Structures Alteration Veins Comments



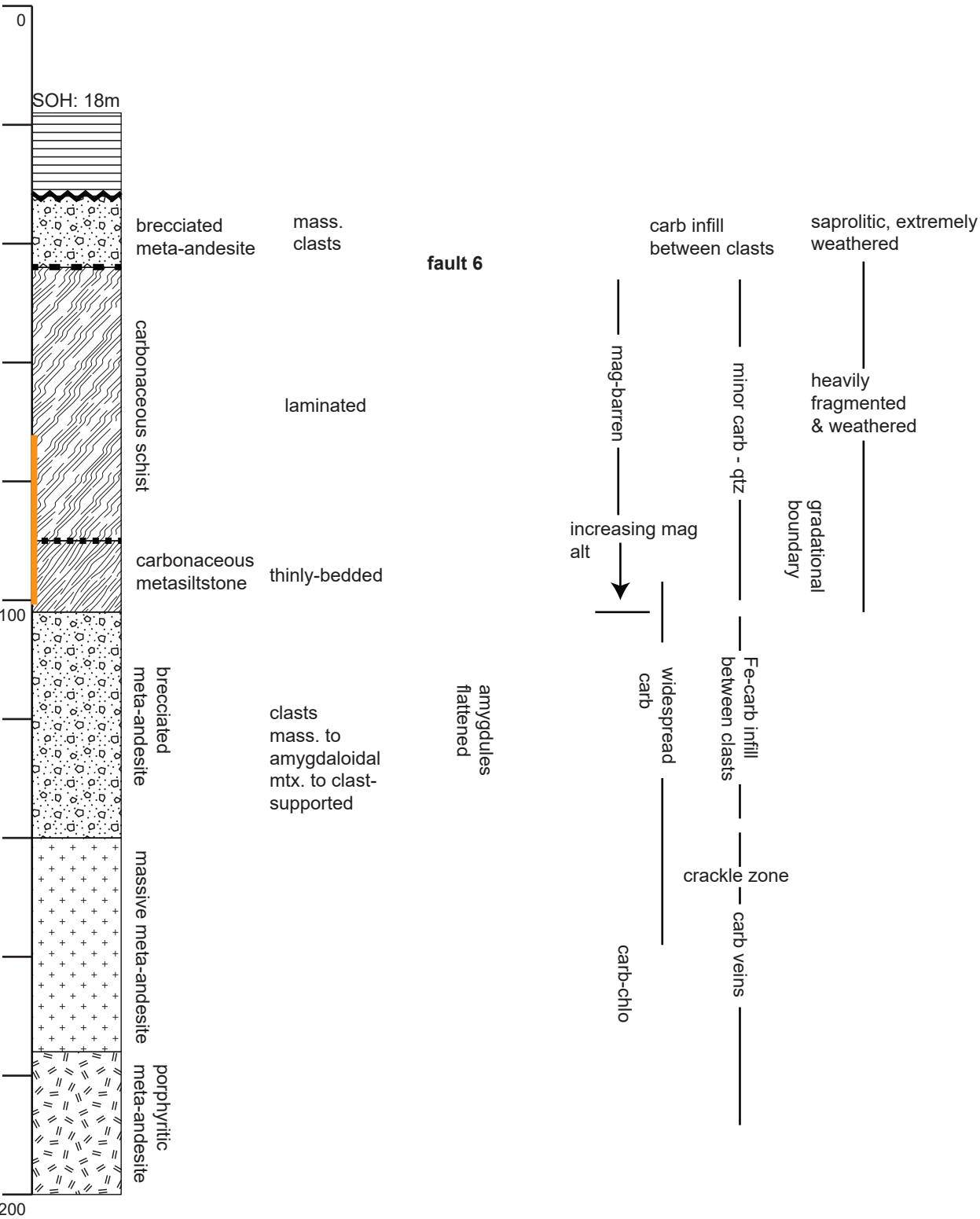
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Hole ID: EMMD182 (cont.)



Hole ID: EMMD097 Site: E1S Total Depth: 276m E/N (m): 478595 / 7738624 A/I(°): 270 / -70

Depth Rock type Textures Structures Alteration Veins Comments



Cont. next page

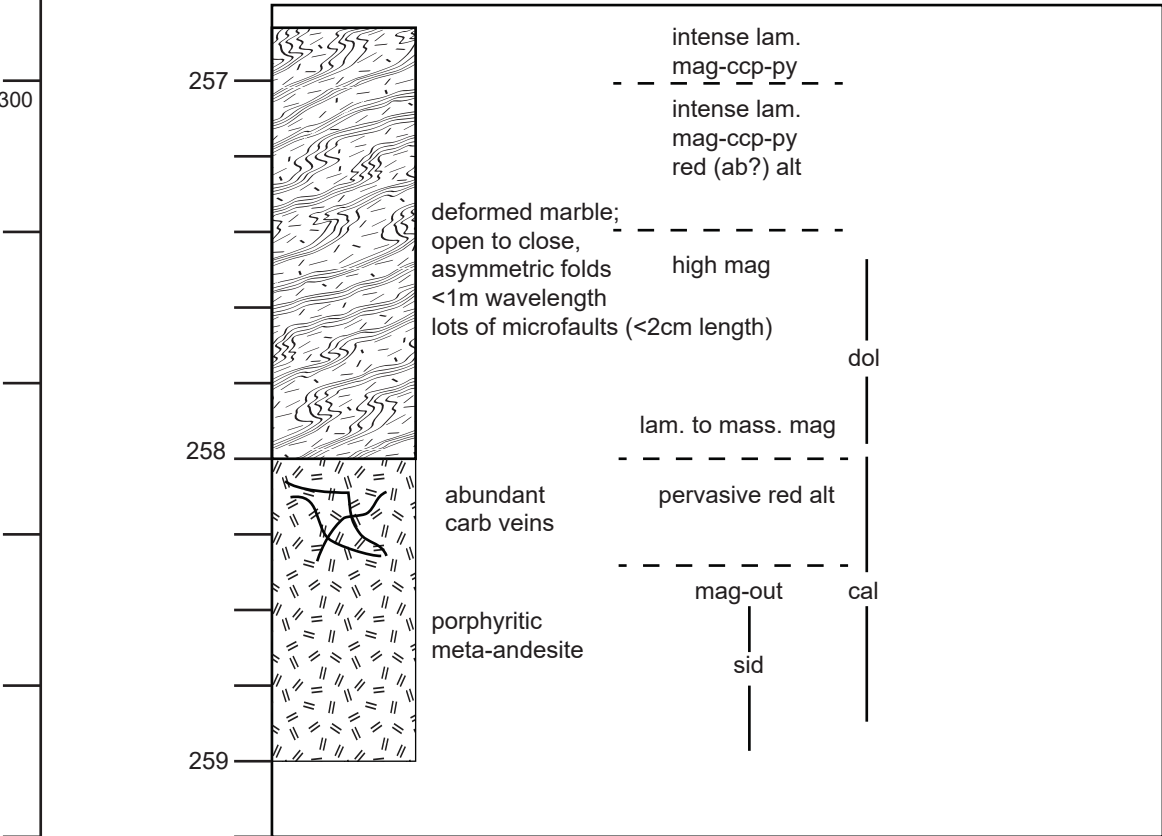
10 m

Hole ID: EMMD097 (cont.)

Depth	Rock type	Textures	Structures	Alteration	Veins	Comments
200	porphy. meta-andes.					
	metatuff w/ minor marble	some volc. brec.				carb-poor
	marble			intense lam. mag-py-ccp; interlayered w/ red alt. (qtz? ab?)	carb-fluo-bar-sulf	
	porphy. meta-andes.	conglomeritic	sheared qtz-rich lyr	high sid		
	marble	fine-gr.	boundinaged qtz-rich layers			
	porphy. meta-andes.			red (silica?) alt near contact		
				abundant carb no mag (abrupt at contact)		

EOH: 273m

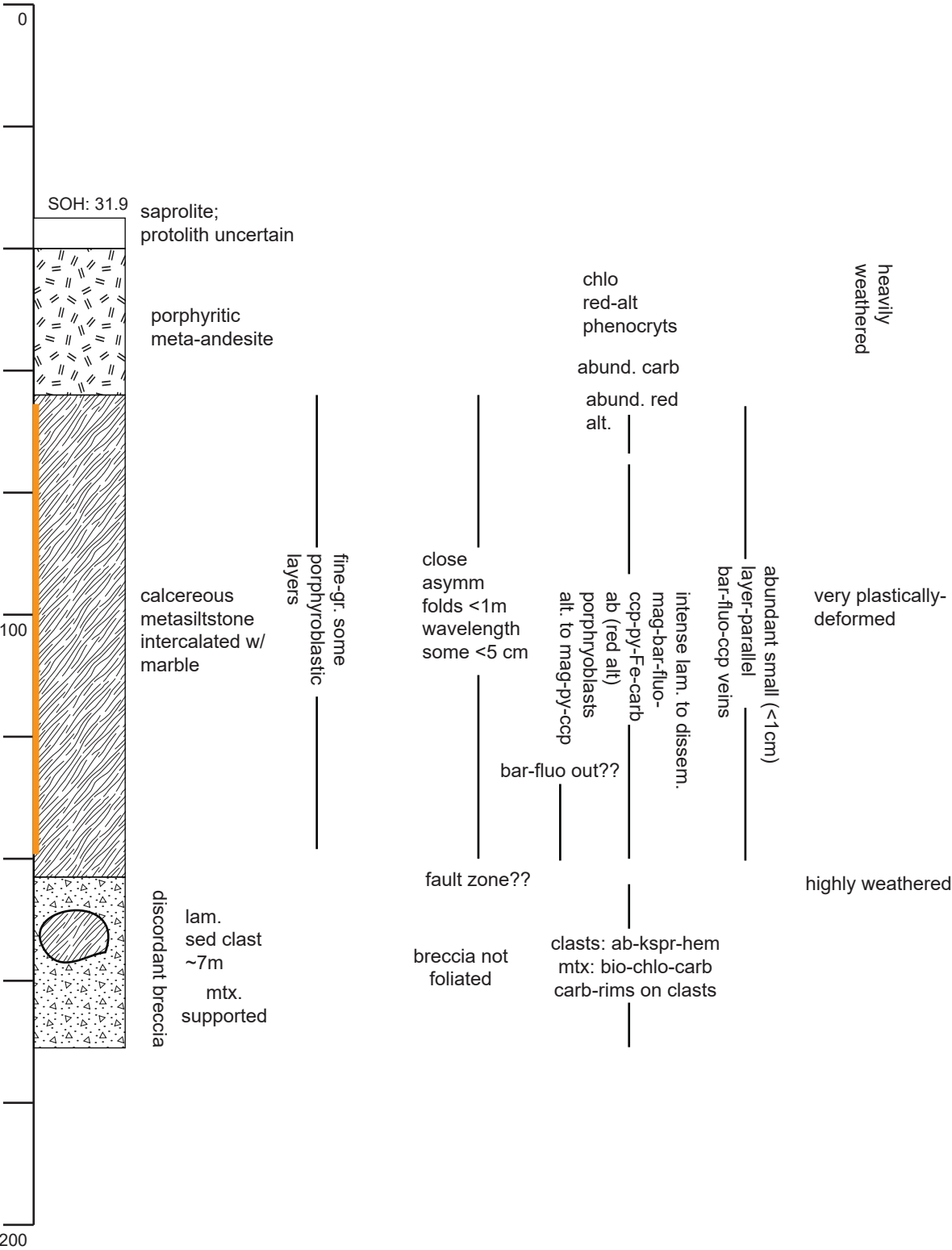
Detail log of marble / meta-andesite contact 257 - 259m

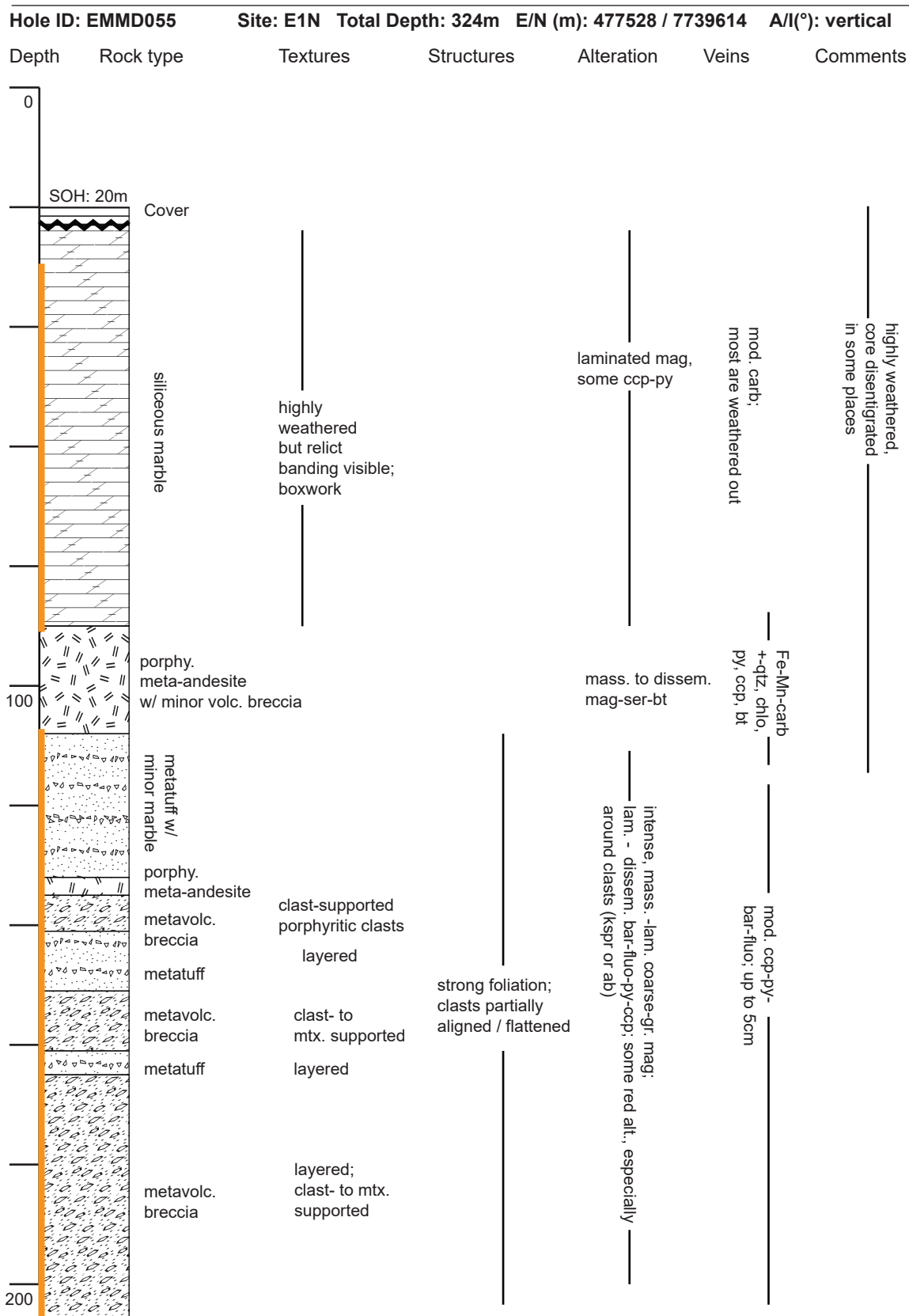


10 m

Hole ID: EMMD013 Site: E1E Total Depth: 172m E/N (m): 478400 / 7739626 A/I(°): vertical

