



Deformation-enhanced fluid evolution and skarn–IOCG transition in the Paleoproterozoic Elaine Dorothy Cu–Au system, Mount Isa Inlier, Australia

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Received: 18 March 2026 / Accepted: 30 September 2026
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Abstract

The Elaine Dorothy Cu–Au deposit, located in the Mary Kathleen Domain of the Mount Isa Inlier, Australia, records the interaction of Paleoproterozoic skarn metasomatism, fluid evolution, and deformation. The deposit is hosted by carbonate- and calc-silicate-rich rocks of the Corella Formation and comprises diopside–garnet–scapolite–wollastonite±amphibole assemblages associated with pyrrhotite–chalcopyrite–pyrite mineralisation. Field relationships and mineral textures indicate that sulphide deposition began during or shortly after prograde skarn formation and subsequently evolved from disseminated and vein-controlled to semi-massive, massive, and shear-zone-hosted mineralisation. LA-ICP-MS analyses of pyrite, pyrrhotite, chalcopyrite, and magnetite record systematic variation in trace-element compositions during this evolution. Early Py1 is enriched in Co and Se and displays Co/Sb–Se/As characteristics consistent with a magmatic–hydrothermal contribution. Se-in-pyrite thermometry yields formation temperatures of up to 544 ± 36 °C for the earliest stage, decreasing to approximately 323–417 °C in later Py1 and 342 ± 11 °C for Py2. The transition from Co-rich Py1 to Co-poor, Ni-enriched Py2, together with pyrrhotite-dominated assemblages and cross-cutting chalcopyrite–pyrrhotite textures, records progressive changes in fluid chemistry and conditions of sulphide stability. Variable magnetite trace-element compositions and brecciation further indicate repeated modification during continued fluid circulation. Structural relationships demonstrate that deformation enhanced permeability along the Mary Kathleen structural architecture, promoting fluid focusing, sulphide redistribution, and local concentration within retrograde alteration zones. We interpret Elaine Dorothy as a deformation-enhanced Paleoproterozoic calcic skarn that evolved toward a skarn–IOCG transitional system, rather than as a classic IOCG end member. The deposit demonstrates how deformation, fluid–rock interaction, and evolving redox–sulphur-fugacity conditions progressively modify an early calcic skarn framework, enhancing permeability and fluid focusing, and generating IOCG-affinity characteristics through continued hydrothermal reworking rather than a discrete IOCG-forming event. This provides a process-based framework for recognising structurally reworked skarn systems in Proterozoic mineral provinces.

Keywords Skarn–IOCG transition · Paleoproterozoic Fe–Cu skarns · Magmatic–hydrothermal contribution · Elaine Dorothy · Mount Isa Inlier

Editorial handling: D. Banks

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Introduction

Paleoproterozoic skarn deposits (2.5–1.6 Ga) are widely associated with early basin development, continental arc to extensional magmatism, large-scale metasomatism during orogenic evolution and extensive carbonate-bearing successions (Einaudi et al. 1981; Liu et al. 2023; Meinert et al., 2005). In contrast to many Phanerozoic skarns that host high-grade Fe, W, Sn, Cu, Pb, Zn, Mo, Ag, Au, U, REE, F, and B mineralisation (Chang et al. 2008; Haldar 2018; Xie et al. 2021), Paleoproterozoic examples are typically enriched in Fe, Zn–Pb–Ag, Cu–Au and Au (Jansson et al. 2022; Liu et al. 2023; Wang and Williams 2001). These differences in metal associations may reflect variations in magma composition, host-rock chemistry, fluid composition and redox state, as well as the tectonic and geodynamic environments in which the skarns formed. Einaudi et al. (1981) argued instead that the age distribution of skarn types reflects differences in erosion level rather than a change in ore-forming processes through time. Where such systems are subsequently deformed and hydrothermally reworked, the resulting assemblages can resemble those of iron oxide–copper–gold (IOCG) deposits, and the distinction between the two becomes difficult to draw.

Classical skarn models involve high-temperature metasomatic fluid–rock interaction adjacent to intrusions, progressing from contact metamorphism through prograde skarn formation to retrograde alteration (Einaudi et al. 1981; Meinert et al., 2005; Meinert 1992). However, many Paleoproterozoic skarns do not conform to this relatively simple intrusion-centred model. Instead, they record complex interactions between magmatism, regional deformation, basin architecture and hydrothermal fluid flow, with mineralisation commonly focused along major structures and extending beyond the immediate contact aureole of the causative intrusion while subsequent deformation and metamorphic overprinting can remobilise and texturally modify early-formed skarn assemblages (Dieng et al. 2015; Hellingwerf 1984). Apart from the Tongon skarn hosted in greenschist-facies volcanoclastic rocks with no primary carbonates, most Paleoproterozoic skarns are carbonate-hosted and structurally controlled and localised along regional shear zones (Lawrence et al. 2017; Meinert et al., 2005). These systems may exhibit mineralogical zoning involving garnet, pyroxene, wollastonite, and vesuvianite, together with locally massive sulphide and oxide assemblages near marble fronts (Chang et al. 2008). Structurally controlled skarn mineralisation is also documented in the Archean and Paleoproterozoic terranes where calcic pyroxene–garnet alteration is associated with deeper structural levels and shear-zone-hosted mineralisation (e.g., Mueller et al. 2004; Phillips and Groves 1983). The resulting mineralogical zoning, metal

associations, and structural controls may therefore record both the conditions of initial skarn formation and subsequent deformation-enhanced fluid–rock interaction.

IOCG deposits comprise a diverse group of structurally-controlled magmatic-hydrothermal deposits characterised by Fe-oxide-rich alteration and economic Cu±Au mineralisation, commonly accompanied by variable enrichments in LREE, U, Ag, Mo, Ni, Co, Ba, F, and P and extensive hydrothermal Na–Ca–K alteration (Barton 2013; Groves et al. 2010; Hitzman et al. 1992; Hitzman and Valenta 2005; Williams et al., 2005). Although IOCG and calcic skarn deposits are conventionally classified as distinct deposit types, their alteration and mineralisation characteristics can overlap where Fe-rich hydrothermal fluids interact with carbonate-bearing rocks. In such settings, calc-silicate assemblages may develop through metasomatic interaction with carbonate host rocks, while contemporaneous or later Fe–Cu±Au mineralisation, magnetite-rich alteration and structurally focused fluid flow may produce IOCG-like characteristics. In Proterozoic systems, these relationships may reflect spatial association, temporal overprinting, or progressive hydrothermal modification of earlier carbonate-related assemblages (e.g., Masurel et al. 2017). Consequently, skarn and IOCG systems may represent overlapping components of complex, multistage hydrothermal systems rather than mutually exclusive genetic categories.

Distinguishing inherited skarn assemblages from later hydrothermal modification is therefore critical for reconstructing mineralisation conditions and determining whether Fe–Cu–Co±Au enrichment represents a primary skarn event or subsequent deformation-enhanced hydrothermal redistribution. Trace-element geochemistry can address this problem because Co, Ni, As, Se, Bi, and Pb in pyrite, pyrrhotite, chalcopyrite, and magnetite can record changes in fluid composition and physicochemical conditions during mineralisation (cf. Li et al. 2018; Reich et al. 2016; Tang et al. 2025; Van Ryt et al. 2020; Zhang et al. 2022). Laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) trace element analyses can therefore provide constraints on fluid formation temperature, redox conditions, metal transport, and sulphidation state (Dora et al. 2020; Tang et al. 2025; Xie et al. 2020), particularly where deformation and recrystallisation have obscured primary mineralogical relationships.

The Elaine Dorothy deposit, located ~60 km east-southeast of Mount Isa within the Mary Kathleen Domain of the Mount Isa Inlier (Fig. 1a–b), provides an opportunity to investigate these relationships. The deposit represents a Paleoproterozoic Cu–Co–Au–REE system spatially associated with regional shear zones (Hatcher 2012). Elaine Dorothy is characterised by calc-silicate skarn assemblages, Fe–Cu–Co±Au mineralisation, magnetite development,