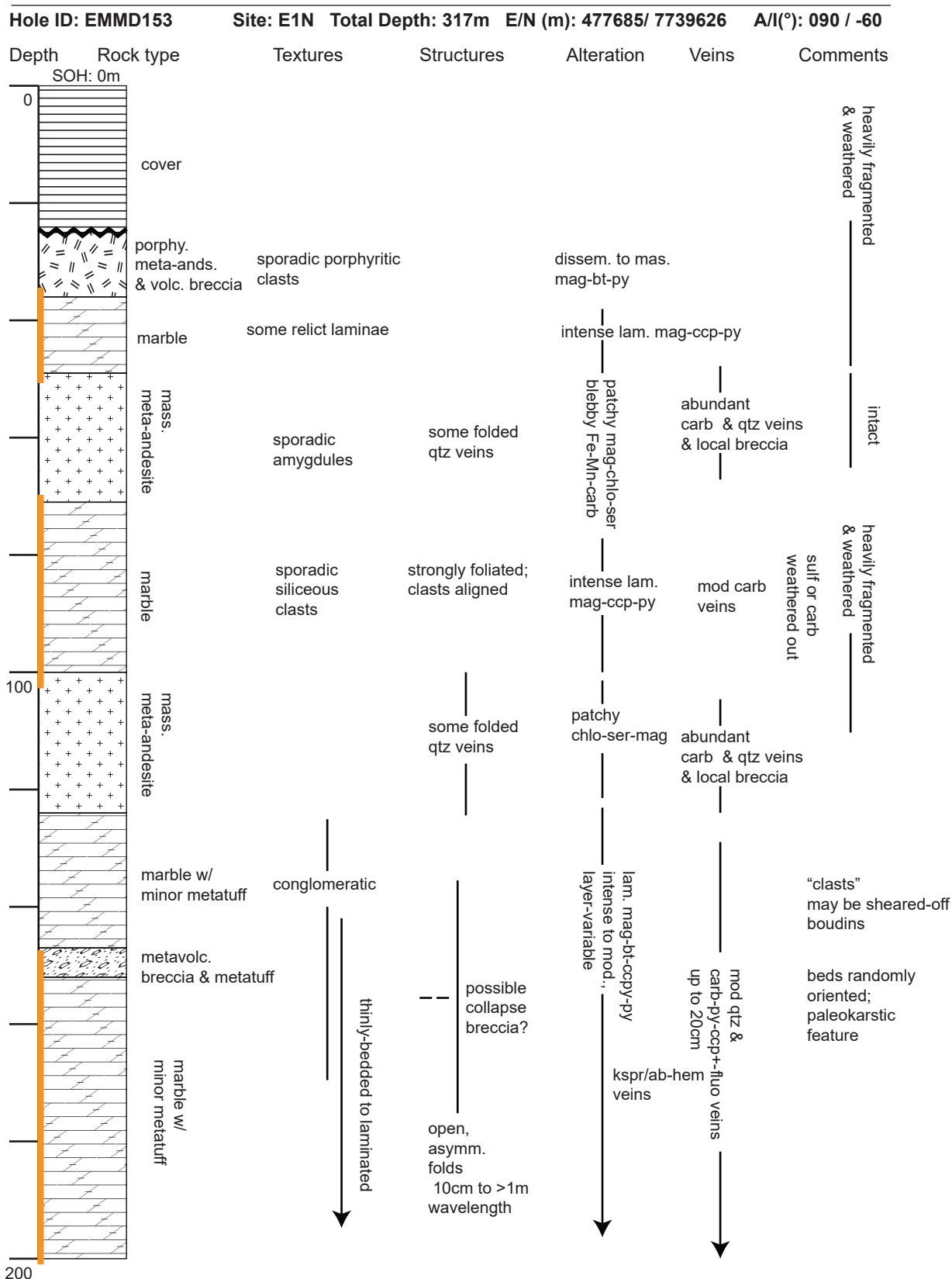
Depth Rock type Textures Structures Alteration Veins Comments





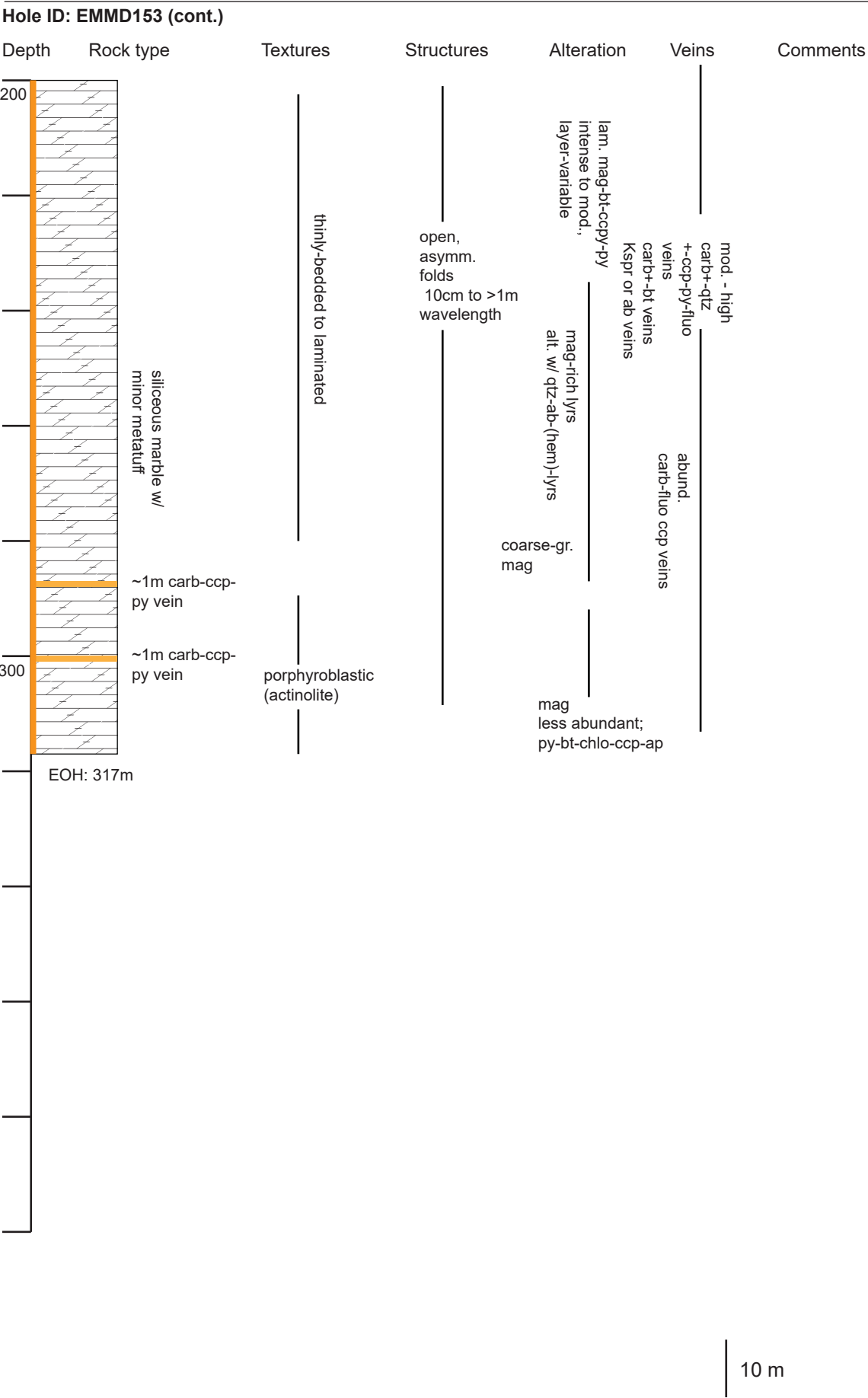
Note: core missing below 207m

10 m



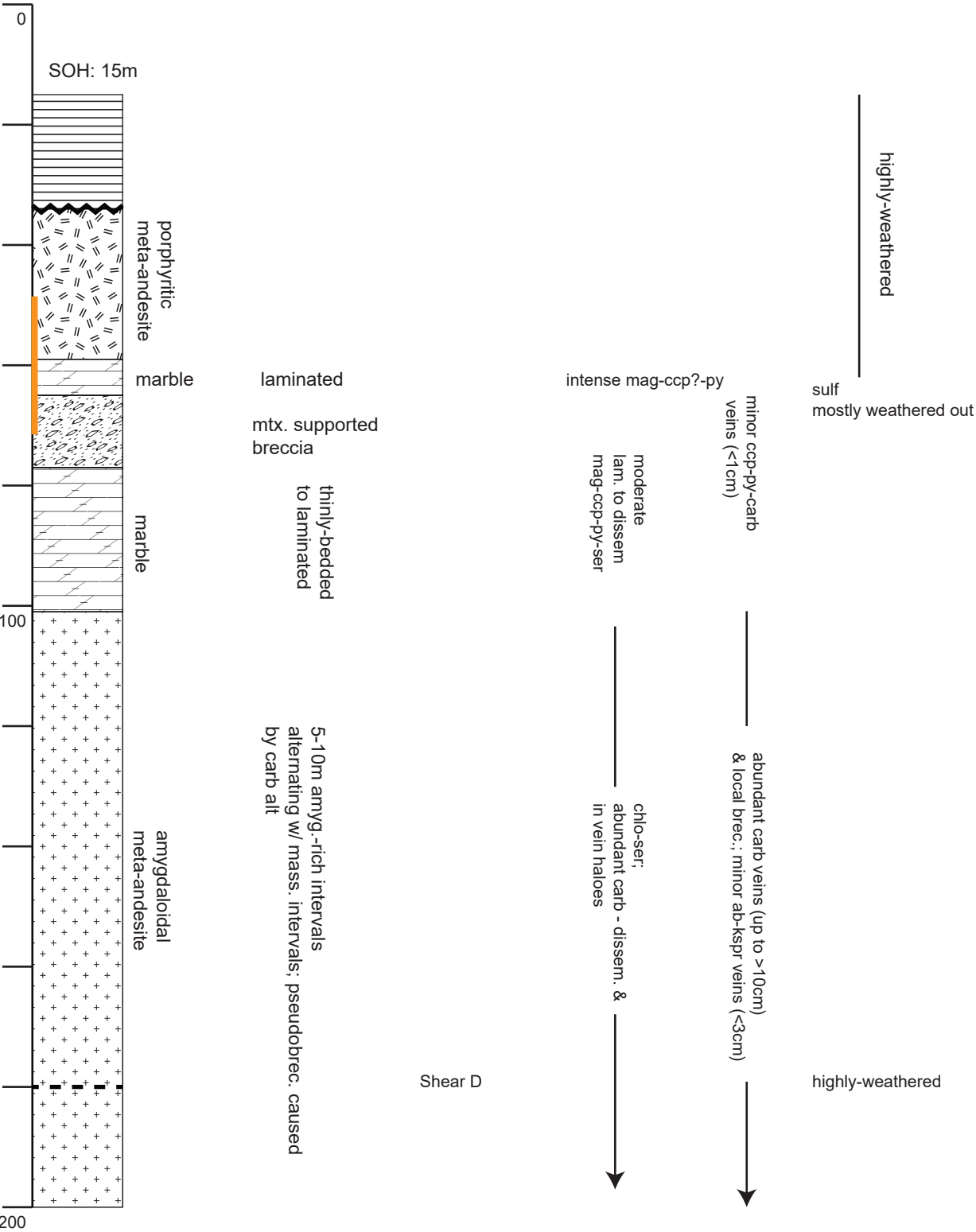
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10 m

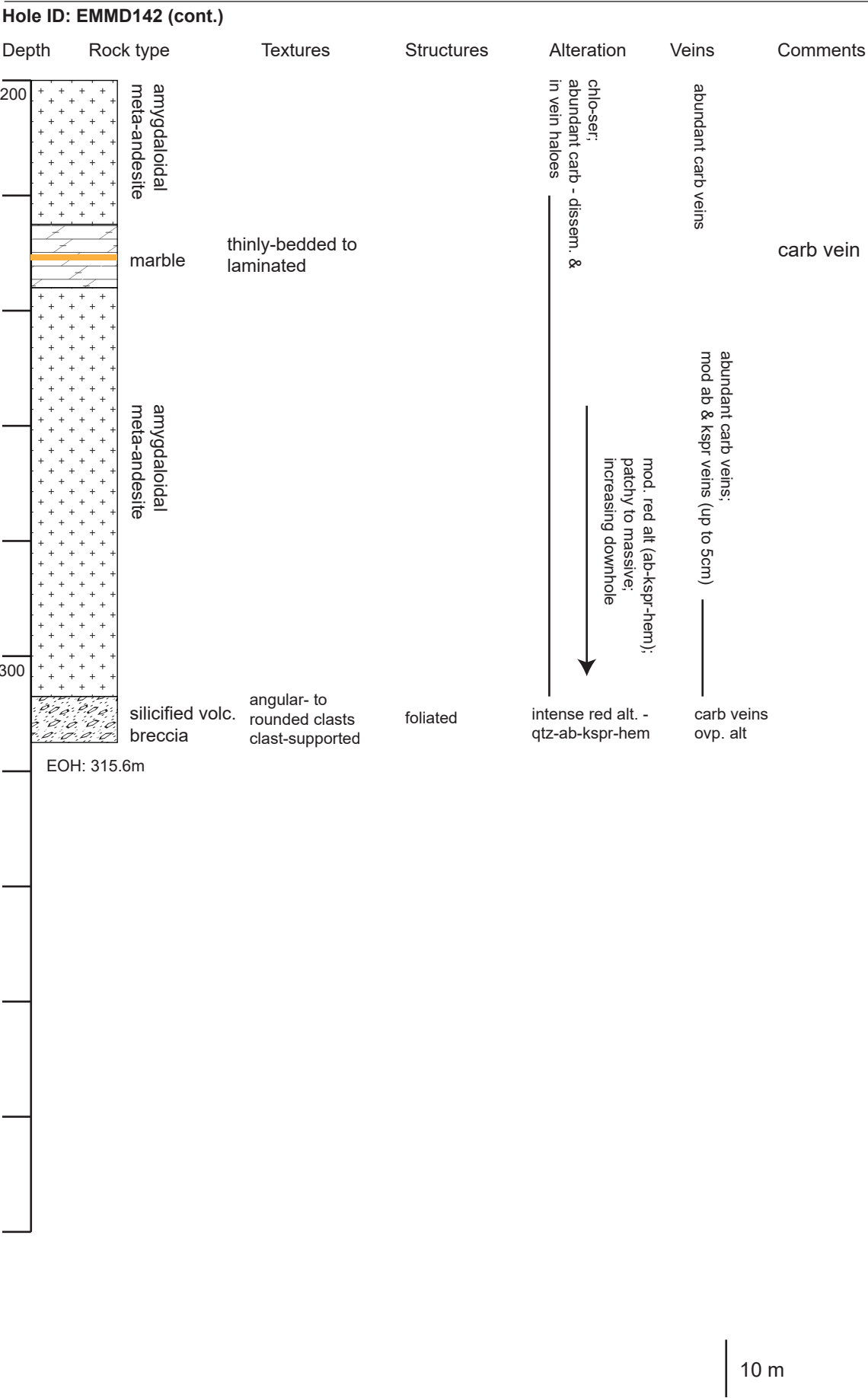


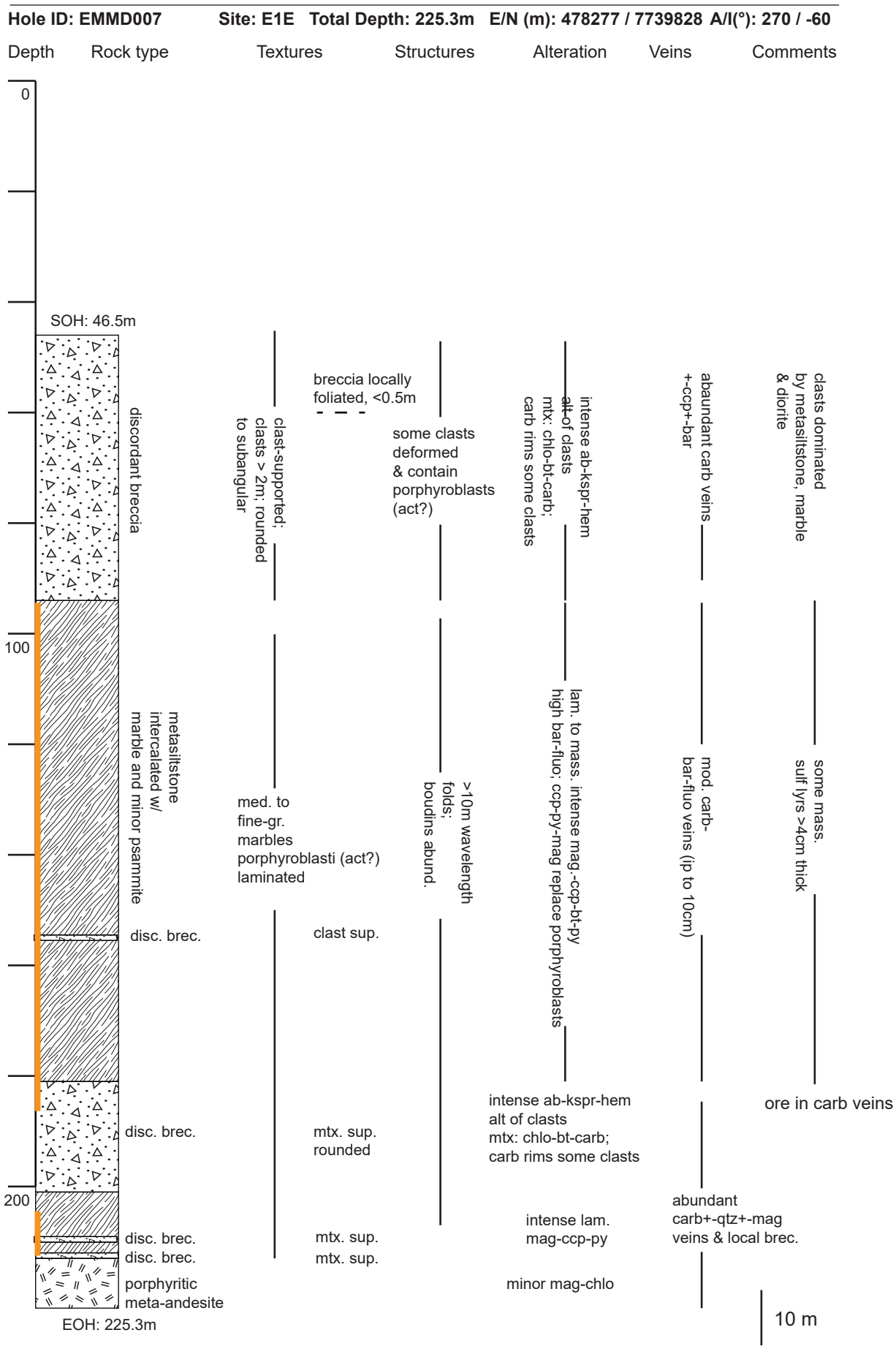
Hole ID: EEMMD142 Site: E1N Total Depth: 316m E/N (m): 477832 / 7739573 A/I(°): 270 / -60

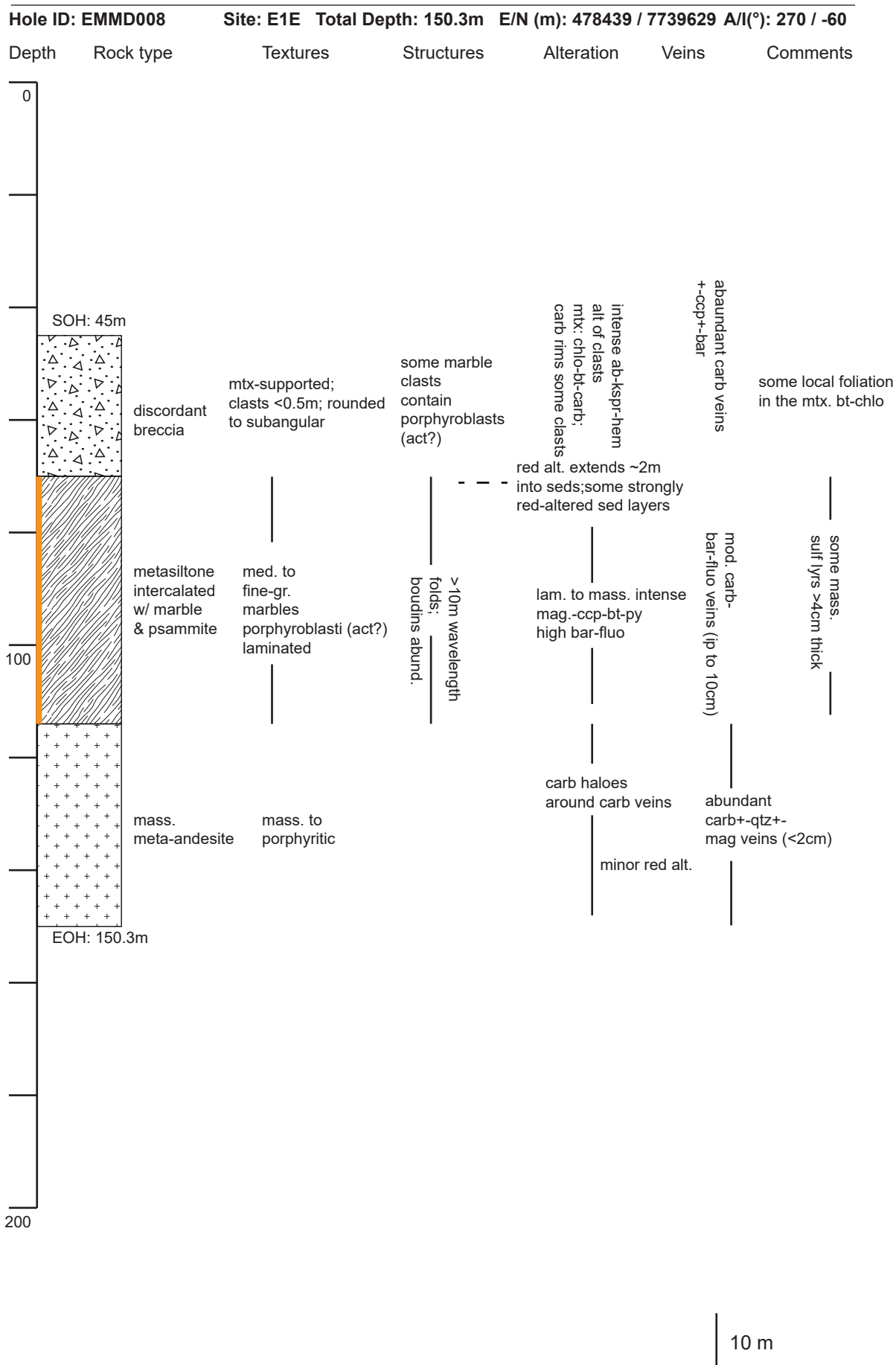
Depth Rock type Textures Structures Alteration Veins Comments

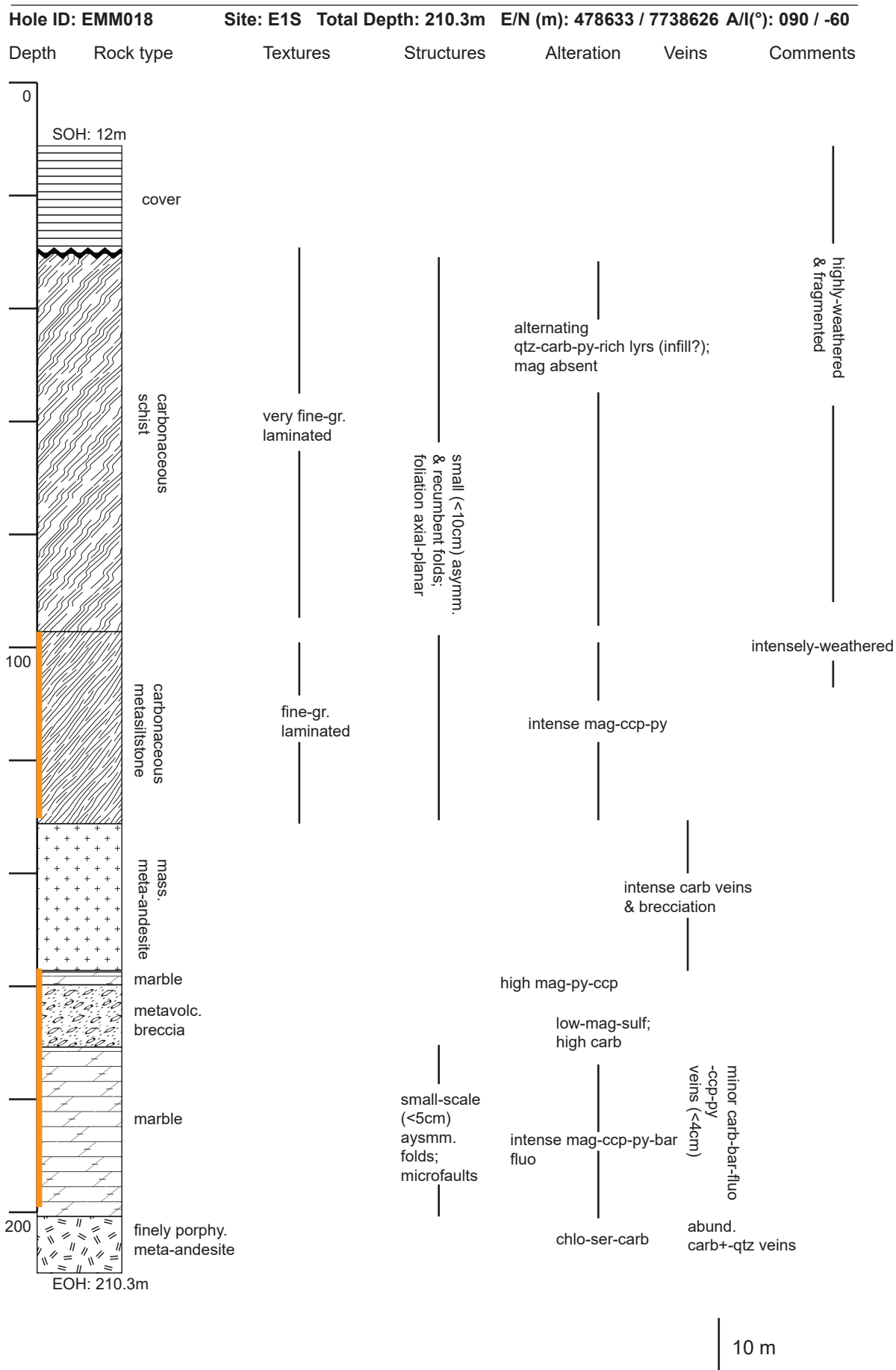


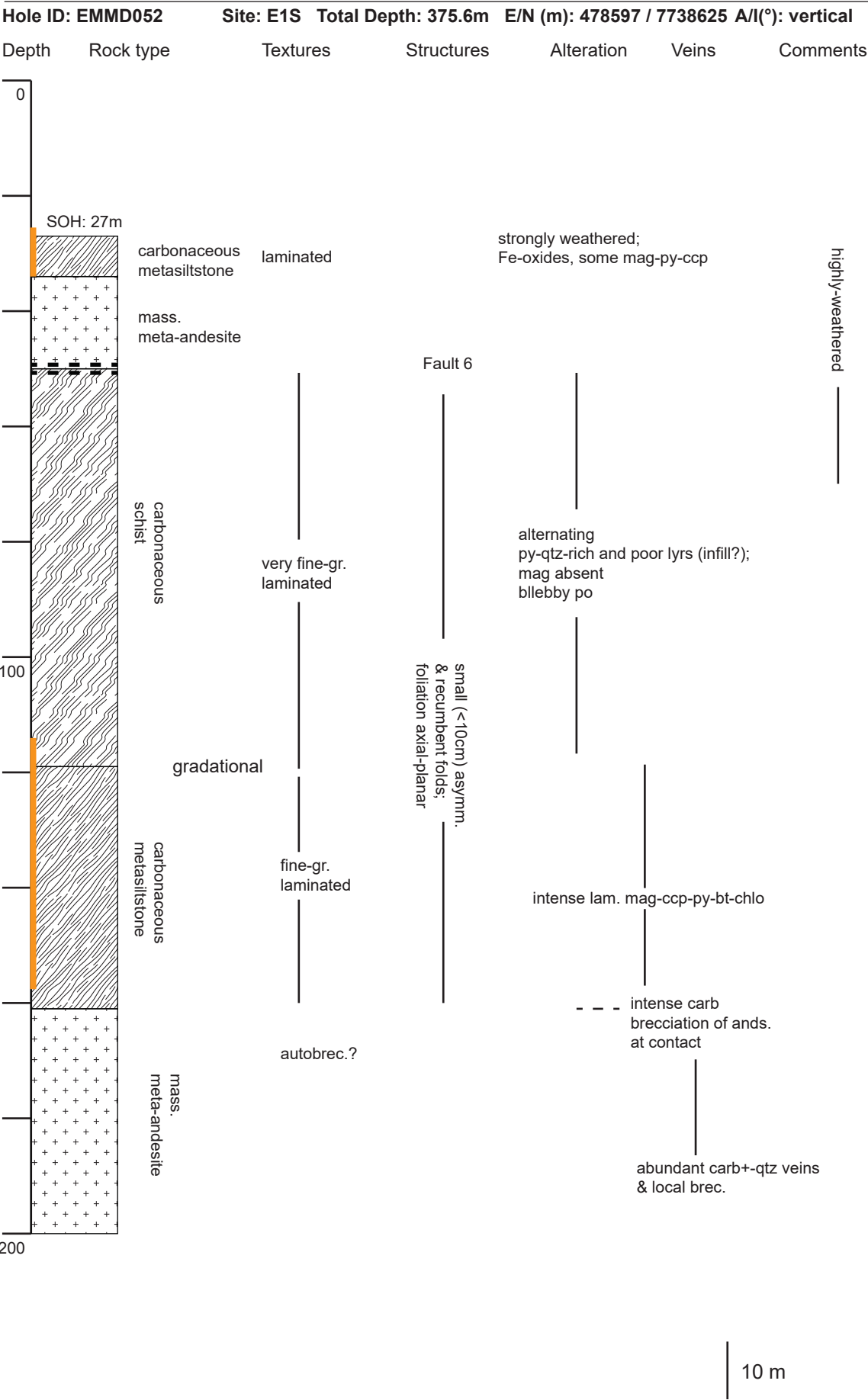
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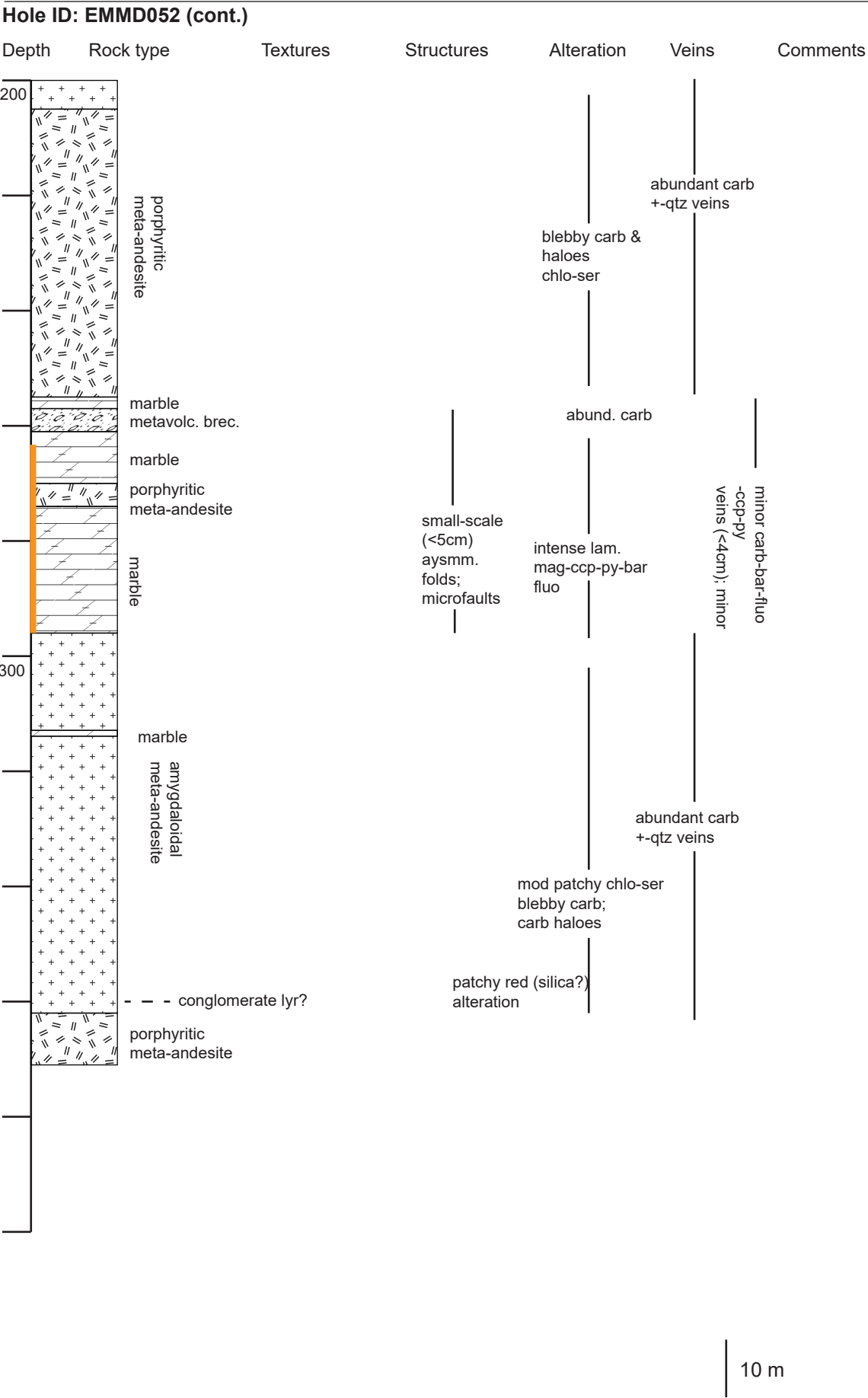