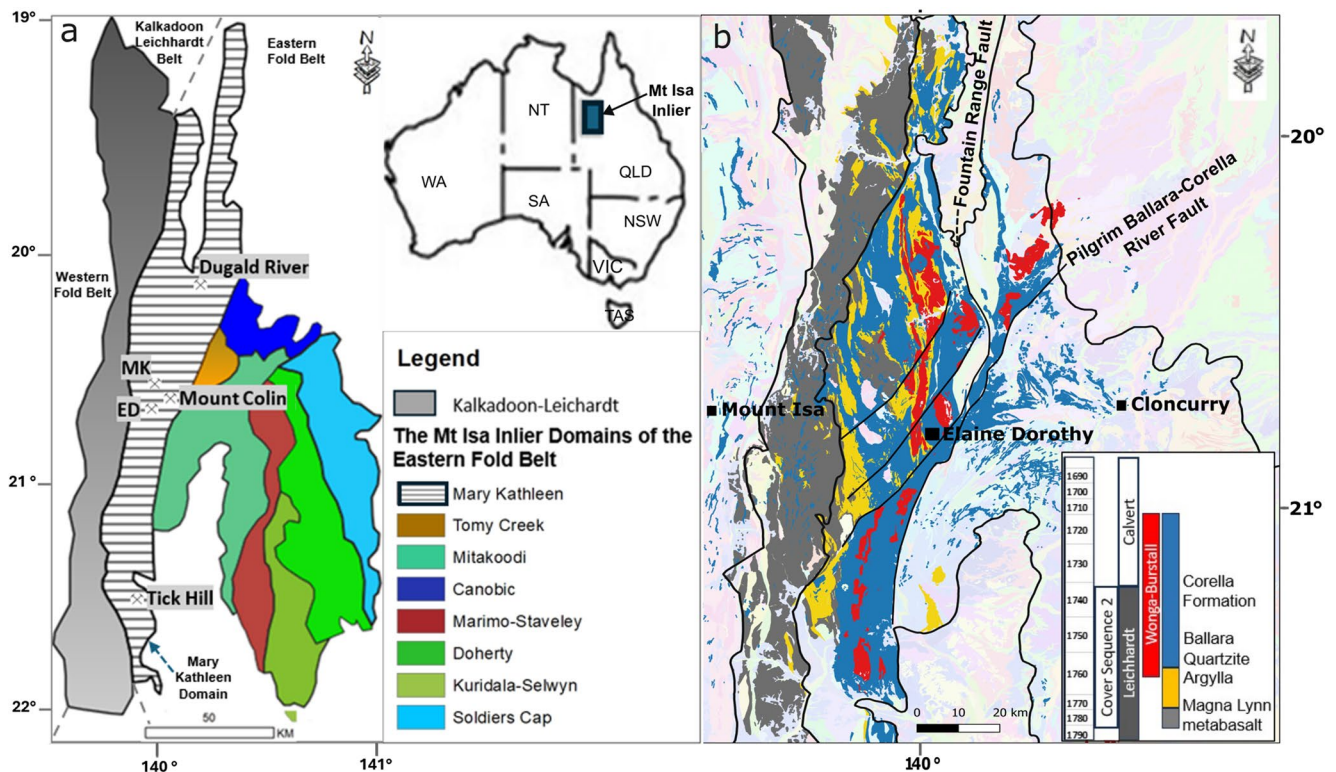


Fig. 1 (a) Structural subdivision of the Mount Isa Inlier and domains of the Eastern Fold Belt, modified after Creus et al. (2023) and Case et al. (2018); inset shows the location of Elaine Dorothy (ED) and the

Mary Kathleen mine (MK) in Australia. (b) Simplified regional geology map of the Mary Kathleen Domain modified after the Department of Resources Queensland (2022)

and strong structural control. Magnetite locally replaces garnet within albite-altered domains, recording episodic Fe metasomatism during deformation and fluid infiltration (e.g., Su et al. 2021). However, Fe metasomatism is volumetrically subordinate to sulphide mineralisation, with pyrrhotite-dominated assemblages representing the dominant Fe-bearing phase (Cave et al. 2024). These characteristics raise the question of whether Elaine Dorothy represents a conventional calcic skarn modified by later deformation and hydrothermal fluids, or a transitional system in which skarn formation evolved into IOCG-style mineralisation. Here we integrate regional geology, deposit-scale geological mapping, ore petrography, structural observations, and LA-ICP-MS trace element data from pyrite, pyrrhotite, chalcopyrite, and magnetite, to constrain mineral paragenesis, fluid evolution, and redox-sulphur fugacity controls at Elaine Dorothy.

Regional geological background

The Mount Isa Inlier comprises three N-S trending tectonostratigraphic belts: the Western Fold Belt, Kalkadoon-Leichhardt Fold Belt, and Eastern Fold Belt (Fig. 1a; Foster and Austin 2008; Page and Sun 1998). The Kalkadoon-Leichhardt Fold Belt comprise the oldest rocks in the inlier

and records deformation and metamorphism associated with the Ca. 1890–1850 Ma Barramundi Orogeny (Page and Williams 1988; Spence et al. 2022). Following the Barramundi Orogeny, three periods of superbasin formation including the Ca. 1790–1740 Ma Leichhardt Superbasin, 1730–1640 Ma Calvert Superbasin, and 1640–1580 Ma Isa Superbasin were identified in most exposed rocks in the Inlier (Gibson et al. 2016). The Eastern Fold Belt is further subdivided into multiple structural-metamorphic domains, including the Mary Kathleen, Tomy Creek, Mitakoodi, Canobie, Marimo-Staveley, Doherty-Fig Tree Gully, Kuridala-Selwyn, and Soldiers Cap domains (Fig. 1a), based on differences in basin evolution, structural grain, metamorphic grade, and geochronological architecture (Creus et al. 2023; Withnall et al. 2013).

The Mary Kathleen Domain (MKD) forms part of the structurally complex northern continuation of the Cloncurry IOCG province and is bounded to the west by the Kalkadoon-Leichhardt Fold Belt and to the east by the Pilgrim-Ballara-Corella River Fault system (Fig. 1b). MKD records a prolonged history of Paleoproterozoic basin development, magmatism, deformation, metamorphism, and hydrothermal activity, including extensive Na–Ca and Fe–Mg metasomatism, and is a host to structurally controlled Cu–Au mineralisation. Major mineral systems in MKD include the

carbonate – hosted Elaine Dorothy Cu–Au system, the Mary Kathleen U–REE deposit, the Mount Colin Cu–Au skarn, the SEDEX-style Dugald River Zn–Pb–Ag, and the Tick Hill Au system (Case et al. 2018; Cave et al. 2024; Creus et al. 2023; Le et al. 2021; Oliver et al. 1999).

The geology of MKD comprises sedimentary and volcanic successions of the Leichhardt Superbasin, with the basal Magna Lynn Metabasalt overlain by felsic volcanic rocks of the Argylla Formation (1782 ± 3 Ma; Neumann et al. 2009). These units are succeeded by the Ballara Quartzite (1767 ± 4 Ma; Neumann et al. 2009), and unconformably overlain by the Corella Formation deposited between 1770 ± 3 Ma and 1710 Ma (Foster and Austin 2008; Gibson et al. 2016; Neumann et al. 2009). The Corella Formation hosts the Elaine Dorothy deposit and is the most extensive stratigraphic unit within the MKD, comprising predominantly NNW- to NW-trending, contact and regionally metamorphosed evaporitic calc-silicate rocks, calcareous siltstone, limestone, quartzite, metapelite, and minor basaltic protoliths (Morrissey and Tomkins 2020; Oliver et al. 1991; Spence et al. 2022). The Mount Albert Group of the Calvert Superbasin unconformably overlies it.

The magmatic history of the Mount Isa Inlier is divided into six igneous events between ca. 1880 Ma and ca. 1490 Ma: the Kalkadoon (ca. 1880–1850 Ma), Argylla (ca. 1820–1770 Ma), Wonga-Burstall (ca. 1750–1690 Ma), Sybella (ca. 1680–1650 Ma), Tommy Creek (ca. 1640–1610 Ma), and Williams (ca. 1550–1490 Ma) Igneous Events (Noptalung et al. 2026). Intrusions within the MKD belong mostly to the Kalkadoon, Argylla and Wonga-Burstall events, with the Williams Igneous Event cropping out only in the northern MKD (Cocker et al. 2025). The Wonga-Burstall Igneous Event includes the intrusions closest in age to skarn formation at Elaine Dorothy: the Burstall Granite, dated at 1743 ± 2 Ma and 1739 ± 5 Ma (Spence et al. 2021) and 1752 ± 7 Ma (Cocker et al. 2025), and the Lunch Creek Gabbro dated at 1745 ± 7 Ma and 1742 ± 7 Ma (Cocker et al. 2025). The Wonga Suite plutons are mylonitic and lie within the high-strain Wonga Belt north of the Fountain Range Fault, whereas Burstall Suite plutons occupy low-strain domains and are weakly deformed to undeformed (Spence et al. 2021).