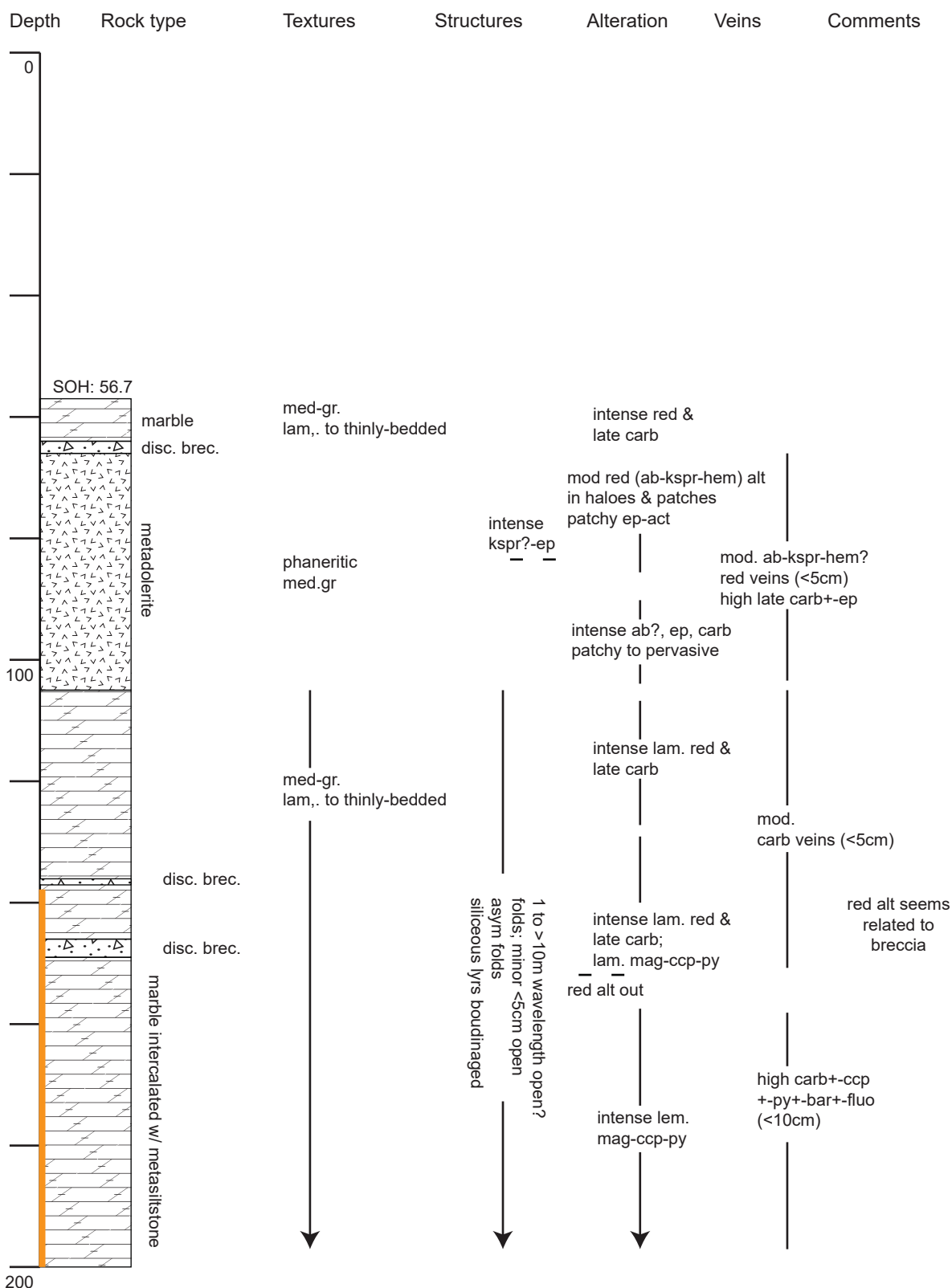


Hole ID: EMMD049 Site: E1S Total Depth: 283.8m E/N (m): 478623 / 7738625 A/I(°): 200 / -80						
Depth	Rock type	Textures	Structures	Alteration	Veins	Comments
0						
SOH: 29m	carbonaceous schist	very fine-gr.		alternating py?-qtz-rich layers mag-barren		boxworks; sulf weathered
	carbonaceous metasiltstone	fine-gr.		intense lam mag-ccp-py		highly-weathered
			small (<10cm) asymm. & recumbent folds; foliation axial-planar			
	carbonaceous schist	very fine-gr.	Fault 6	alternating py-qtz-rich layers mag-barren		
100	carbonaceous metasiltstone	fine-gr.		intense lam mag-ccp-py		
	core missing below 142m					
200						

Hole ID: EMM014		Site: E1S		Total Depth: 201.5m	E/N (m): 478589 / 7738726		A/I(°): 090 / -75	
Depth	Rock type	Textures	Structures	Alteration	Veins	Comments		
0								
	SOH: 54m							
	carbonaceous schist	very fine-gr.	minor (<10cm) asymm.folds: foliation axial-planar		high carb veins (<1cm)			
100								
	carbonaceous metasilstone							
	mass. meta-andesite							
	porphyritic meta-andesite							
	marble	laminated	minor (<5cm) asymm.folds					
	metavolc. brecc. & metatuff							
200	marble	mtx. sup	foliated					
	EOH: 201.5m							

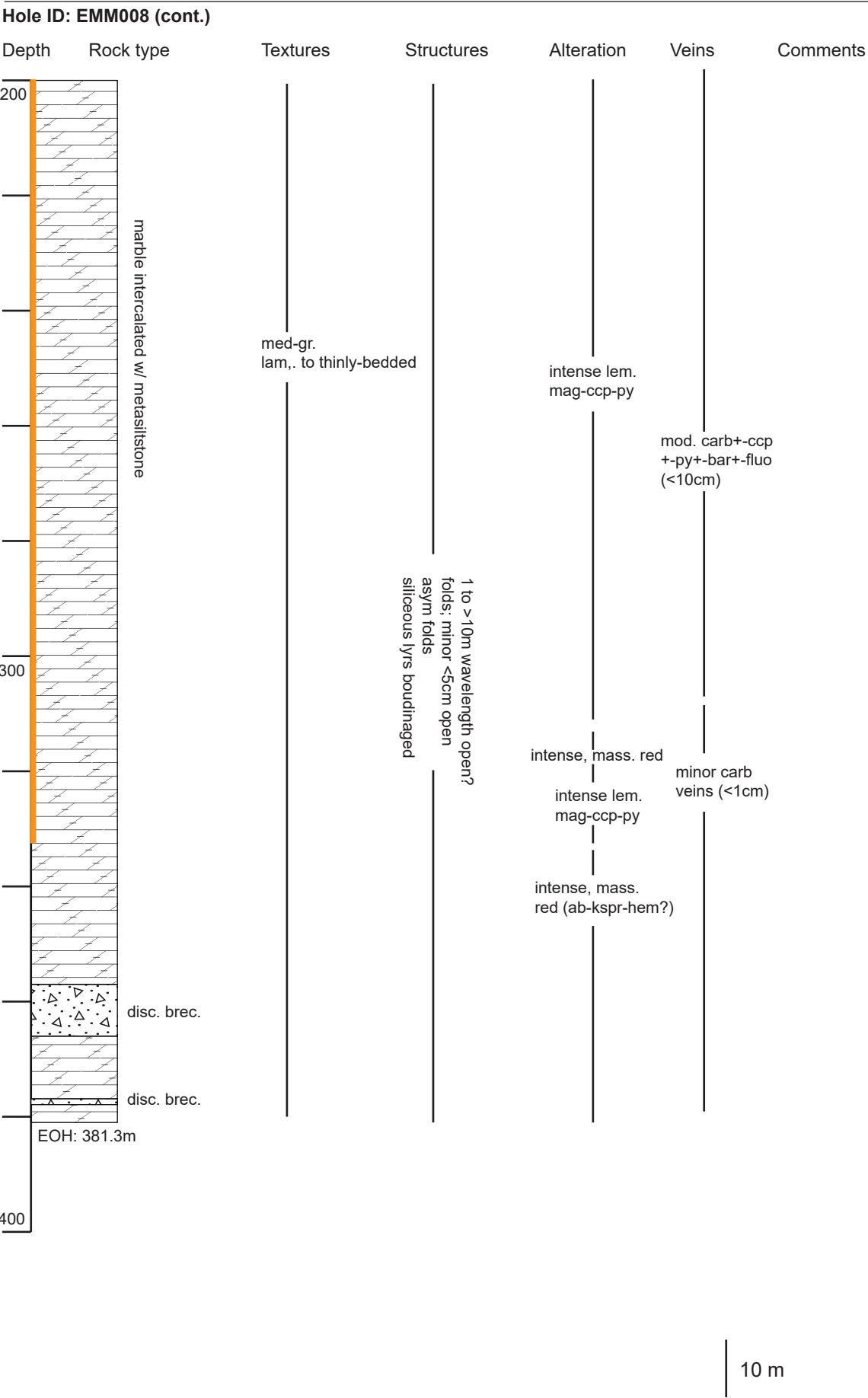
10 m

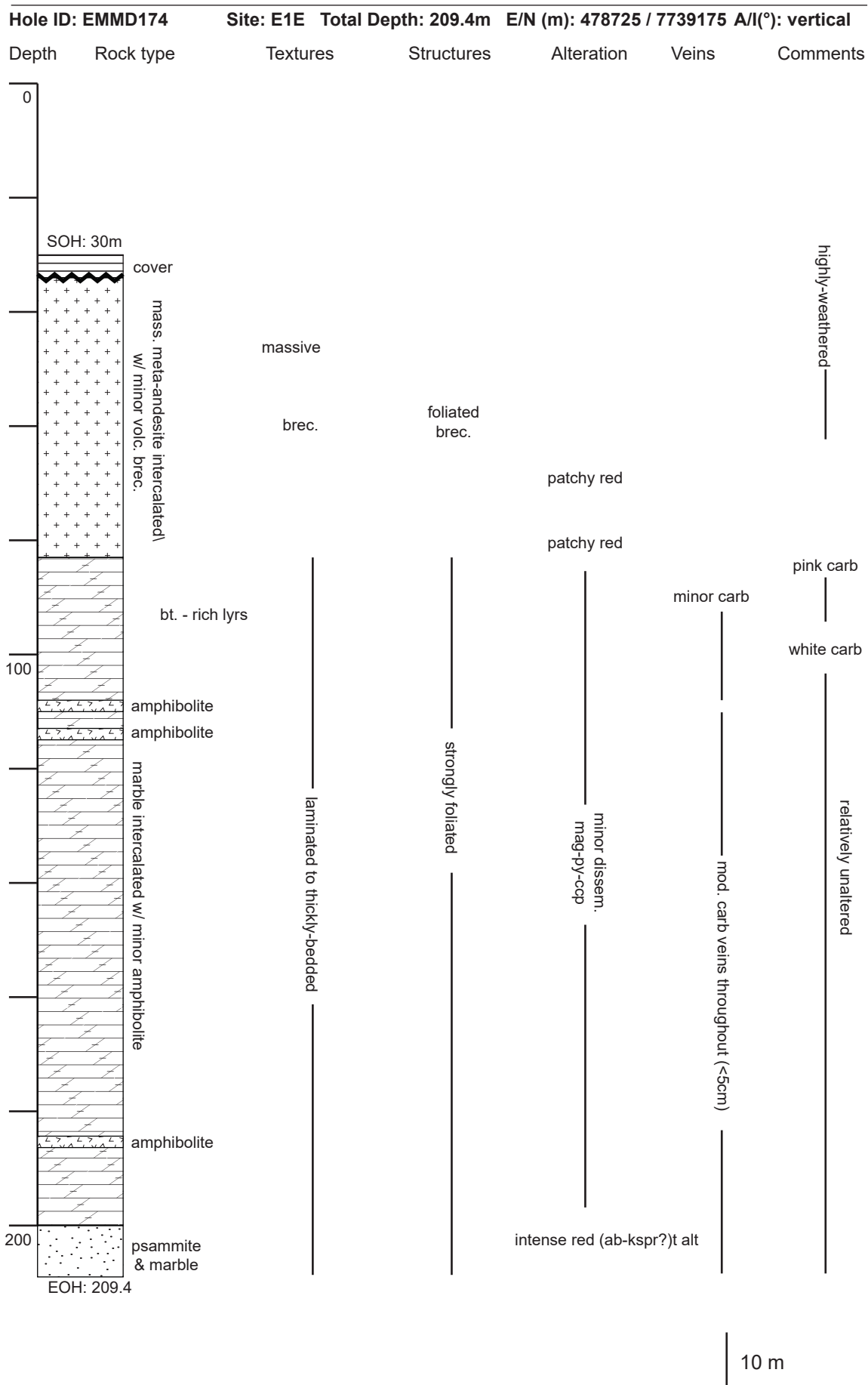
Hole ID: EMM008 Site: E1E Total Depth: 381m E/N (m): 478358 / 7739799 A/I(°): 270 / -60