The Wonga Orogeny is characterised by at least two recognised deformation phases with evidence for later shortening (Spence et al. 2021, 2022). D_1 the earliest is characterised by upright E–W- to WNW-trending planar and linear fabrics preserved as centimetre- to metre-scale tight to isoclinal folds within the Corella Formation, accompanied by amphibolite-facies peak metamorphism and extensive saline hydrothermal fluid flow that produced scapolitisation of mafic rocks and regional skarn development (Morrissey and Tomkins 2020; Neumann et al. 2009; Spence et al. 2021,

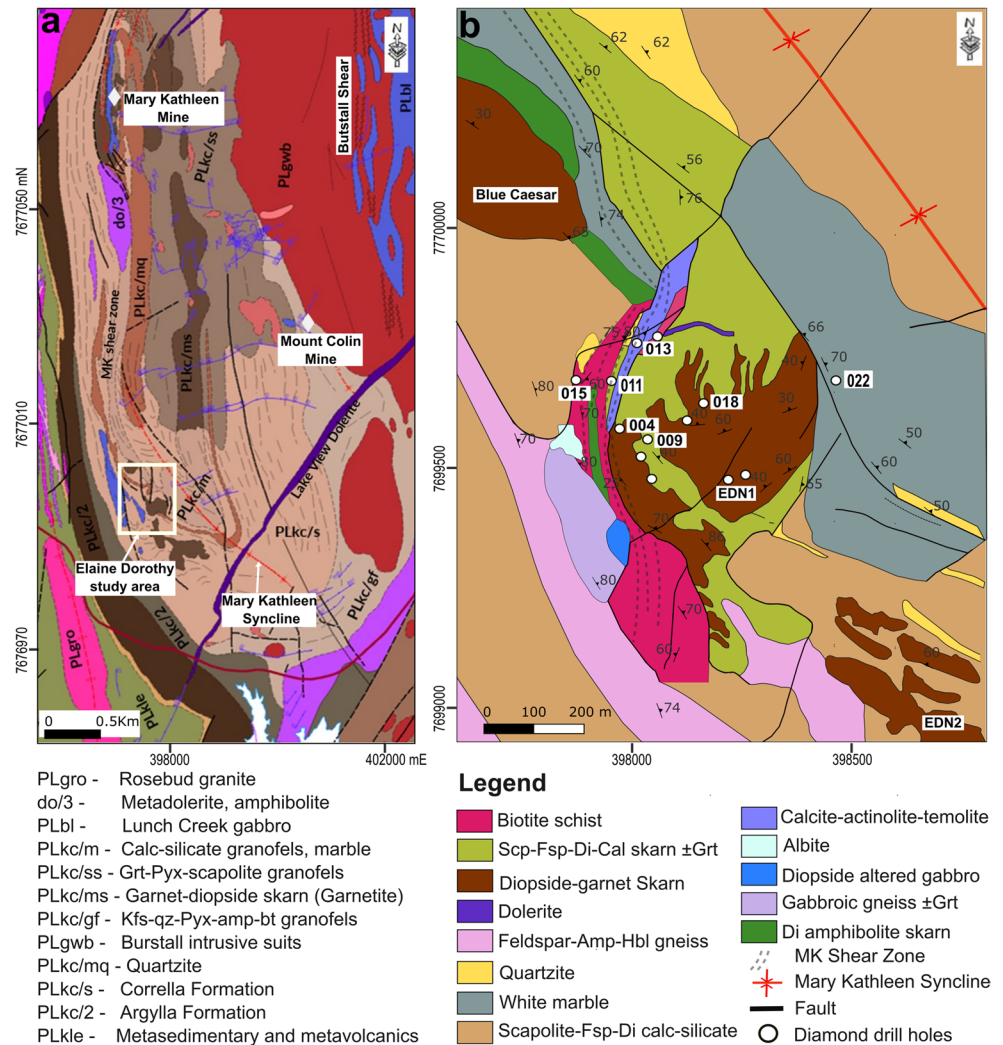
2022). At the Tick Hill Au deposit (Fig. 1a), amphibolite-facies metamorphism (~ 550 – 650 °C) was followed by retrograde fluid-assisted reworking, with fluid inclusion, stable isotope, and petrographic studies indicating closely coupled, structurally controlled metamorphic–hydrothermal processes (Le et al. 2021, 2022, 2024). Garnet–diopside alteration developed during D_1 enhanced rheological contrasts within the stratigraphy, promoting strain localisation during subsequent deformation (Abu Sharib and Sanislav 2013; Morrissey and Tomkins 2020). D_2 overprinted D_1 structures and is expressed by N–S-trending upright isoclinal folds with a steeply west-dipping axial planar foliation. The Mary Kathleen Syncline, a tight doubly plunging structure (Oliver et al. 1991), is interpreted to have formed during D_2 and was subsequently modified during D_3 (Spence et al. 2021). D_3 is associated with later shortening and partial refolding of earlier structures along NW–SE-trending axial traces (Spence et al. 2021). These successive deformation phases produced a complex structural architecture within the Corella Formation and established multiple potential pathways for subsequent fluid circulation. Post- D_2 / D_3 deformation includes N–S trending brittle-ductile shear zones associated with the Isan Orogeny (~ 1600 – 1500 Ma; Abu Sharib and Sanislav 2013; Oliver et al. 1991). These structures overprint earlier fabrics that further localised hydrothermal fluid circulation (Page and Sun 1998; Spence et al. 2022). Such multi-stage structural reactivation produced vertically extensive, anastomosing shear systems that acted as long-lived conduits for fluid flow and mineralisation (Creus et al. 2023, 2024).

The Elaine Dorothy deposit lies on the western limb of the Mary Kathleen Syncline, immediately adjacent to the N–S trending Mary Kathleen Shear Zone (Fig. 2a). The deposit is hosted within NNW- to NW-trending Corella Formation lithologies where progressive deformation and hydrothermal fluid flow produced skarn alteration, Na–Ca and Fe–Mg metasomatism, and sulphide-dominant mineralisation (Oliver et al. 1985, 1999; Sha et al. 2013; Spandler et al. 2016; Spence et al. 2022). The regional association of carbonate-rich host rocks, Paleoproterozoic magmatism, multiple deformation events, and structural reactivation provides a geological framework for investigating the structural and hydrothermal evolution of the Elaine Dorothy deposit.

Previous work

Compared with other deposits in MKD, Elaine Dorothy has received relatively limited academic attention. Apart from studies by Spandler et al. (2016), Sha et al. (2013), and Page (1983), most published research in MKD has focused on the Mary Kathleen U–REE deposit, situated within the

Fig. 2 (a) Simplified geological map of the Mary Kathleen Syncline and the Mary Kathleen (MK) Shear Zone. Geological unit labels are as per Queensland Geological Survey maps. (b) Geology map of the Elaine Dorothy deposit showing drill-hole locations. Hole numbers are as provided by the core facility with prefixes MKED004, MKED009, MKED013, MKED018 and MKED022. Mineral abbreviations are adopted from Whitney and Evans (2010): Scp – scapolite; Fsp – feldspar; Di – diopside; Cal – calcite; Grt – garnet; Kfs – K-feldspar; Qz – quartz; Pyx – pyroxene; Amp – amphibole; Bt – biotite



Mary Kathleen Shear Zone, 5 km north of Elaine Dorothy (i.e., Neumann et al. 2009; Oliver et al. 1985, 1991, 1999), and the Mount Colin deposit on the Eastern Limb of the Mary Kathleen Syncline (Fig. 2a; Cave et al. 2024). Publicly available information on Elaine Dorothy is largely restricted to company exploration reports produced between 2010 and 2021, together with historical diamond-drill core from the 1980s and selected holes drilled between 2010 and 2012 held at the Queensland Geological Survey facilities and Hammer Metals' facilities in Mount Isa. The most comprehensive pre-existing geological evaluation of the deposit was undertaken by Hatcher (2012), for Chinalco Yunnan Copper Resources Limited, the then deposit tenement holders.

Historical exploration established Elaine Dorothy as a Cu–Co–Au–REE system centred on broad and coherent zones of Cu, Co, Mo, and Ce mineralisation (Hatcher 2012). Geological mapping, scintillometer surveys, and drilling adjacent to the Mary Kathleen Shear Zone, west of the Mary Kathleen Syncline, close to the southern hinge (the Elaine

Dorothy study area; Fig. 2a), identified several large skarn bodies (Blue Caesar, Elaine Dorothy - annotated EDN1 and EDN2; Fig. 2b), and three areas of radiometric anomalism, which coincide with airborne uranium anomalies and with narrow east-west trending lenses of surface mineralisation within scapolite-diopside±garnet units (Fig. 2b). An exploration target of 26.1 Mt grading 0.56% Cu and 0.09 g/t Au has been reported, with drilling intersecting up to 1.98 g/t Au, 0.57% Cu and 482 ppm Co over intervals between 70 and 491 m (Hatcher 2012). Elevated Cu–Au–Co grades in MKD are spatially associated with the Mary Kathleen Shear Zone (Oliver et al. 1985, 1999; Sha et al. 2013; Spandler et al. 2016; Spence et al. 2022). The principal Cu–Au–Co mineralisation is associated with late-stage shearing and pervasive sodic metasomatism, which replaced calc-silicate units adjacent to biotite-rich shear zones with massive albite (Cave et al. 2024; Oliver et al. 1999).

Despite this exploration history, the geological and genetic evolution of Elaine Dorothy remains poorly constrained. In particular, the relationships between deformation, skarn

formation, metasomatism, fluid flow, and sulphide mineralisation have not been systematically evaluated, and the temporal evolution of the hydrothermal system and mineralisation remain unresolved. These knowledge gaps provide the basis for the integrated geological mapping, structural, mineralogical, and geochemical investigation presented in this study.