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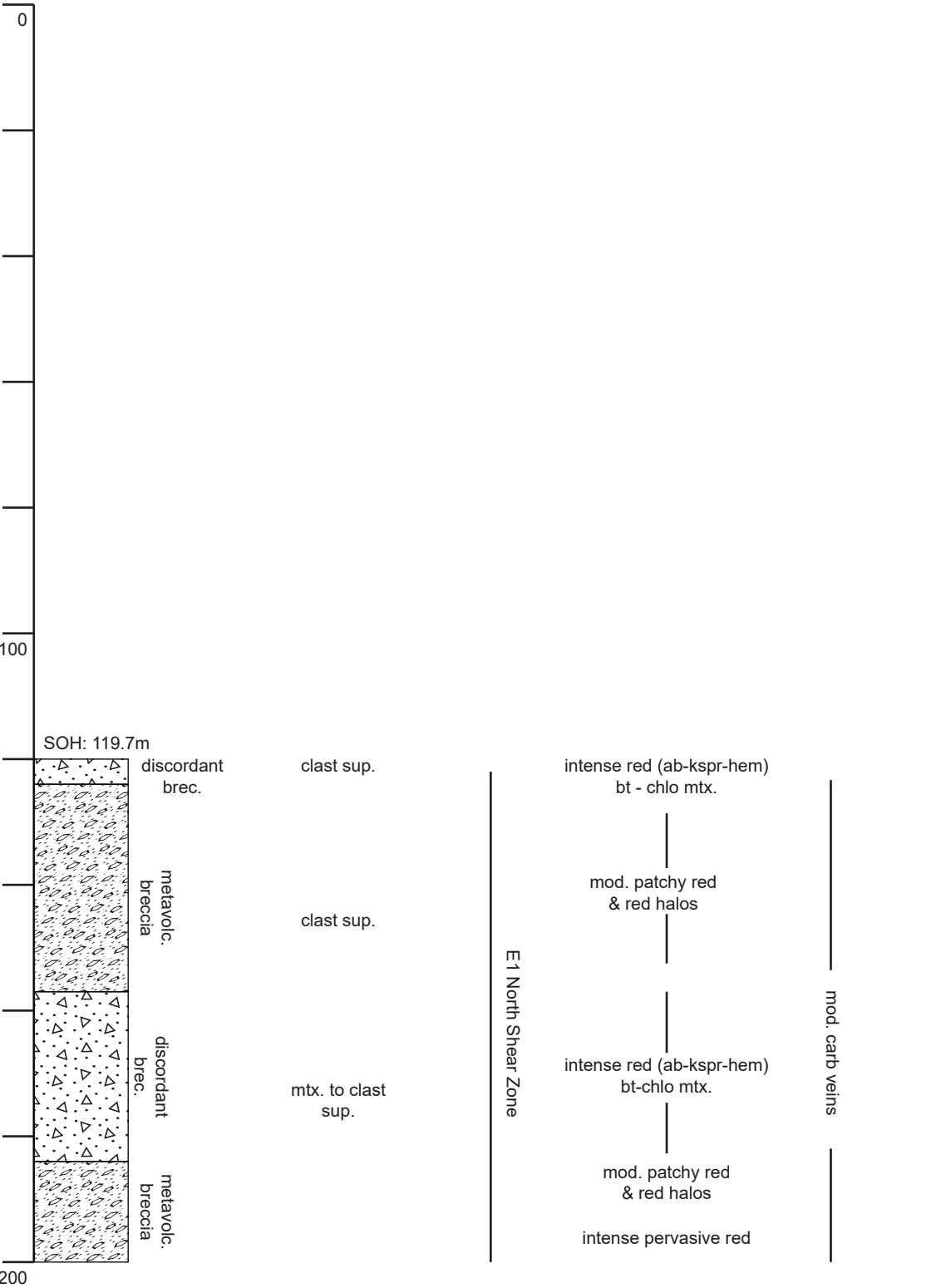
10 m





Hole ID: EMMD022 Site: E1N Total Depth: 369.3m E/N (m): 477470 / 7739517 A/I(°): 095 / -65

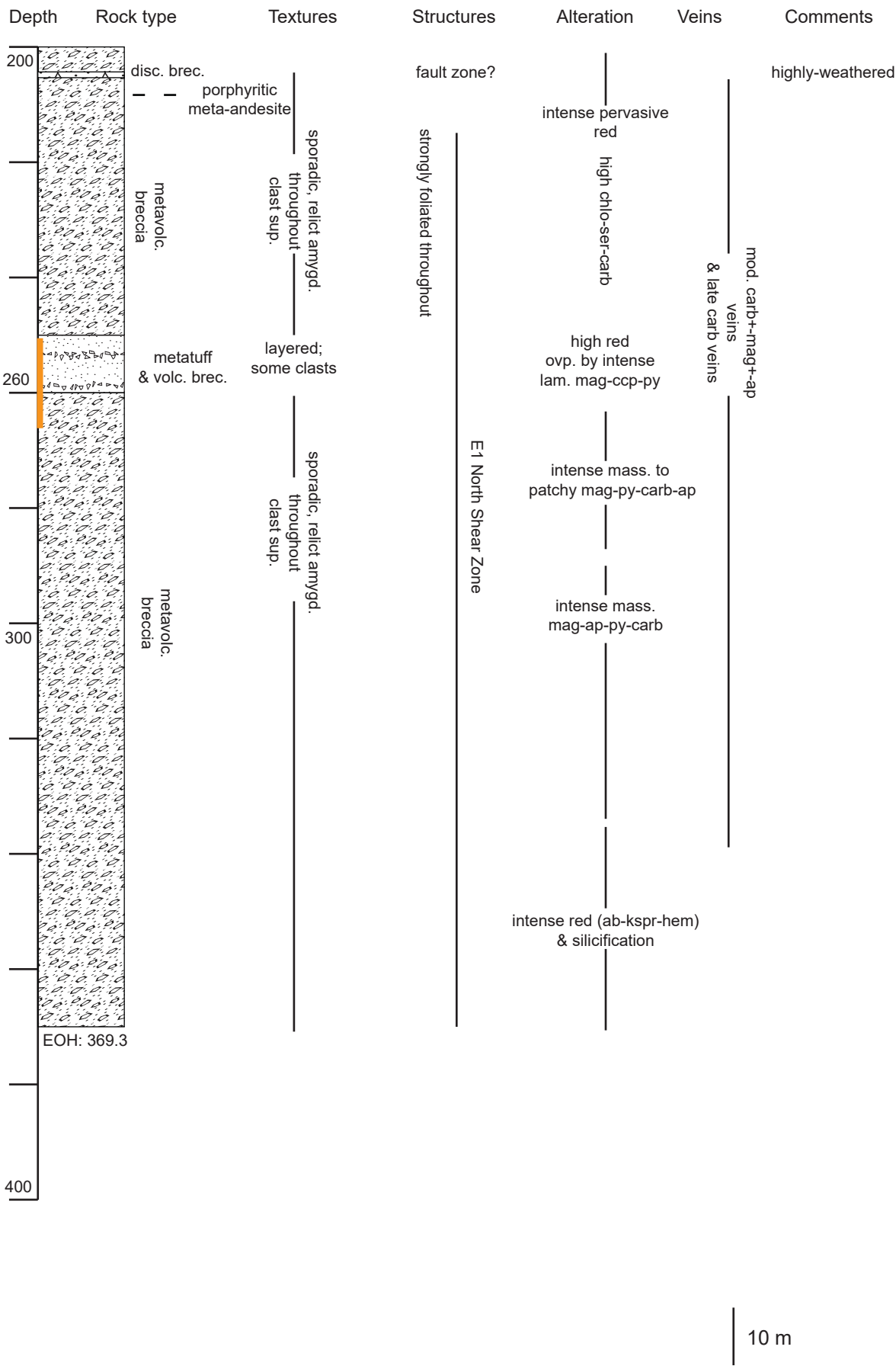
Depth Rock type Textures Structures Alteration Veins Comments

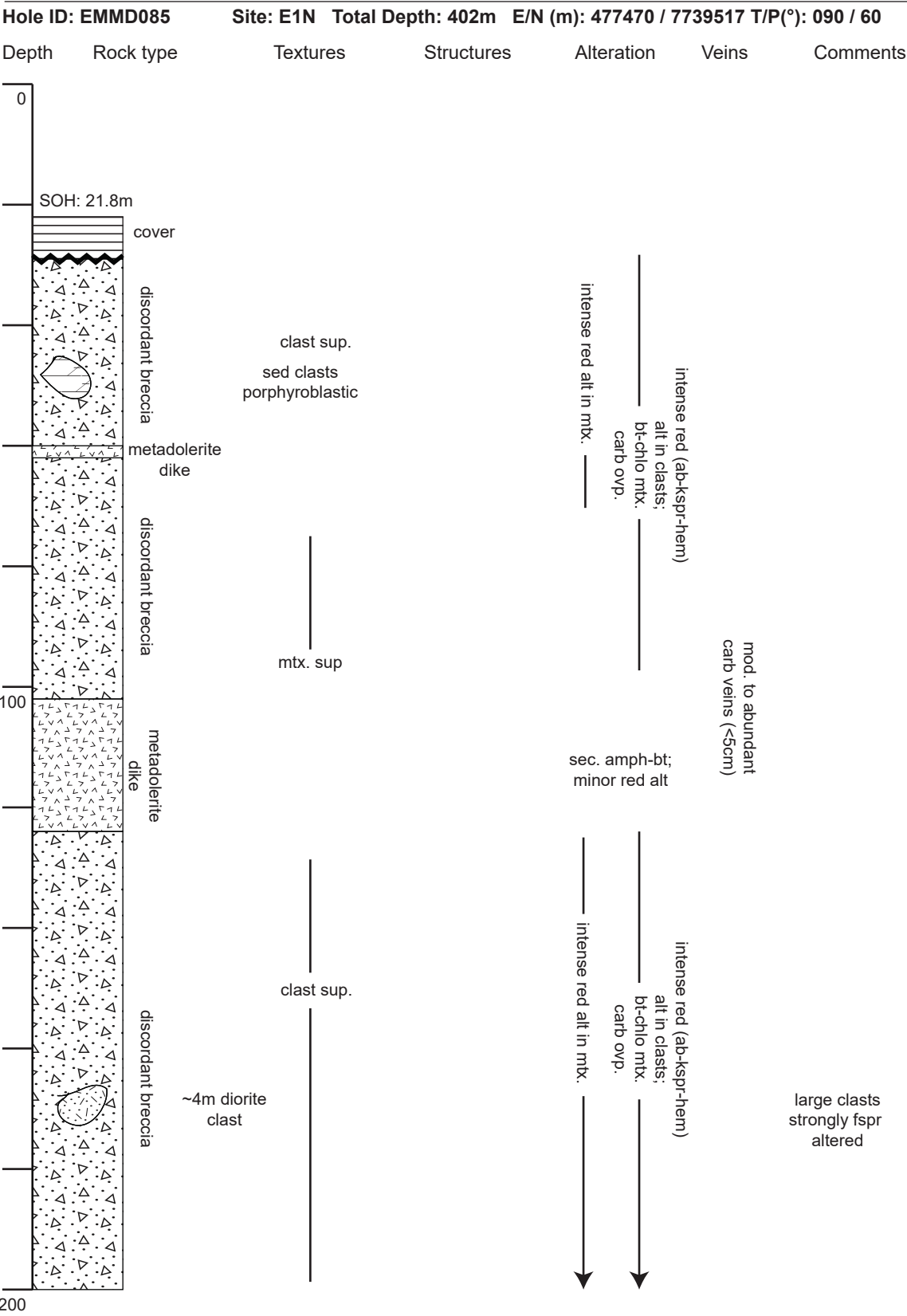


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10 m

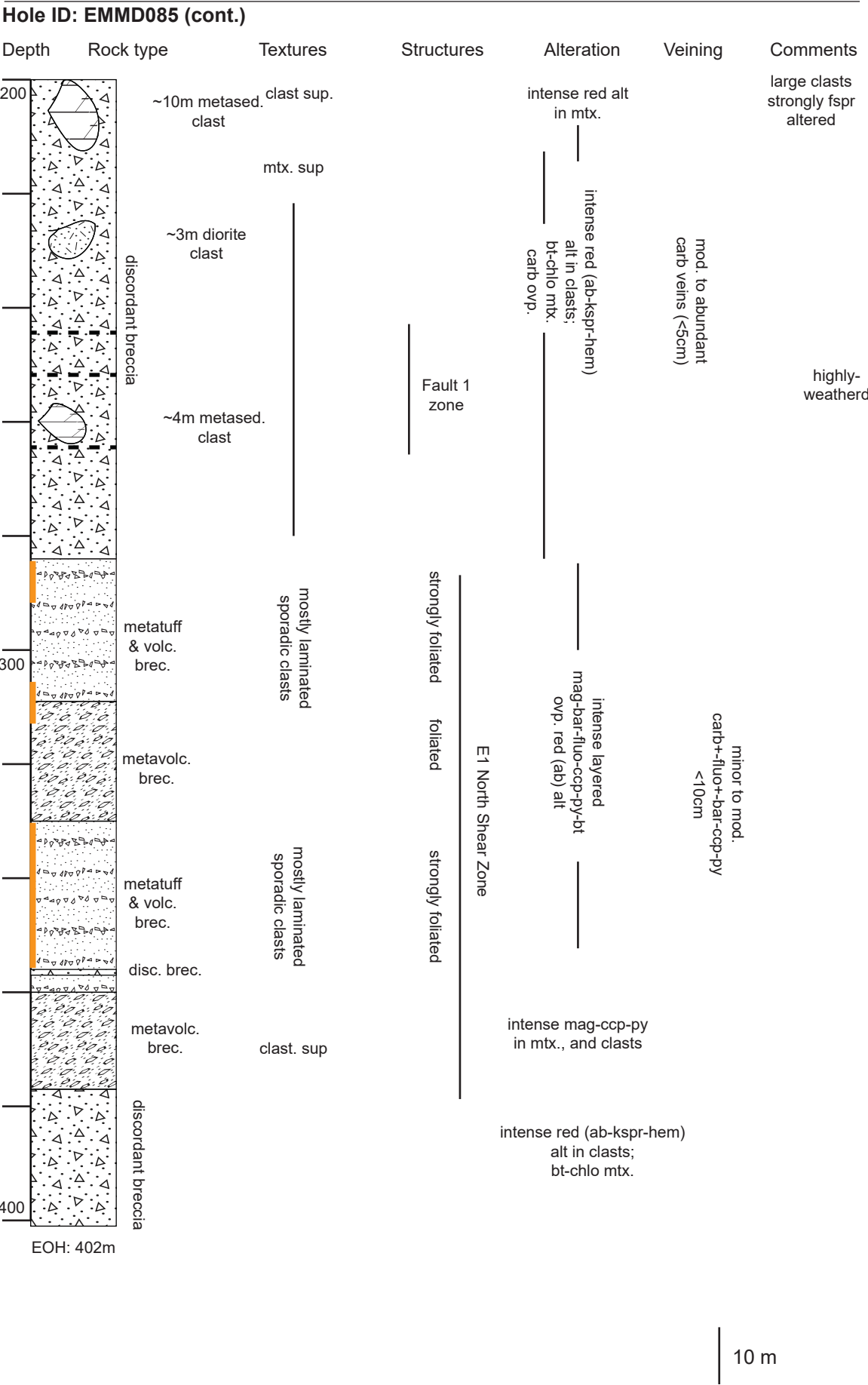
Hole ID: EMD022 (cont.)





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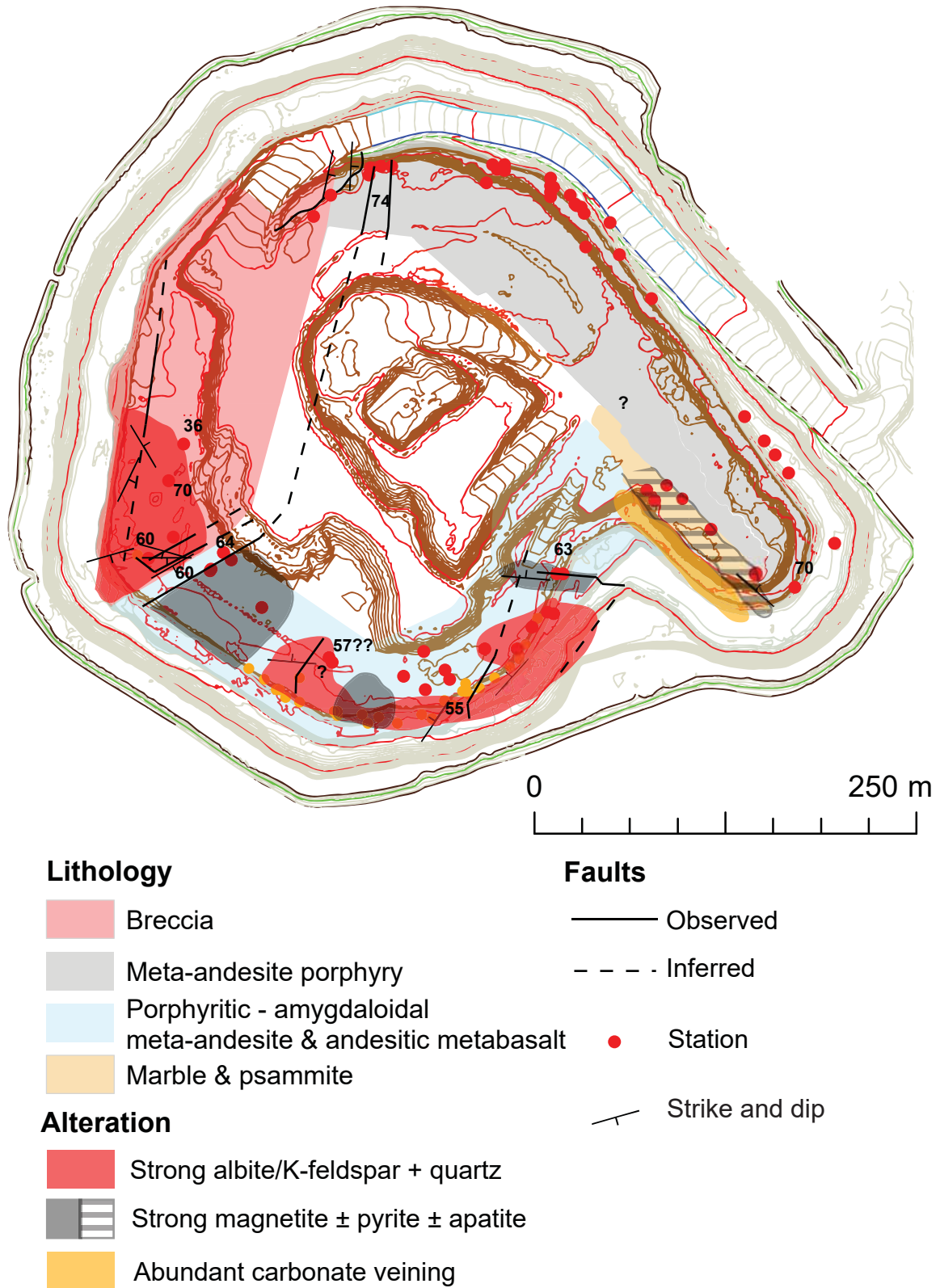
10 m



Hole ID: EMDD074		Site: E1N		Total Depth: 202.6m		E/N (m): 677563 / 7739425		T/P(°): 090 / 60	
Depth	Rock type	Textures	Structures	Alteration	Veins	Comments			
0									
SOH: 19.1m									
	metavolc. brecc.	clast supported; some amygdaloidal clasts up to 0.5m	strongly foliated	intense patchy to mass. mag-carb-py-ap	high carb+-mag+-ap veins & crackle brecciation	highly-weathered			
100			some clasts rotated?						
	metatuff	layered; sporadic clasts		intense mag-py-carb; mostly in mtx.					
	metavolc. brecc.	clast supported; some amygdaloidal clasts up to 0.5m		intense patchy to mass. mag-carb-py-ap	high. carb+-mag+-ap veins & crackle brecciation				
200	EOH: 202.6m								
				intense pervasive red					

10 m

Geological Map of the E1 North Open Pit, April 2013

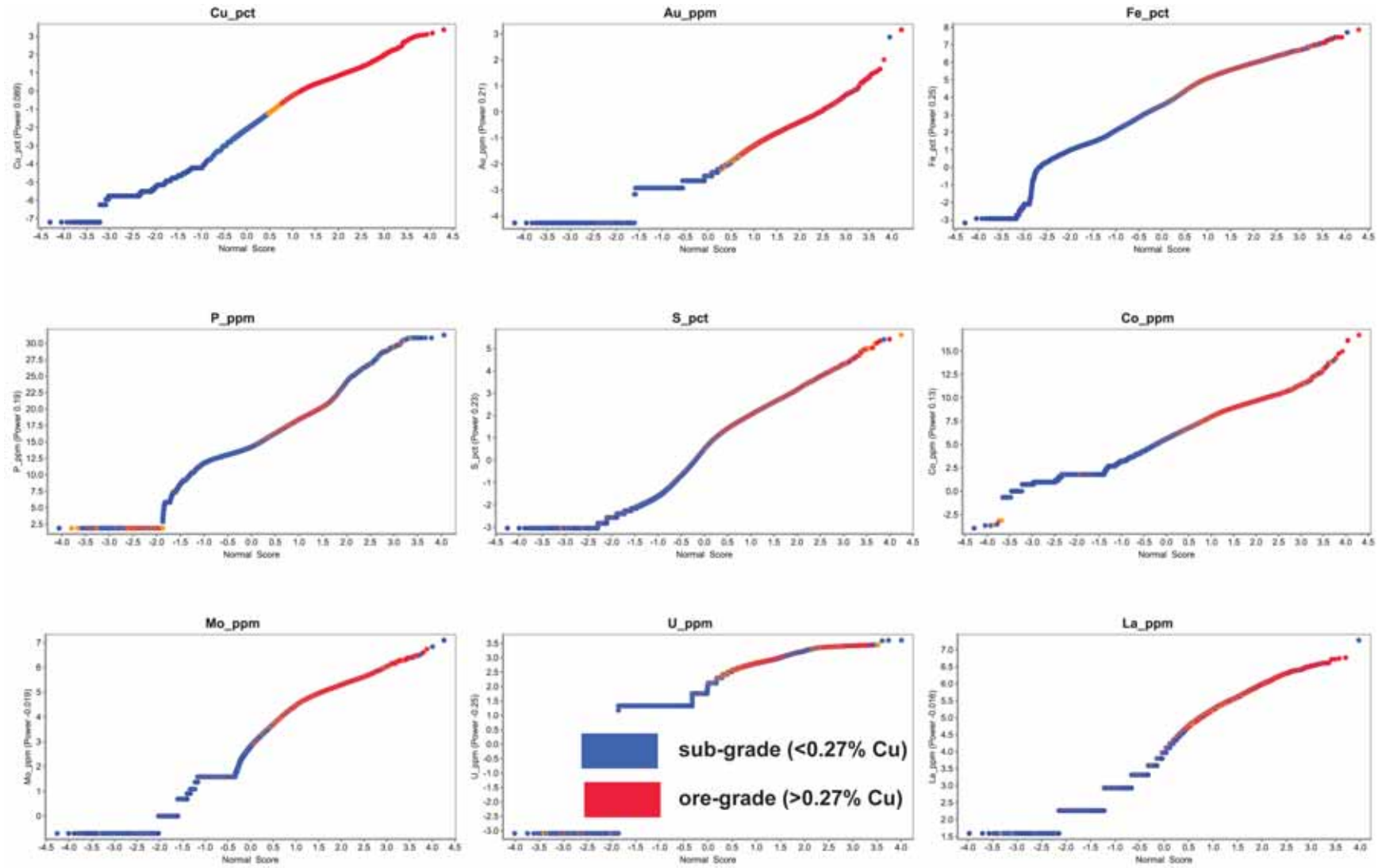


Note: This map was compiled during multiple half-day incursions between March 2013 and April 2014

Table E-3: Summary Statistics for Interpolated Elements

Element (ppm)	Cu	Au	Fe	P	S	Co	Mo	U	La
Count Numeric	58723	38933	56200	20017	45976	57026	48781	16350	14031
Count Text	0	0	0	0	0	0	0	0	0
Count Null	0	19790	2523	38706	12747	1697	9942	42373	44692
Count Negative	0	0	0	0	0	0	0	0	0
Count Zero	39	2125	0	0	0	0	0	0	0
Unique Values	2569	218	4317	2004	1793	962	556	786	109
Minimum	0	0	0	5	0	0	1	0	5
Maximum	19	11	77	26600	36	7600	2037	6786	2260
Mean	0	0	15	1682	3	124	50	79	120
Median	0	0	13	980	2	69	18	19	60
Standard Deviation	1	0	10	2185	3	160	77	204	143
Interquartile Range	0	0	15	1370	4	140	59	65	150
Range	19	11	77	26595	36	7600	2037	6786	2255
1 percentile	0	0	2	5	0	5	1	0	5
5 percentile	0	0	3	100	0	5	1	5	10
10 percentile	0	0	4	280	0	10	3	5	10
25 percentile	0	0	7	630	0	24	5	5	20
75 percentile	0	0	22	2000	4	164	64	70	170
90 percentile	1	0	30	3430	7	326	149	160	300
95 percentile	2	0	34	4750	8	428	203	320	400
99 percentile	3	1	42	11950	13	669	336	1162	680

Probability plots of modeled elements



Appendix F

Fluid Inclusion Data

Table F-1: Stage 3 Barite FIA 2A Fluid inclusion Data; Sample EMMD055-239.4m

FI Number	Phase	System	Liquid Phase %	Final melting (ice)	Th _{l-v} (°C)	Bubble diameter (mm)	Inclusion length (mm)	Inclusion width (mm)	Inclusion shape	Comments	Salinity (wt % NaCl)	ρ_{bulk} (g/cm ³)	dP/dT (bar/°C)	Trapping Pressure (bar) 315° C
Chip 1														
C101	L+V	H ₂ O-NaCl	0.95	-2.4	-	7	60	40	I	leaked after?	4.0	-	-	-
C102	L+V	H ₂ O-NaCl	0.95	-4.1	-	4	20	10	I	-	6.6	-	-	-
C103	L+V	H ₂ O-NaCl	0.95	-2.5	-	4	60	30	I	-	4.2	-	-	-
C105	L+V	H ₂ O-NaCl	0.95	-3.0	-	8	30	30	I	leaked?	5.0	-	-	-
C106	L+V	H ₂ O-NaCl	0.95	-2.8	-	4	20	15	I	-	4.6	-	-	-
C107	L+V	H ₂ O-NaCl	0.95	-2.2	-	7	40	25	I	-	3.7	-	-	-
C108	L+V	H ₂ O-NaCl	0.95	-4.7	-	3	15	10	I	-	7.4	-	-	-
C109	L+V	H ₂ O-NaCl	0.9	-0.8	-	10	50	15	I	leaked?	1.4	-	-	-
C110	L+V	H ₂ O-NaCl	0.9	-0.5	-	4	40	30	I	-	0.9	-	-	-
Chip 2														
C201	L+V	H ₂ O-NaCl	0.95	-6.0	220	4	40	20	I	-	9.2	-	-	-
C203	L+V	H ₂ O-NaCl	0.95	-9.0	-	3	5	10	I	-	12.8	-	-	-
C205	L+V	H ₂ O-NaCl	0.95	-8.0	217	1.5	15	15	I	-	11.7	-	-	-
C206	L+V	H ₂ O-NaCl	0.95	-5.0	217	2	30	10	I	-	7.9	-	-	-
C211	L+V	H ₂ O-NaCl	0.9	-4.0	-	10	50	20	I	leaked after	6.4	-	-	-
C212	L+V	H ₂ O-NaCl	0.95	0.0	-	5	30	20	I	leaked after	0.0	-	-	-
C210	L+V	H ₂ O-NaCl	0.95	-2.0	-	3	15	15	I	leaked after	3.4	-	-	-
C207	L+V	H ₂ O-NaCl	0.95	-5.1	219	2	40	10	I	-	8.0	-	-	-
C208	L+V	H ₂ O-NaCl	0.9	-	221	5	30	15	I	-	-	-	-	-
C214	L+V	H ₂ O-NaCl	0.9	-0.1	-	8	40	30	I	leaked after	0.2	-	-	-
C218	L+V	H ₂ O-NaCl	0.9	-3.5	-	9	50	18	I	leaked after	5.7	-	-	-
C219	L+V	H ₂ O-NaCl	0.9	-3.7	-	5	15	10	I	-	6.0	-	-	-
C202	L+V	H ₂ O-NaCl	0.95	-4.9	220	5	60	10	I	-	7.7	-	-	-
C209	L+V	H ₂ O-NaCl	0.95	-4.9	232	4	30	10	I	-	7.7	-	-	-
C225	L+V	H ₂ O-NaCl	0.95	-10.0	-	1	15	15	I	-	13.9	-	-	-
C2Th01	L+V	H ₂ O-NaCl	0.95	-	210	3	20	10	I	-	-	-	-	-
C2Th02	L+V	H ₂ O-NaCl	0.9	-	209	4	15	4	I	-	-	-	-	-
C2Th03	L+V	H ₂ O-NaCl	0.9	-2.1	180	3	30	20	I	-	3.5	0.92	16.6	2300
C2Th04	L+V	H ₂ O-NaCl	0.95	-3.0	209	2	15	10	I	-	5.0	-	-	-
C2Th05	L+V	H ₂ O-NaCl	0.95	-	247	2	10	10	I	-	-	-	-	-
C2Th06	L+V	H ₂ O-NaCl	0.95	-5.0	148	1	10	6	I	-	7.9	0.98	19.4	3300