Methods

Rock sampling and preparation

Detailed geological mapping, diamond drill core logging, rock sampling, and alteration observations were undertaken at the Elaine Dorothy deposit to characterise lithological variability, structural architecture, alteration assemblages, and sulphide paragenesis. Core availability was incomplete, with only selected intervals available for drill holes MKED009, MKED013, MKED015, MKED018, and MKED022 (Fig. 2b) archived at the Queensland Geological Survey core facility, Mount Isa. Since continuous core coverage from surface to total drilled depth was not available, geological observations and sample selection were based on the available core intervals and representative mineralised samples were selected from MKED009, MKED018, and MKED022 to capture spatial and textural variability in sulphide mineralisation and alteration and supplemented by samples from surface exposures and material from company reports including samples from MKED004 and MKED011. Samples were prepared as polished epoxy resin blocks and polished thin and thick sections for petrographic and geochemical analysis. Selected samples, drill hole depth, prepared epoxy blocks and respective ICPMS spots are provided in Supplementary Material S1.

Mineralogical and textural characterisation

Representative samples were examined using transmitted- and reflected-light microscopy with a Zeiss Primo-tech microscope and scanning electron microscope (SEM) using Hitachi SU5000 at the Advanced Analytical Centre, James Cook University (AAS, JCU). Backscattered-electron (BSE) and secondary-electron (SE) imaging was used to characterise mineral textures, grain boundaries, replacement relationships, and microstructural features.

LA-ICP-MS trace-element analysis

Trace-element composition of pyrite, chalcopyrite, pyrrhotite, and magnetite were determined by spot analysis using an Analyte G2 Excimer Laser Ablation System coupled to

a Thermo iCAP-TQ ICP-MS at AAS, JCU. Analyses were conducted using a 50 μm spot size, $\sim 2 \text{ kJ/cm}^2$ energy density, and 7 Hz repetition rate. Helium was used as the primary carrier gas and mixed with argon prior to introduction into the ICP-MS. NIST SRM 612 was used as the external calibration standard for sulphides and GSD-1G for magnetite, with STD-GL3 analysed to monitor matrix effects and instrument stability. Internal standardisation used stoichiometric Fe concentrations of 46.55 wt% for pyrite, 62.33 wt% for pyrrhotite, 30.43 wt% for chalcopyrite, and 72.4 wt% for magnetite. A total of 520 spot analyses were obtained from pyrite, chalcopyrite, pyrrhotite, and magnetite. The monitored isotopes included Al, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Zr, Mo, Ag, Cd, In, Sn, Sb, Ba, La, W, Au, Tl, Pb, Bi, and Si. Data reduction was performed using Iolite 4 (Paton et al. 2011). Time-resolved signals were inspected to exclude transient spikes associated with micro-inclusions or mixed-phase ablation, and only stable signal intervals were integrated for final concentration calculations. A summary of measured element concentrations is presented in Tables 1, 2, 3 and 4, and the complete analytical dataset is provided in the Supplementary Material S2.

Results

Deposit geology

The dominant lithologies at the Elaine Dorothy deposit comprise banded scapolite-feldspar-diopside calc-silicates interlayered with folded and weakly foliated white marble, blocky quartzite and amphibolite, all attributed to the Corella Formation (Fig. 2b). The calc-silicates are fine- to medium-grained and characterised by alternating cream-pink scapolite-feldspar bands and green diopside layers and minor garnet (Fig. 3a). Compositional banding is locally disrupted by fracturing and boudinage of competent, silicate-rich layers, accompanied by ductile deformation and flow of adjacent, less competent calcite-rich marble (Fig. 3a). White marble is dolomitic with a saccharoidal texture and local calcite veinlets (Fig. 3b) and is interlayered with white to pink blocky quartzite (Fig. 3c).

West of the deposit are NW-trending mafic gabbroic gneiss and diopside altered gabbroic units (Fig. 2b). The gneiss is dark grey, fine- to medium-grained, strongly foliated, and composed predominantly of mafic amphibole–hornblende–diopside–biotite layers alternating with the felsic quartz–feldspar–microcline–wollastonite layers with minor diopside and garnet (Fig. 3d–e). The diopside-altered gabbro is dark green, weakly foliated, and comprises subhedral to euhedral amphibole and diopside with quartz, wollastonite, microcline, and plagioclase; locally, these

Table 1 Pyrite (Py) trace element concentrations in ppm at Elaine Dorothy

Ore type	Mineral	Statistics (ppm)	Co	Ni	Cu	Ge	As	Se	Ag	Pb	Bi
Vein infill in scapolite-feldspar-diopside skarn (n=18)	Py-1	Mean	10,655	36.7	1.07	5.73	72.4	41.2	0.04	0.84	5.39
	Py-1	SD	1497	6.80	1.19	0.45	22.1	7.49	0.10	1.43	12.7
Vein infill in diopside amphibolite skarn (n=10)	Py-1	Mean	12,910	44.1	18.3	5.82	3046	22.2	2.41	4.44	6.71
	Py-1	SD	2589	16.8	21.5	0.32	2059	8.87	3.31	4.30	4.97
Vein infill in diopside-calcite amphibolite skarn (n=14)	Py-1	Mean	11,371	38.1	1.58	3.48	3064	14.4	0.09	3.35	1.11
	Py-1	SD	3763	9.68	1.76	0.25	3380	7.55	0.16	7.66	1.74
Disseminated sulphides (n=12)	Py-1	Mean	6061	18.7	5.55	5.75	814	3.47	0.33	0.86	0.42
	Py-1	SD	3179	15.7	7.33	0.51	505	1.35	0.87	1.87	0.54
Shear zone hosted sulphides (n=6)	Py-1	Mean	1816	93.0	0.54	5.97	261	10.3	0.29	1.00	0.51
	Py-1	SD	521	14.4	0.22	0.55	22.8	2.42	0.17	1.37	0.64
Disseminated sulphides (n=37)	Py-2	Mean	499	185	3.26	5.66	1803	7.74	0.12	0.39	1.04
	Py-2	SD	326	164	4.05	0.38	983	4.67	0.28	0.62	2.02
Massive sulphides (n=15)	Py-2	Mean	633	1303	4.12	5.73	0.57	31.0	0.66	1.29	3.39
	Py-2	SD	177	132	3.86	0.31	0.13	4.17	0.48	1.95	2.81
Shear zone hosted sulphides (n=24)	Py-2	Mean	297	200	1.63	6.09	164	14.7	0.01	1.46	0.70
	Py-2	SD	167	101	1.73	0.45	30.6	5.09	0.02	2.17	0.99

Table 2 Pyrrhotite trace element concentrations in ppm at Elaine Dorothy

Ore type	Mineral	Statistics (ppm)	Co	Ni	Cu	Ge	As	Se	Ag	Pb	Bi
Vein infill in scapolite-feldspar-diopside skarn (n=18)	Po	Mean	684	2374	1.59	7.38	0.58	66.6	0.11	0.33	0.59
	Po	SD	87.7	609	1.15	0.44	0.11	9.59	0.10	0.47	0.73
Vein infill in diopside amphibolite Skarn (n=19)	Po	Mean	608	2746	2.26	7.30	0.85	38.6	0.43	1.18	2.80
	Po	SD	90.2	332	1.87	0.73	0.16	2.99	0.30	1.14	2.87
Vein infill in diopside-calcite amphibolite skarn (n=36)	Po	Mean	15.5	2769	1.65	3.80	bdl	37.9	0.08	1.14	0.94
	Po	SD	7.32	586	0.77	0.74	bdl	21.4	0.07	1.91	1.35
Massive sulphides (n=14)	Po	Mean	1045	2283	3.43	7.35	0.79	39.7	0.67	0.47	2.43
	Po	SD	115	374	6.51	0.44	0.17	3.21	0.63	0.55	2.96

bdl below the limit of detection, Po pyrrhotite

Table 3 Chalcopyrite trace element concentrations in ppm at Elaine Dorothy

Ore type	Mineral	Statistics (ppm)	Co	Ni	Zn	Ge	As	Se	Ag	Au	Pb	Bi
Vein infill in scapolite-feldspar-diopside skarn (n=18)	Ccp	Mean	1.50	19.3	431	3.47	0.47	71.9	7.50	0.14	1.08	1.18
	Ccp	SD	0.82	6.06	24.2	0.26	0.13	5.05	0.42	0.11	0.68	0.75
Vein infill in diopside amphibolite skarn (n=15)	Ccp	Mean	2.96	24.0	438	3.62	2.69	46.9	6.92	0.06	4.73	6.37
	Ccp	SD	2.03	8.73	117	0.48	2.78	3.79	1.32	0.02	3.88	4.37
Vein infill in diopside-calcite amphibolite skarn (n=10)	Ccp	Mean	1.09	31.1	506	1.87	bdl	bdl	1.05	0.10	9.82	7.80
	Ccp	SD	1.50	3.23	135	0.28	bdl	bdl	0.57	0.06	4.16	7.99
Disseminated sulphides (n=14)	Ccp	Mean	1.09	bdl	243	3.17	57.5	20.8	3.93	0.10	2.14	5.79
	Ccp	SD	0.78	bdl	245	0.61	103	5.90	2.97	0.11	2.41	4.66
Massive sulphides (n=18)	Ccp	Mean	4.91	28.4	122	3.49	0.40	39.5	5.32	0.20	1.92	6.80
	Ccp	SD	2.40	3.86	8.64	0.31	0.10	3.82	2.05	0.13	1.74	5.61

bdl below the limit of detection, Ccp chalcopyrite

assemblages are overprinted by albite, calcite, and tremolite (Fig. 3f).

At least three skarn bodies, approximately 200–500 m wide, occur on the western limb of the Mary Kathleen Syncline along contacts between calc-silicate and marble units (Blue Ceaser, EDN1, and EDN2; Fig. 2b). EDN1 is exposed as a topographic high in the central study area and comprises banded, calc-silicate blocks characterised by green diopside

bands and brown, patchy garnet-rich domains within pink brown granoblastic scapolite–feldspar alteration (Fig. 3g–h). Scapolite crosscuts and surrounds diopside, locally overprinting and obscuring the original compositional banding, while garnet occurs as irregular, patchy domains, and are overprinted calcite. Marble layers adjacent to EDN1 is locally extensively replaced by diopside with minor garnet (Fig. 3i).

Table 4 Magnetite trace element concentrations (ppm) at Elaine Dorothy

Ore type	Mineral	Statistics (ppm)	Mg	Al	Ca	Ti	V	Cr	Mn	Co	Ni	Zn	As	Ag	Bi
Vein infill in scp-fsp-di skarn. (n-15)	Mgt	Mean	264	804	10,772	38.7	10.3	bdl	58.8	191	322	13.6	21.7	0.41	49.6
	Mgt	Std	351	1036	11,179	26.5	7.92	bdl	20.1	316	750	24.9	30.3	0.52	70.9
Vein infill in di-amp skarn. (n-20)	Mgt	Mean	4786	1228	16,644	140	38.5	15.2	53.3	46.3	208	71.8	16.3	1.69	86.1
	Mgt	Std	9953	2155	22,857	49.3	56.1	18.8	23.6	104	580	145	19.8	3.27	227
Disseminated sulphides. (n-20)	Mgt	Mean	31.7	132	bdl	125	422	778	169	0.56	43.8	3.27	bdl	0.02	0.09
	Mgt	Std	40.8	43.6	bdl	77.1	129	1396	65.9	0.24	16.3	1.82	bdl	0.01	0.07

bdl below the limit of detection, *Mgt* magnetite, *scp* scapolite, *fsp* feldspar, *di* diopside, *amp* amphibolite

A strand of the Mary Kathleen Shear Zone occurs immediately west of EDN1 and comprises strongly foliated and sheared biotite schist with crenulation and kink-band deformation and intercalated calc-silicate lithons (Fig. 3j). The schist is fine- to coarse-grained and interlayered with diopside-garnet skarn in the southeast (Fig. 2b), and with albite-altered calc-silicate and gabbroic units to the west (Fig. 3j). Biotite exhibits kink-band deformation and overprints earlier skarn minerals, and is subsequently overprinted by late sulphides, albite, and chlorite along flake boundaries and cleavage planes (Fig. 3k-l). Later retrograde alteration assemblages at Elaine Dorothy include actinolite, tremolite, calcite, epidote, chlorite, fluorite with supergene malachite and hematite.

Ore textures and sulphide mineralogy

Mineralisation at Elaine Dorothy is preferentially developed along contacts between carbonate-rich units to the east and calc-silicate rocks to the west (Fig. 2b). The mineralised system includes diopside-garnet skarn, banded scapolite-feldspar-diopside skarn, diopside-amphibole-carbonate±garnet skarn, and diopside-amphibole skarn, with variable magnetite. These lithofacies occur along a ~2.5-km-long NNW–NNE-trending corridor, within which sulphide abundance and texture vary systematically with host-rock composition and structural position.

Near-surface exposures along the biotite-rich shear zone contain massive supergene gossan and malachite with moderate pyrite and chalcopyrite. At ~27 m depth, sulphides occur as disseminated and stringer pyrrhotite, pyrite, and patchy chalcopyrite within garnet-diopside calc-silicate rocks. At greater depth, these assemblages locally transition into massive garnetite from ~70 m downward, where disseminated and vein-hosted sulphides increase to semi-massive and massive sulphide assemblages (Fig. 4). Four principal textural styles of sulphide mineralisation are recognised: (1) sulphide vein infill, (2) disseminated sulphides, stringers and vein networks, (3) semi-massive to massive sulphide ore, and (4) shear-zone-hosted sulphides.

Sulphide vein infills

Iron–Cu sulphide vein infills occur within fine-grained scapolite-feldspar-diopside calc-silicate, diopside-amphibolite-carbonate±garnet, and moderately brecciated diopside-amphibolite±garnet skarns (Fig. 4a-d). Veins comprise medium-grained diopside, pyrrhotite, pyrite, chalcopyrite, and calcite, and minor garnet, amphibole, magnetite, and allanite (Fig. 5a-c). Two texturally distinct generations of pyrite are recognised. Py1 occurs as coarse, subhedral to euhedral, moderately fractured and locally

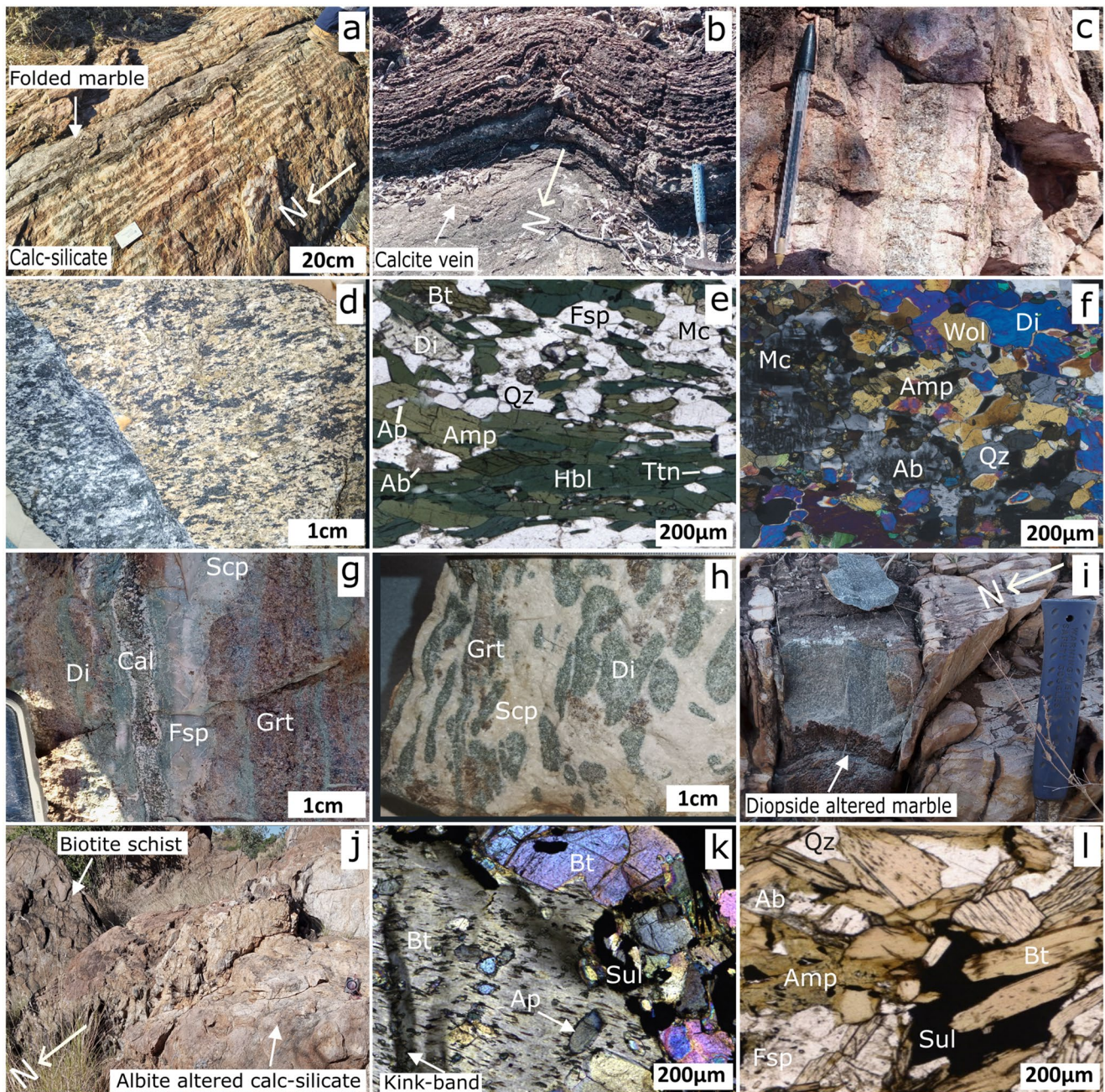


Fig. 3 Photographs and photomicrographs showing the main lithological units at the Elaine Dorothy deposit. **(a)** Foliated, banded scapolite-feldspar-diopside calc-silicate. **(b)** Foliated and folded white marble. **(c)** Banded blocky quartzite. **(d)** Gabbroic gneiss showing foliated feldspar, amphibole, hornblende, and minor quartz, diopside, titanite, apatite, albite, and biotite under **(e)** plane-polarised light (PPL). **(f)** XPL image of diopside-altered gabbro comprising diopside-wollastonite-amphibole-quartz-microcline, overprinted by albite. **(g)** Scapolite-feldspar-diopside-garnet calc-silicate showing skarn minerals and hydrothermal calcite overprinting foliation. **(h)** Brecciated scapolite-diopside-garnet skarn showing scapolite crosscutting and

surrounding diopside, locally obscuring the original compositional banding. **(i)** Diopside-altered marble layer within scapolite-feldspar-diopside-calcite skarn. **(j)** Contact between biotite schist and albite-altered calc-silicate, photographed facing south from the southeast of EDN1. **(k-l)** XPL images showing kink-band deformation in biotite and overprinting amphiboles and sulphides in biotite schist. Abbreviations: Ab – albite; Ttn – titanite; Ap – apatite; Fsp – feldspar; Amp – amphibole; Hbl – hornblende; Qz – quartz; Mc – microcline; Di – diopside; Wol – wollastonite; Bt – biotite; Cal – calcite; Grt – garnet; Sul – sulphides