L, liquid; V, vapour; I, irregular

Table F-1: Stage 3 Barite FIA 2A Fluid inclusion Data; Sample EMD055-239.4m

FI Number	Phase	System	Liquid Phase %	Final melting (ice)	Th _{l-v} (°C)	Bubble diameter (mm)	Inclusion length (mm)	Inclusion width (mm)	Inclusion shape	Comments	Salinity (wt % NaCl)	ρ_{bulk} (g/cm ³)	dP/dT (bar/°C)	Trapping Pressure (bar) 315° C
C2Th07	L+V	H ₂ O-NaCl	0.95	-5.2	190	2	15	5	I	-	8.1	0.94	17.0	2200
C2Th08	L+V	H ₂ O-NaCl	0.95	-4.0	180	2	20	10	I	-	6.4	0.94	17.2	2400
C2Th09	L+V	H ₂ O-NaCl	0.95	-3.3	185	4	32	23	I	-	5.4	0.92	16.7	2200
C2Th10	L+V	H ₂ O-NaCl	0.95	-1.1	238	2	20	17	I	-	1.9	-	-	-
C2Th11	L+V	H ₂ O-NaCl	0.95	-	201	3	20	8	I	-	-	-	-	-
C2Th12	L+V	H ₂ O-NaCl	0.95	-	198	2	25	20	I	-	-	-	-	-
C2Th13	L+V	H ₂ O-NaCl	0.95	-	197	2	10	5	I	-	-	-	-	-
C2Th14	L+V	H ₂ O-NaCl	0.95	-	207	1.5	15	5	I	-	-	-	-	-
C220	L+V	H ₂ O-NaCl	0.9	-	-	5	30	20	I	leaked	-	-	-	-
C217	L+V	H ₂ O-NaCl	0.9	-	-	5	15	10	I	leaked	-	-	-	-
C216	L+V	H ₂ O-NaCl	0.7	-	-	17	40	30	I	leaked	-	-	-	-
C213	L+V	H ₂ O-NaCl	0.7	-14.7	-	20	110	30	I	necking?	-	-	-	-
C227	L	H ₂ O-NaCl	-	-	-	-	30	30	I	leaked	-	-	-	-
C226	L+V	H ₂ O-NaCl	0.7	-	-	7	14	6	I	leaked	-	-	-	-
C204	L+V	H ₂ O-NaCl	0.9	-	-	8	50	20	I	-	-	-	-	-
Chip 3														
C3Th15	L+V	H ₂ O-NaCl	0.9	-5.0	166	10	70	20	I	-	7.9	0.96	18.3	2800
C3Th16	L+V	H ₂ O-NaCl	0.9	-4.4	168	15	80	20	I	-	7.0	0.95	18.0	2700
Chip 4														
C401	L+V	H ₂ O-NaCl	0.95	0.0	169	4	38	15	I	-	0.0	0.90	16.9	2500
C402	L+V	H ₂ O-NaCl	0.9	-0.5	204	8	60	45	I	-	0.9	-	-	-
C403	L+V	H ₂ O-NaCl	0.95	-0.9	180	5	30	27	I	metastable	1.6	0.90	16.5	2300
C404	L+V	H ₂ O-NaCl	0.7	-3.6	200	3	13	5	I	-	5.9	-	-	-
C405	L+V	H ₂ O-NaCl	0.9	-1.2	200	8	40	30	I	-	2.1	-	-	-
C406	L+V	H ₂ O-NaCl	0.95	-3.8	-	3	24	16	I	metastable	6.2	-	-	-
C407	L+V	H ₂ O-NaCl	0.95	-	180	4	25	25	I	metastable	-	-	-	-
C408	L+V	H ₂ O-NaCl	0.95	-0.7	160	5	45	10	I	metastable	1.2	0.92	17.2	2700

Table F-2: Late Stage 3 FIA 2B and 2D Data

FI Number	Min /FIA	Origin	Phases	System	Liquid Phase %	Tm - eutectic (°C±10)	Tm - HH (°C ± 5)	Tm - Ice (°C ±1)	Bubble diameter (mm)	Inclusion length (mm)	Inclusion width (mm)	Inclusion shape	Inclusion area (mm ²)	Wt % NaCl	Wt % CaCl ₂	Comments
EMMD077-239.4m																
Chip 2																
C2SF01			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-33	-19.0	2	15	10	CR	75	4.4	16.0	refilled
C2SF02			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-33	-19.0	2	15	12	T	90	4.4	16.0	
C2SF03			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-36	-12.5	3	22	15	CI	165	2.6	13.6	
C2SF05	Barite/FI A 2B	S	L+V	H ₂ O-CaCl ₂ -NaCl	95	-60	-32	-14.9	3	40	20	CI	400	4.3	13.6	
C2SF06			L+V	H ₂ O-CaCl ₂ -NaCl	95	-63	-30	-11.5	3	30	20	CR	300	4.7	10.7	
C2SF07			L+V	H ₂ O-CaCl ₂ -NaCl	95	-59.5	-32	-9.1	2	15	15	CR	113	3.2	10.0	
C2SF08			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-32	-10.5	6	40	20	CR	400	3.5	11.0	
C2SF09			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-30	-15.0	3	15	10	CR	75	5.5	12.5	
Chip 1																
C1SF10			L+V	H ₂ O-CaCl ₂ -NaCl	90	-	-	-	5	20	15	T	150	-	-	leaked
C1SF11			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-34	-16.9	2	25	18	CI	225	3.7	15.4	
C1SF12	Barite/FI A 2B	S	L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-33	-13.0	2	25	5	CI	63	3.6	13.0	
C1SF13			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-33	-19.0	2	10	8	C	40	4.4	16.0	
C1SF14			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-29	-17.0	2	15	8	R	60	6.6	12.7	
C1SF15			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-29	-14.0	3	18	9	I	81	5.9	11.4	
E1S: EMM019-310.9m																
Chip 1																
C1A1002			L+V	H ₂ O-CaCl ₂ -NaCl	95	-49	-	-19.0	3	27	19	I	513	-	-	leaked
C1A1003			L+V	H ₂ O-CaCl ₂ -NaCl	90	-49	-33	-19.1	3	20	17	C	534	4.4	16.0	
C1A1004			L+V	H ₂ O-CaCl ₂ -NaCl	95	-49	-32	-19.2	2	20	8	IR	160	4.9	15.6	
C1A1005			L+V	H ₂ O-CaCl ₂ -NaCl	90	-	-32	-21.0	3	15	13	T	98	5.2	16.3	
C1A1006			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-31	-20.8	2	15	14	I	210	5.8	15.7	
C1A1007			L+V	H ₂ O-CaCl ₂ -NaCl	95	-48	-31	-20.8	2	13	10	H	-	5.8	15.7	
C1A1008			L	H ₂ O-CaCl ₂ -NaCl	100	-	-31	-20.6	-	11	11	C	190	5.8	15.6	
C1A1009			L	H ₂ O-CaCl ₂ -NaCl	100	-	-36	-20.3	-	12	12	C	226	3.3	17.7	
C1A1010	Barite/FI A 2B	S	L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-35	-20.3	2	18	7	CR	126	3.7	17.4	
C1A1011			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-	-20.3	2	15	10	I	150	-	-	
C1A1012			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-29	-19.7	2	10	10	IR	100	7.2	13.8	
C1A1013			L	H ₂ O-CaCl ₂ -NaCl	100	-	-	-21.3	-	15	10	I	150	-	-	
C1A1014			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-35	-21.3	2	12	9	I	108	3.8	17.8	
C1A1015			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-30	-20.0	2	10	9	I	90	6.4	14.7	
C1A1016			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-33	-19.1	2	10	7	C	110	4.4	16.0	
C1A1017			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-29	-20.2	1	9	7	CR	63	7.3	14.0	
C1A1018			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-	-14.2	2	8	7	C	88	-	-	

HH, hydrohalite; L, liquid; V, vapour; I, irregular; IC, irregular circle; C, circular; CI, curved irregular; CR, curved rectangular; R, rectangular; T, triangular; H, hexagonal; L (shape column), L-shaped

Table F-2: Late Stage 3 FIA 2B and 2D Data

FI Number	Min /FIA	Origin	Phases	System	Liquid Phase %	Tm - eutectic (°C±10)	Tm - HH (°C ± 5)	Tm - Ice (°C ±1)	Bubble diameter (mm)	Inclusion length (mm)	Inclusion width (mm)	Inclusion shape	Inclusion area (mm ²)	Wt % NaCl	Wt % CaCl ₂	Comments
C1A1020			L	H ₂ O-CaCl ₂ -NaCl	100	-	-	-20.2	-	14	12	C	264	-	-	
C1A1021			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-29	-18.0	1	20	12	R	240	6.8	13.1	
C1A1022			L	H ₂ O-CaCl ₂ -NaCl	100	-	-36	-19.0	-	10	9	T	45	3.2	17.1	
C1A1023			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-	-20.6	3	14	10	I	140	-	-	
C1A1024			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-32	-21.1	2	18	7	IR	126	5.2	16.4	
C1A1025			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-29	-12.6	2	8	8	C	101	5.6	10.7	
C1A1026			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-35	-14.1	1	15	8	CR	120	3.0	14.3	
C1A1027			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-33	-14.6	1	9	7	C	99	3.8	13.9	
C1A1028			L	H ₂ O-CaCl ₂ -NaCl	100	-	-	-19.9	-	7	7	C	77	-	-	
C1A1029			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-36	-22.1	2	7	7	I	49	3.5	18.4	
C1A1031			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-34	-22.3	1	8	7	C	88	4.3	17.8	
C1A1032			L	H ₂ O-CaCl ₂ -NaCl	100	-	-30	-19.2	-	10	6	C	94	6.3	14.4	
C1A1033	Barite/FI A 2B	S	L+V	H ₂ O-CaCl ₂ -NaCl	90	-	-33	-22.1	2	10	9	R	90	4.8	17.3	
C1A1034			L+V	H ₂ O-CaCl ₂ -NaCl	70	-	-36	-21.0	4	11	8	I	88	3.4	18.0	
C1A1035			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-29	-21.0	1	12	7	I	84	7.4	14.3	
C1A1036			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-30	-18.9	2	14	8	I	112	6.2	14.2	
C1A2001			L	H ₂ O-CaCl ₂ -NaCl	100	-	-	-16.9	-	7	7	T	25	-	-	
C1A2002			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-30	-19.2	1	9	6	H	-	6.3	14.4	
C1A2003			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-31	-19.4	2	9	7	IR	63	5.6	15.1	
C1A2004			L	H ₂ O-CaCl ₂ -NaCl	100	-	-	-19.4	-	9	6	C	85	-	-	
C1A2005			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-35	-16.8	2	10	8	CR	80	3.3	15.7	
C1A2006			L+V	H ₂ O-CaCl ₂ -NaCl	70 - 90	-	-32	-20.2	3	6	6	C	57	5.1	16.0	
C1A2009			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-33	-18.1	2	13	6	IR	78	4.3	15.6	
C1A2010			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-29	-21.0	2	13	6	CR	78	7.4	14.3	
C1A2011			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-32	-20.8	2	14	10	I	140	5.2	16.3	
C1A2012			L+V	H ₂ O-CaCl ₂ -NaCl	90	-	-35	-21.4	3	7	5	I	35	3.8	17.8	
C1A2013			L+V	H ₂ O-CaCl ₂ -NaCl	90	-	-31	-21.6	3	15	10	T	75	5.9	16.0	
Chip 2																
C2A1001			L	H ₂ O-CaCl ₂ -NaCl	100	-	-35	-13.9	-	7	7	CR	49	3.0	14.2	
C2A1002			L	H ₂ O-CaCl ₂ -NaCl	100	-	-	-13.8	-	8	7	C	88	-	-	
C2A1003			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-31	-22.5	2	10	9	T	45	6.0	16.3	
C2A1004	Barite/FI A 2B	S	L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-36	-17.2	2	8	7	R	56	3.0	16.2	
C2A1005			L+V	H ₂ O-CaCl ₂ -NaCl	90	-	-32	-20.9	3	11	9	R	99	5.2	16.3	
C2A1007			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-34	-16.9	2	10	10	T	50	3.7	15.4	
C2A1008			L+S?	H ₂ O-CaCl ₂ -NaCl	95	-	-29	-23.7	-	9	7	C	99	7.9	15.3	
C2A1009			L+S?	H ₂ O-CaCl ₂ -NaCl	95	-	-32	-23.7	-	8	8	I	64	5.5	17.4	

Table F-2: Late Stage 3 FIA 2B and 2D Data

FI Number	Min /FIA	Origin	Phases	System	Liquid Phase %	Tm - eutectic (°C±10)	Tm - HH (°C ± 5)	Tm - Ice (°C ±1)	Bubble diameter (mm)	Inclusion length (mm)	Inclusion width (mm)	Inclusion shape	Inclusion area (mm ²)	Wt % NaCl	Wt % CaCl ₂	Comments
C2A1010			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-33	-23.7	2	8	8	C	101	4.9	17.9	
C2A1011			L+S?	H ₂ O-CaCl ₂ -NaCl	95	-	-29	-22.7	-	7	5	I	35	7.8	14.9	
C2A1013			L+S?	H ₂ O-CaCl ₂ -NaCl	95	-	-30	-22.7	-	15	11	T	83	6.8	15.7	
C2A1014	Barite/FI A 2B	S	L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-30	-21.8	1	9	8	C	113	6.7	15.4	
C2A1015			L+S?	H ₂ O-CaCl ₂ -NaCl	95	-	-31	-23.4	-	12	10	R	120	6.2	16.7	
C2A1016			L+V+S	H ₂ O-CaCl ₂ -NaCl	95	-	-34	-23.4	1	11	7	I	77	4.4	18.3	
C2A1017			L+S?	H ₂ O-CaCl ₂ -NaCl	95	-	-29	-23.8	-	12	12	CR	144	8.0	15.3	
EIS: EMM019-311.1m																
Chip 2																
C2A1001			L+V	H ₂ O-CaCl ₂ -NaCl	90	-	-34	-18.8	2	13	11	C	225	3.9	16.3	metastable
C2A1002			L	H ₂ O-CaCl ₂ -NaCl	100	-	-33	-13.1	-	8	7	H	-	3.6	13.0	
C2A1003			L	H ₂ O-CaCl ₂ -NaCl	100	-	-35	-14.8	-	17	10	I	170	3.1	14.7	
C2A1004			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-29	-13.0	2	20	7	IR	140	5.7	10.9	
C2A1005			L	H ₂ O-CaCl ₂ -NaCl	100	-	-	-14.7	-	17	8	I	136	-	-	
C2A1006			L	H ₂ O-CaCl ₂ -NaCl	100	-	-	-14.1	-	12	9	H	-	-	-	
C2A1011			L+V	H ₂ O-CaCl ₂ -NaCl	90	-	-29	-17.1	2	12	8	C	151	6.6	12.8	
C2A1012			L	H ₂ O-CaCl ₂ -NaCl	100	-	-36	-17.0	-	12	7	CR	84	3.0	16.1	
C2A1013			L	H ₂ O-CaCl ₂ -NaCl	100	-	-	-16.2	-	9	6	I	54	-	-	
C2A1014			L	H ₂ O-CaCl ₂ -NaCl	100	-	-	-16.2	-	9	6	CR	54	-	-	
C2A1015			L	H ₂ O-CaCl ₂ -NaCl	100	-	-29	-10.5	-	9	8	C	113	5.0	9.5	
C2A1016	Calcite/F IA 2D	P	L	H ₂ O-CaCl ₂ -NaCl	100	-	-35	-13.6	-	20	10	IR	200	3.0	14.0	
C2A1017			L	H ₂ O-CaCl ₂ -NaCl	100	-	-33	-12.7	-	20	12	C	377	3.5	12.8	
C2A1018			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-	-21.7	2	15	12	C	283	-	-	
C2A1019			L	H ₂ O-CaCl ₂ -NaCl	100	-	-29	-12.8	-	25	10	I	250	5.6	10.8	
C2A1020			L	H ₂ O-CaCl ₂ -NaCl	100	-	-30	-13.8	-	18	11	IR	198	5.2	12.0	
C2A1021			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-	-	6	13	7	I	91	-	-	leaked
C2A1022			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-	-13.9	1	12	8	H	-	-	-	
C2A1023			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-31	-15.3	3	9	6	T	27	4.9	13.3	
C2A1024			L	H ₂ O-CaCl ₂ -NaCl	100	-	-	-13.0	-	12	9	I	108	-	-	
C2A1025			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-35	-13.1	2	10	9	I	90	2.9	13.7	
C2A1026			L	H ₂ O-CaCl ₂ -NaCl	100	-	-30	-17.0	-	10	7	C	110	5.9	13.4	
C2A1027			L	H ₂ O-CaCl ₂ -NaCl	100	-	-31	-15.0	-	10	6	CR	60	4.9	13.1	
C2A1028			L+V	H ₂ O-CaCl ₂ -NaCl	95	-	-34	-12.6	1	9	5	IR	45	3.1	13.1	