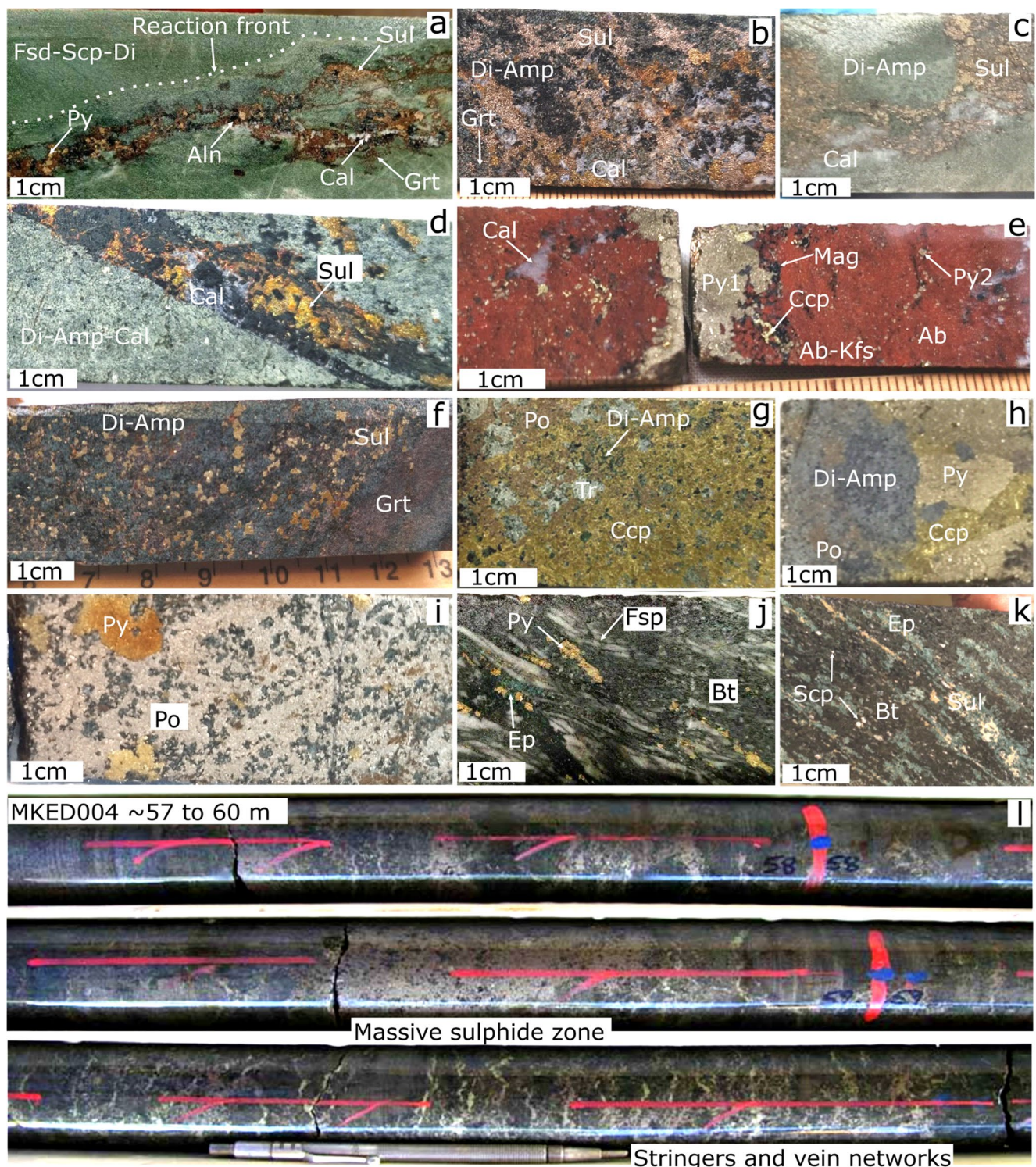


Fig. 4 Photographs of ore textures observed at the Elaine Dorothy deposit. (a) Allanite–calcite–garnet–sulphide vein infill hosted in fine-grained scapolite–feldspar–diopside calc-silicate, forming a sharp reaction front marking the extent of fluid infiltration into the calc-silicate. (b–c) Sulphide–calcite±garnet vein infill in medium-grained diopside–amphibolite skarn. (d) Sulphide–calcite vein infill in moderately brecciated diopside–amphibole–carbonate skarn. (e) Disseminated sulphide–calcite–magnetite and stringer ore hosted in ferruginous K-feldspar–albite–altered rock. (f) Disseminated and stringer sulphides in medium-grained diopside–amphibole–garnet

skarn. (g–i) Massive sulphide ores hosted in diopside–amphibole skarn, overprinted by tremolite. (j–k) Sheared quartz–feldspar–diopside–biotite schists containing sulphides and actinolite–tremolite–epidote alteration. (l) Drill cores from MKED004 showing a progression from stringer and vein networks through semi-massive to massive sulphides in diopside–amphibole skarn. Abbreviations: Scp – scapolite; Fsp – feldspar; Di – diopside; Sul – sulphides; Aln – allanite; Cal – calcite; Grt – garnet; Py – pyrite; Amp – amphibole; Mag – magnetite; Ccp – chalcopyrite; Kfs – K-feldspar; Ab – albite; Po – pyrrhotite; Tr – tremolite; Bt – biotite; Ep – epidote

deformed, inclusion-rich grain, whereas Py2 forms fine- to medium-grained, euhedral, relatively unfractured and inclusion-poor crystals (Fig. 5a–b). Both generations commonly have straight crystal faces against chalcopyrite and diopside and locally pyrrhotite. Magnetite occurs as angular granular fragments, some with matching margins that seem to indicate disruption of a single grain, separated and enclosed by chalcopyrite and pyrrhotite (Fig. 5a-inset). Diopside grains in contact with pyrite, pyrrhotite, and chalcopyrite commonly display embayed, irregular, and ragged margins, along which chalcopyrite and calcite form interconnected networks, producing a characteristic nibbling texture consistent with local replacement of diopside (Fig. 5a, d). Pyrrhotite and chalcopyrite form lobate boundaries and low-dihedral-angle wetting textures against diopside and other silicates and locally occur together within tensional fractures cutting Py1 (Fig. 5b–c). Allanite in the vein assemblages contains inclusions of pyrrhotite, uraninite, and thorite, and diopside adjacent to porous allanite locally develops amphibole-rich reaction rims (Fig. 5c). A notable feature is the occurrence of chalcopyrite, pyrite, and pyrrhotite inclusions within apparently unfractured diopside, where the inclusions are not aligned along fractures (Fig. 5b, d). Chalcopyrite occurs along diopside grain boundaries and locally fills fractures and cavities (Fig. 5d). Conversely, diopside locally occurs as inclusions within chalcopyrite as well as Py1 (Fig. 5e).

Disseminated sulphides, stringers, and vein networks

Disseminated and stringer sulphides are developed around vein networks across the main lithologies but are most abundant in the magnetite–hematite–K-feldspar–albite-altered calc-silicates and garnet–diopside–amphibolite skarn (Fig. 4f–g). The two pyrite phases are recognised here with Py1 occurring as coarse-grained, micro-fractured, inclusion-rich, intensely deformed and brecciated in the grain boundary contact with albite (Fig. 5f). In contrast, Py2 is finer grained, euhedral to locally rounded, inclusion-poor, and forms straight crystal faces against albite and silicate minerals, and overprint calcite, and biotite (Fig. 5g). Chalcopyrite and pyrrhotite occur in trace to moderate amounts in this assemblage, whereas hematite locally overprints magnetite (Fig. 5f).

Semi-massive bands and massive sulphide ore

Massive sulphide mineralisation is concentrated within moderately brecciated diopside–amphibole (actinolite–tremolite) and carbonate-altered zones where stringer pyrrhotite–chalcopyrite–pyrite assemblages cross-cut diopside–amphibolite–carbonate host rocks and locally

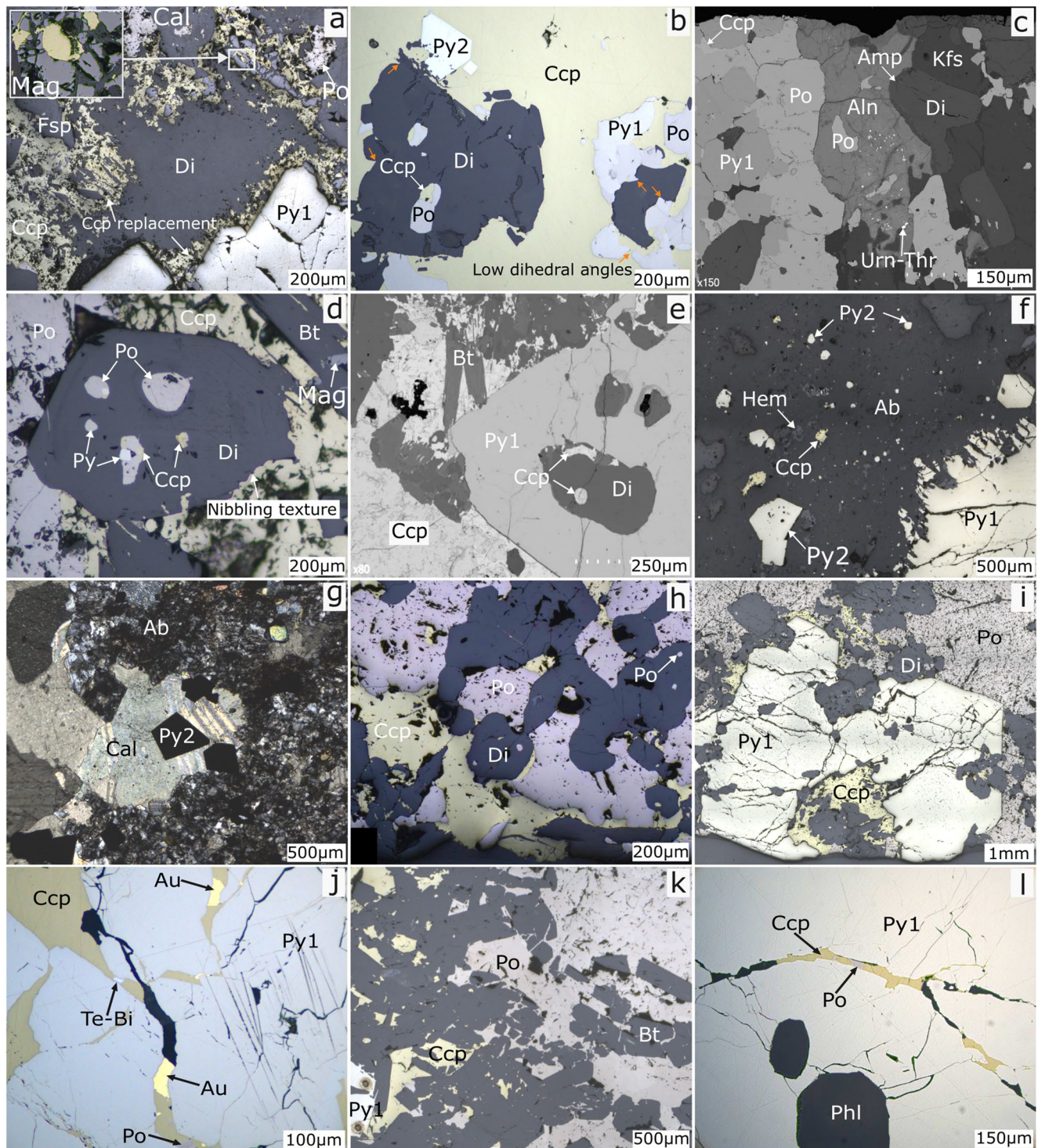
grade into semi-massive bands and homogeneous massive sulphide lenses (Fig. 4g–i, l). Massive sulphide zones predominantly consist of medium- to coarse-grained, intergrown, anhedral to subhedral diopside–pyrrhotite–chalcopyrite±pyrite, locally overprinted by amphibole and calcite (Fig. 4g–i). Diopside and pyrrhotite form intimate intergrowths, with rounded to euhedral pyrrhotite inclusions locally preserved within diopside grains (Fig. 5h). Chalcopyrite occupies grain boundaries and fractures between diopside and pyrrhotite and locally embays and replaces diopside and amphibole along grain boundaries, producing a characteristic nibbling texture (Fig. 5h–i). The few pyrite crystals in this assemblage are very coarse and intensely fractured, with straight euhedral faces developed against pyrrhotite (Fig. 5i). Native gold and Bi–Te phases occur with gangue minerals in chalcopyrite–pyrrhotite veinlets that occupy fractures and magins in Py1 (Fig. 5j).

Shear-zone-hosted sulphides

Within amphibole–biotite–quartz–feldspar–calcite–epidote–chlorite alteration zones developed in sheared and brecciated quartz–feldspar–biotite schists with disseminated scapolite, sulphides occur predominantly as disseminations, with local foliation-parallel veinlets and microfracture infillings (Fig. 4j–k). Pyrrhotite and chalcopyrite occur along cleavage planes and grain boundaries of retrograde biotite, feldspar, quartz, and albite, forming irregular anhedral to subhedral grains and aggregates preferentially distributed along the schistosity of the sheared biotite schist. Locally, sulphides form interconnected stringers and fracture-controlled aggregates, producing a heterogeneous distribution within the deformed host rock (Figs. 4j–k and 5k). Pyrite-1 (Py1) is locally fractured and preserves straight crystal faces against the surrounding biotite, whereas chalcopyrite and pyrrhotite infill fractures within Py1 (Fig. 5k–l). The whole sulphide assemblage is locally overprinted by phlogopite–calcite–epidote–tremolite–actinolite alteration (Figs. 4j–k and 5l).

LA-ICP-MS analysis results

A total of 520 LA-ICP-MS spot analyses were conducted on pyrite, pyrrhotite, chalcopyrite, and magnetite from the principal ore types. The four ore types described above are distinguished and grouped according to their host lithology, sulphide texture and structural setting: vein infills hosted in three calc-silicate lithologies, disseminated and stringer sulphides in ferruginous K-feldspar–albite alteration and diopside–garnet skarn, semi-massive to massive lenses in diopside–amphibole–calcite skarn, and shear zone-hosted



sulphides in quartz-feldspar-biotite schists (Tables 1, 2, 3 and 4). Vein infill ore is reported separately for scapolite-feldspar-diopside skarn (Fig. 4a), brecciated veins in diopside-amphibolite skarn (Fig. 4c), and veins in diopside-calcite-amphibolite skarn (Fig. 4b, d), because these hosts

differ in carbonate content and reactivity. Disseminated ore is reported separately for Py1 and Py2 (Fig. 4e, f), which are texturally distinct (Fig. 5f-g). Semi-massive to massive ore (Fig. 4g-i) and shear zone-hosted ore (Fig. 4j) are each treated as single groups.

Fig. 5 Photomicrographs of sulphide textures from the Elaine Dorothy deposit. Sulphide vein-infill ore: **(a)** Reflected-light (RL) image showing feldspar–diopside–calcite–pyrite–pyrrhotite and brecciated granular magnetite (inset), overprinted by chalcopyrite along grain boundaries and as fracture infills. **(b)** RL image showing diopside containing sulphide inclusions and surrounded by chalcopyrite, with intergrown pyrrhotite and Py1 displaying low dihedral angles against silicates, and euhedral Py2 forming straight faces against chalcopyrite. **(c)** Backscattered electron (BSE) image illustrating an intergrown sulphide–allanite–diopside assemblage, with euhedral porous allanite containing pyrrhotite, thorite, and uraninite inclusions; amphibole occurs at the diopside–allanite contact. **(d–e)** RL images showing sulphides enclosed in diopside and diopside inclusions in sulphides; Py1 forms straight crystal faces against chalcopyrite, and chalcopyrite also occurs along cleavage planes in biotite. **(f–g)** Disseminated sulphide ore comprising microfractured Py1 and euhedral Py2 with straight crystal faces against albite, calcite, and silicate minerals, with minor chalcopyrite and hematite. **(h–j)** Massive sulphide ore showing intergrown chalcopyrite–pyrrhotite–diopside assemblages, with fractured coarse euhedral Py1 containing chalcopyrite–pyrrhotite–Te–Bi–native gold fracture fills. **(k–l)** RL images of shear-zone-hosted sulphide ore showing pyrrhotite and chalcopyrite along the schistosity of sheared biotite schist; pyrrhotite–chalcopyrite fracture fills occur within Py1, and the assemblage is locally overprinted by phlogopite. Abbreviations: Mag – magnetite; Cal – calcite; Di – diopside; Fsp – feldspar; Po – pyrrhotite; Ccp – chalcopyrite; Py – pyrite; Aln – allanite; Amp – amphibole; Urn – uraninite; Thr – thorite; Kfs – K-feldspar; Bt – biotite; Ab – albite; Hem – hematite; Au – native gold; Te–Bi – tellurium–bismuth-rich phase; Phl – phlogopite

Pyrite

Pyrite shows the strongest enrichment in Co and As, with locally significant Ni. Co average concentrations reach 12,910 ppm, As 3,064 ppm, and Ni 1,303 ppm. Py1 consistently contains substantially more Co than Py2, with the highest average Co concentrations recorded in vein-infill assemblages. Py1 from vein infills hosted by scapolite–feldspar–diopside, diopside–amphibolite, and diopside–carbonate–amphibolite skarns contain average Co concentrations of 10,655, 12,910, and 11,371 ppm, respectively (Table 1). In contrast, Py1 from disseminated and shear zone-hosted mineralisation contains lower average Co concentrations of 6,061 and 1,816 ppm, respectively. Ni shows the opposite tendency to Co between the pyrite generations. Py1 generally contains low Ni concentrations, with averages of 36.7–93.0 ppm, whereas Py2 is relatively Ni-rich, reaching an average of 1,303 ppm in massive sulphide samples. Py1 from brecciated vein-infill and diopside–carbonate–amphibolite skarn also contains elevated As, reaching average concentrations of 3,046 and 3,064 ppm, respectively. Se concentrations are generally low, with the highest average value of 41.2 ppm recorded in Py1 from vein-infill mineralisation in scapolite–feldspar–diopside skarn. Cu, Ge, Ag, Pb, and Bi are generally present at concentrations below 10 ppm in both pyrite generations.