Appendix G

Stable Isotope Raw Data

Appendix G: Stable Isotope Raw Data: SHRIMP $\delta^{34}\text{S}$

Table G-1: $\delta^{34}\text{S}$ SHRIMP Results					
Drillhole - depth or sample ID	Paragenetic Stage, description and protolith	Spot	Mineral	$\delta^{34}\text{S}$ (‰ CDT)	Error (‰; 95% CI)
E1 North					
EMMD001-195.25m	Stage 3; Laminated mag-bar-fluo-ccp-cal-rich rock; marble?	S1-1.1	ccp	-1.92	0.51
		S1-1.2	ccp	-1.72	0.51
		S1-2.1	ccp	-0.83	0.51
		S3-1.1	ccp	-2.19	0.51
		S3-1.2	ccp	-2.00	0.51
		S5-1.1	ccp	-0.78	0.51
		S5-2.1	ccp	-1.05	0.51
		BA1.1	bar	17.65	0.29
		BA2.1	bar	17.55	0.29
		BA2.2	bar	16.43	0.28
		S3-BA1.1	bar	16.60	0.28
		S3-BA1.2	bar	15.93	0.28
EMMD075-205.3m	Stage 3; Laminated mag-bar-fluo-ccp-cal-rich rock; marble?	S1-1.1	ccp	0.88	0.51
		S1-1.2	ccp	0.52	0.51
		S1-2.1	ccp	-0.38	0.51
		S2-1.1	ccp	0.25	0.51
		S2-2.1	ccp	-0.05	0.51
		S2-3.1	ccp	0.53	0.51
		S2-4.1	ccp	1.10	0.51
		S2-5.1	ccp	0.58	0.51
		S2-6.1	ccp	1.94	0.51
		S2-6.2	ccp	0.30	0.51
		S2-Ba1.1	bar	20.55	0.30
		S2-Ba2.2	bar	20.86	0.30
		S2-Ba3.1	bar	20.52	0.31
		S2-Ba4.2	bar	20.84	0.30
		S2-Ba6.1	bar	21.22	0.33
		S1-Ba2.1	bar	20.54	0.34
		S1-Ba1.1	bar	18.43	0.34
		S1-Ba1.2	bar	21.01	0.34
EMMD085-310.5m	Stage 3; Laminated, folded, mag-bar-qtz-ser-fluo-cal-cc-rich rock; intermediate metavolcanic?	S1-1	py	4.53	0.38
		S1-2	py	3.38	0.38
		S1-3	py	7.66	0.38
		S1-4	py	4.10	0.38
		S1-5	py	3.17	0.38
		S1-6a	ccp	-2.89	0.39
		S1-9a	ccp	-5.23	0.39
		S1-7a	ccp	-3.63	0.39
		S1-10a	ccp	-5.83	0.39
		S1-6b	bar	20.03	0.38
		S1-7b	bar	17.61	0.38
		S1-8b	bar	16.78	0.38
		S1-9b	bar	20.34	0.38
		S1-10b	bar	16.58	0.38
EMMD167-105.9m	Stage 2c?; Pyrite infill in qtz-cal vein cutting laminated carbonaceous phyllite	S1-1	py	5.65	0.33
		S1-2	py	5.04	0.33
		S1-3	py	4.52	0.33
EMMD033-79.5m	Stage 2a with Stage 3 overprint; Coarse-crystalline ap-mag-py (Stage 2)-cal-qtz alteration; late ccp (Stage 3) overprint; probably metavolcanic	S1-P1	py	1.73	0.28
		S1-P2	py	1.18	0.20
		S2-P1	py	1.89	0.28
		S2-P2a	py	1.41	0.16
		S2-P2b	py	2.19	0.27
		S1-CP1	ccp	0.72	0.18
		S1-CP2	ccp	-0.74	0.14
		S2-CP1	ccp	0.68	0.18

CI, confidence interval; cal, calcite; mag, magnetite; bar, barite; fluo, fluorite; ccp, chalcopyrite; py, pyrite; qtz, quartz; ap, apatite; ser, sericite; bt, biotite; apy, arsenopyrite; chlo, chlorite

Appendix G: Stable Isotope Raw Data: SHRIMP $\delta^{34}\text{S}$

Table G-1: $\delta^{34}\text{S}$ SHRIMP Results					
Drillhole - depth or sample ID	Paragenetic Stage, description and protolith	Spot	Mineral	$\delta^{34}\text{S}$ (‰ CDT)	Error (‰; 95% CI)
E1 South					
EMM019-311.1m	Stage 3 cal-bar-ccp-fluo vein reopened by late Stage 3 cal in siliceous marble	S1-2.1	ccp	14.09	0.51
		S1-2.2	ccp	13.99	0.51
		S1-2.3	ccp	13.19	0.51
		S1-2.4	ccp	13.64	0.51
		S1-2.5	ccp	13.74	0.51
		S2-1.1	ccp	12.95	0.51
		S2-1.2	ccp	12.63	0.51
		S2-1.3	ccp	13.32	0.51
		S2-2.1	ccp	12.94	0.51
		S2-2.1	ccp	11.40	0.51
		S2-2.2	ccp	12.66	0.51
		S1-Ba1.1	bar	18.83	0.29
		S1-Ba1.2	bar	18.19	0.29
		S1-Ba1.3	bar	20.36	0.28
MA96740 (EMM019-UD)	Stage 3 Laminated mag-bar-fluo-ccp-cal-rich marble	S1-1.1	ccp	8.61	0.51
		S1-1.2	ccp	8.75	0.51
		S2-1.1	ccp	7.49	0.51
		S2-1.2	ccp	6.81	0.51
		S2-1.3	ccp	7.44	0.51
		S3-1.1	ccp	7.82	0.51
		S3-1.2	ccp	7.62	0.51
		S1-BA1.1	bar	27.68	0.30
		S1-BA1.2	bar	27.42	0.31
		S1-BA2.1	bar	26.32	0.32
		S2-BA1.1	bar	25.24	0.35
		S2-BA1.2	bar	25.64	0.34
		S2-BA1.3	bar	26.38	0.35
		S3-BA1.1	bar	27.18	0.34
		S3-BA1.2	bar	27.24	0.34
		S3-BA1.3	bar	26.53	0.35
EMM019-310.9m	Stage 3 cal-bar-ccp-fluo vein reopened by late Stage 3 cal in siliceous marble	S1-3a	ccp	12.98	0.28
		S1-1a	ccp	12.62	0.28
		S1-2a	ccp	10.62	0.28
		S1-1a_bar-1	bar	19.21	0.31
		S1-1a_bar-2	bar	19.78	0.31
		S1-3b_bar-1	bar	20.83	0.31
		S1-3b_bar-2	bar	21.01	0.31
EMM019-202.1m	Stage 2a - 3: Dissem. To blebby py and coarse asy overprinted by Stage 2c - 3 ccp in carbonaceous metasiltstone	S1-P1	py	18.53	0.19
		S1-P2a	py	20.12	0.14
		S1-P2b	py	18.98	0.22
		S2b-CP1	ccp	17.25	0.17
		S2b-CP2	ccp	16.94	0.14
EMM018-86.9m	Stage 2 (a or c?) blebby and dissem. Py overprinted by ccp in laminated carbonaceous phyllite	S2.X	ccp	3.02	0.29
		S1.1	py	2.21	0.40
		S1.2	py	2.07	0.39
		S3.2	py	2.48	0.40
		S3.3	py	1.98	0.41
EMMD052-285.85m	Stage 3; Laminated mag-qtz-py-ccp-bt-rich marble; alternating sulfide-rich and sulfide-bearing laminae	S2-3	py	8.46	0.33
		S3-2a	py	11.96	0.33
		S1-3	py	12.60	0.33
		S2-2	ccp	1.68	0.33
		S3-3a	ccp	11.54	0.42
		S3-4	ccp	11.81	0.43
		S1-2	ccp	11.73	0.42
		S3-2a	ccp	11.09	0.42
		S3-3a	ccp	12.04	0.42
		S3-4	ccp	12.10	0.42
		S3-2b-1	bar	29.17	0.28
		S3-2b-2	bar	29.73	0.27

Appendix G: Stable Isotope Raw Data: SHRIMP $\delta^{34}\text{S}$

Table G-1: $\delta^{34}\text{S}$ SHRIMP Results					
Drillhole - depth or sample ID	Paragenetic Stage, description and protolith	Spot	Mineral	$\delta^{34}\text{S}$ (‰ CDT)	Error (‰; 95% CI)
E1 East					
EMMD007-146.15m	Bt-mag-rich porphyoblastic marble? Actinolite p.blasts replaced by Stage 2 (a or c?): py-mag-and Stage 2c - 3 ccp	S1-1	ccp	14.72	0.39
		S1-4	ccp	14.57	0.39
		S1-2.1	py	18.46	0.38
		S1-3	py	18.27	0.38
		S2-1	py	17.63	0.38
		S2-2	py	17.58	0.38
		S2-3.1	py	18.01	0.38
EMMD007-112m	Stage 3 bar-cal-rich vein cutting metasilstone	1.1	bar	9.78	0.39
		1.2	bar	9.88	0.39
		1.3	bar	9.59	0.39
EMMD007-211m	Stage 3 bar-cal-rich vein cutting metasilstone	1.1	bar	6.85	0.39
		1.2	bar	5.28	0.38
		1.3	bar	4.53	0.38
EMMD008-108.1m	Bt-mag-rich porphyoblastic marble? Actinolite p.blasts replaced by Stage 2 (a or c?): py-mag-and Stage 2c - 3 ccp	S1-1	py	13.38	0.39
		S1-2	py	15.62	0.38
		S1-3	ccp	12.46	0.30
EMMD008-114.15m	Stage 2a qtz vein re-opened by Stage 3 bar-cal-py-ccp vein cutting massive magnetite-altered metasediment	S1-4	ccp	15.01	0.41
		S1-1	ccp	16.91	0.44
		S1-2	py	20.35	0.33
		S1-3	py	18.92	0.33
		S2-2	py	14.65	0.33
		S2-1	py	14.65	0.33
EMMD174-117.7m	Lightly-altered py-mag-ccp-bearing amphibolite; Stage unconstrained	S1-P1	py	0.53	0.18
		S1-P2	py	2.72	0.13
		S2-CP1	ccp	4.29	0.47
		S2-CP2	ccp	3.72	0.47
EMMD174-92.3m	Lightly-altered py-mag-bearing bt-rich Corella marble; Stage unconstrained	S1-P3a	py	8.16	2.83
		S1-P4a	py	2.78	0.11
		S1-P4b	py	0.56	0.64
E8					
EMMD226-130.4m	Stage 2 py-mag-altered amygdaloidal meta-andesite-basalt; Stage 3 ccp overprint	S1-3	ccp	0.47	0.26
		S1-4	ccp	0.90	0.26
		S1-1	py	1.62	0.38
		S1-2	py	1.52	0.38

Appendix G: Stable Isotope Raw Data: SHRIMP $\delta^{34}\text{S}$

Table G-2: Ex-situ Sulfur Isotope Data					
Site	Sample ID	Description and protolith	Mineral	$\delta^{34}\text{S}$ (‰ CDT)	Error (‰; 95% CI)
E1 North	EMMD077-239.4	Stage 3 bar-cal-ccp-fluo vein cutting laminated rock altered by mag-bar-fluo-ccp	ccp	2.7	0.3
			bar	6.7	0.3
	EMMD153-277.5	Stage 2a qtz-mag-vein in siliceous marble re-opened by Stage 2c-3 py-ccp-cal	py	14.5	0.3
			ccp	13.9	0.3
	EMMD055-155.35	Qtz-alb vein (Stage 2b?) reopened by Stage 3 bar-fluo-cal-ccp vein in mag-chlo-fluo-ccp-altered metavolcanic	ccp	1.2	0.3
E1 East			bar	11.5	0.3
	EMMD007-223.6	Stage 2c cal-mag-py vein in meta-andesite	py	21.4	0.3
	EMMD008-114.45	Qtz vein (Stage 2a) re-opened by Stage 3 bar-cal-py-ccp vein in massive mag-altered metasediment	py	19.8	0.3
Snake Creek Anticline			bar	26.5	0.3
	Clon-2A	Scapolite-bt marble with boudinaged albite-qtz-rich layers	BaSO ₄ **	11.6	0.5
	Clon-2B		BaSO ₄ **	12.5	0.5
UQ and UT Standards		NBS127	BaSO ₄	20.3	-
		IAEA-S-1	Ag ₂ S	-0.3	-
		IAEA-S-3	Ag ₂ S	32.3	-

**CAS precipitate

Table G-3: Carbonate Associated Sulfur (CAS) sample prep								
Sample ID	Original weight (g)	Weight after acid digestion (g)	Carbonate Weight (g)	Carbonate (%)	BaSO ₄ (mg)	Carbonate S (ppm)	Whole-rock S (ppm)	$\delta^{34}\text{S}_{\text{CDT}}$ (‰)
02A wash 1					39.5		12.2	12.3, 12.1
02A wash 2					18.2		13.3	13.0, 13.6
02A acid	236	118	118	50%	44.4	14	7	11.6 11.5, 11.7
02B wash 1					28.6		11.0	11.7, 10.3
02B acid	220	100	120	55%	10.8	5	3	12.5 12.3, 12.6
Sample 02A wash milled slightly finer than 02B, which probably accounts for the extra wash needed to remove all 'loose' sulfate. The observation that 'loose' sulfate has the same isotopic composition as the 'acid liberated' sulfate suggest these clean core samples have not been affected by supergene processes, nor were any trace sulfides oxidised during the acid digestion step.								
Comments:								
The S in carbonate and S whole rock values have been calculated assuming that the only S in the rock is in carbonate and the combined washings and acid digestion liberate all this S.								

Table G-4: SHRIMP Sulfur and Oxygen Isotope Standards					
Sulfur					
Standard - mineral	Reference $\delta^{34}\text{S}$ (‰)	Measured $^{32}\text{S}/^{34}\text{S}$	Internal Error $^{32}\text{S}/^{34}\text{S} \pm 95\% \text{ CI}$	Measured $\delta^{34}\text{S}$ (‰)	Internal Error $\delta^{34}\text{S} \pm 95\% \text{ CI}$ (‰)
Norilsk - ccp	8.0	0.0441367	2.42E-06	8.01	0.05
Ruttan - py	1.2	0.0437511	3.58E-02	1.24	0.05
Bar4 - bar	3.5	0.0442447	5.81E-06	3.61	0.13
Bar2 - bar	57.0	0.0465291	NR	57.11	NR
All $\delta^{34}\text{S}$ values normalized to CDT					
Oxygen					
Standard - mineral	Reference $\delta^{18}\text{O}$ (‰)	Measured $^{18}\text{O}/^{16}\text{O}$	Internal error $^{18}\text{O}/^{16}\text{O} \pm 95\% \text{ CI}$	Measured $\delta^{18}\text{O}$ (‰)	Internal Error $\delta^{18}\text{O} \pm 95\% \text{ CI}$ (‰)
Magnetite 5830 - mag	4.5	0.0019769	5.11E-07	4.26	0.26
UWQ-1 - qtz	12.3	0.0020250	6.29E-07	12.26	0.31
All $\delta^{18}\text{O}$ values normalized to VSMOW					

Appendix H
Copyright statements

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