Pyrrhotite

Pyrrhotite is characterised by relatively high Co and Ni concentrations, with maximum average values of 1,045 ppm Co and 2,769 ppm Ni (Table 2). Ni is generally more abundant than Co and is particularly enriched in pyrrhotite from vein-infill and massive sulphide assemblages. Average Ni concentrations reach 2,374 ppm in scapolite–feldspar–diopside skarn, 2,746 ppm in diopside–amphibolite skarn, 2,769 ppm in diopside–carbonate–amphibolite skarn, and 2,283 ppm in massive sulphide samples. In contrast, pyrrhotite from diopside–carbonate–amphibolite skarn contains substantially lower Co concentrations, averaging 15.5 ppm. Co concentrations are highest in massive sulphide ore (1,045 ppm) and in vein-infill assemblages hosted by scapolite–feldspar–diopside and diopside–amphibolite skarns (684 and 608 ppm, respectively). Selenium concentrations are relatively consistent, with average values ranging from 37.9 to 66.6 ppm. Other analysed elements, including Cu, Ge, As, Ag, Pb, and Bi, are generally present at concentrations below 10 ppm (Table 2).

Chalcopyrite

Chalcopyrite contains comparatively low concentrations of most trace elements and is characterised primarily by moderate Zn and Se enrichment, and locally elevated As. Maximum average concentrations reach 506 ppm Zn, 71.9 ppm Se, and 57.5 ppm As (Table 3). Zn concentrations are relatively similar among the principal vein-infill assemblages hosted by scapolite–feldspar–diopside, diopside–amphibolite, and diopside–carbonate–amphibolite skarns, averaging 431, 438, and 506 ppm, respectively. Se is highest in chalcopyrite from scapolite–feldspar–diopside skarn with an average of 71.9 ppm, compared with 46.9 ppm in brecciated diopside–amphibolite skarn. Se was below detection in chalcopyrite from diopside–carbonate–amphibolite skarn. Chalcopyrite from massive sulphide mineralisation contains the lowest average Zn concentration (122 ppm), whereas Ni is below detection in chalcopyrite from disseminated sulphides. Co, Ge, Au, Ag, Pb, and Bi are generally present at concentrations < 10 ppm (Table 3).

Magnetite

Magnetite grains generally contain elevated Mg, Al, and Ca, with maximum average concentrations of 4,786 ppm Mg, 1,228 ppm Al, and 1.7 wt% Ca, respectively (Table 4). Magnetite from vein infills in diopside–amphibolite skarn contains the highest average Mg (4,786 ppm), Al (1,228 ppm), and Ti (140 ppm), compared with 264 ppm Mg, 804 ppm Al, and 38.7 ppm Ti in magnetite from

scapolite–feldspar–diopside skarn vein infills and 31.7 ppm Mg, 132 ppm Al, and 125 ppm Ti in magnetite from disseminated sulphide ores.

Magnetite from scapolite–feldspar–diopside vein infills has the highest mean Co (191 ppm) and Ni (322 ppm), with 1.1 wt% Ca and 49.6 ppm Bi. Magnetite from diopside–amphibolite vein infills has the higher mean Ca (1.7 wt%) and Bi (86.1 ppm), but lower Co (46.3 ppm) and Ni (208 ppm). In disseminated sulphide ores, mean Co, Ni, and Bi concentrations are substantially lower (0.56, 43.8, and 0.09 ppm, respectively), whereas V, Cr, and Mn are highest (422, 778, and 169 ppm, respectively); Ca is below detection (Table 4). Zn, As, and Ag concentrations are variable and show no consistent relationship with magnetite textural setting. Magnetite compositions generally vary both between and within samples (Supplementary Material S2). Because the magnetite grains are commonly fine-grained and brecciated and occur in close association with chalcopyrite and pyrrhotite, some analyses may have been affected by ablation of adjacent sulphides. These analyses were therefore treated with caution during interpretation.

Discussion

Sulphide mineralisation and paragenesis within the Elaine Dorothy skarn system

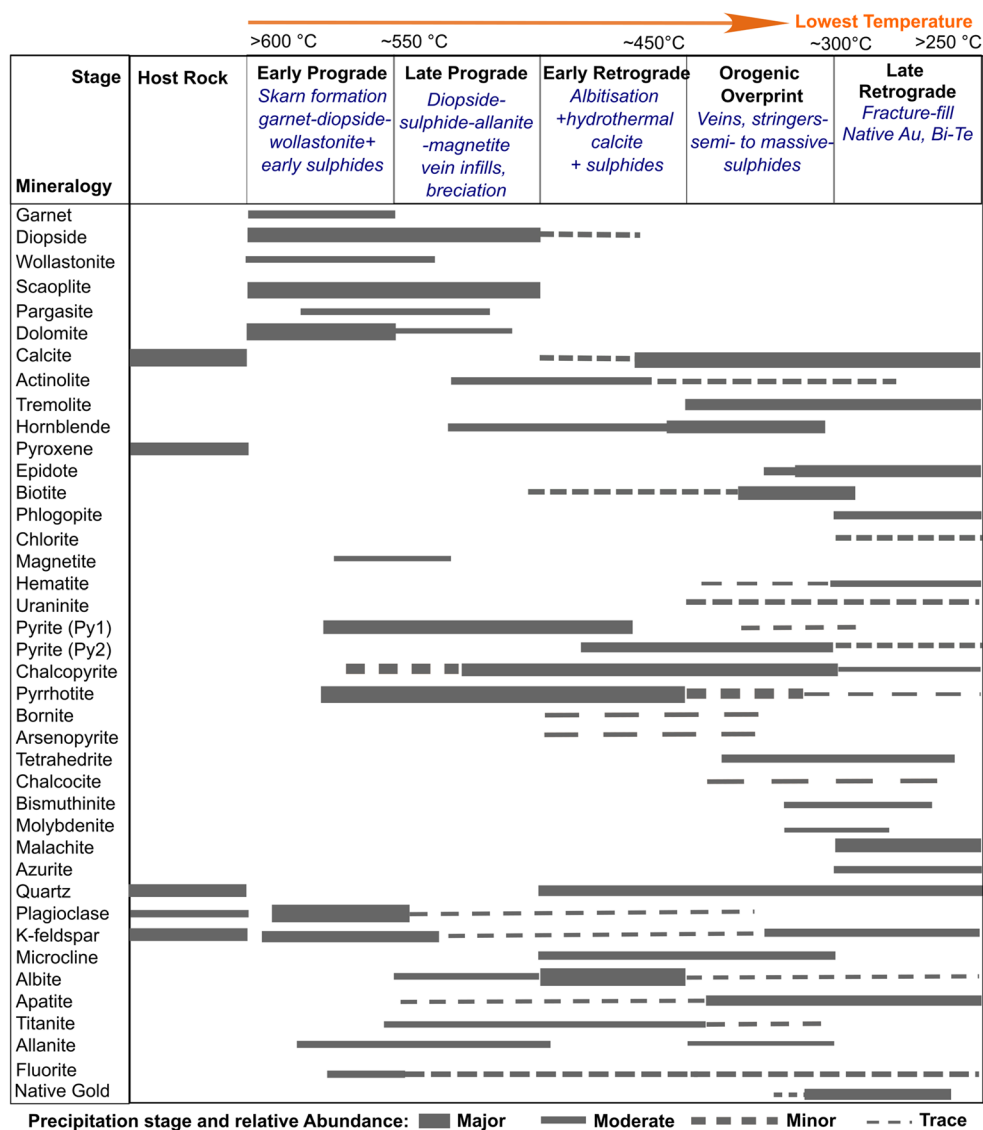
Field observations, ore textures, and mineral relationships indicate that mineralisation at Elaine Dorothy developed through multiple stages of sulphide growth, replacement, fracturing, and remobilisation during progressive skarn alteration and deformation. The four principal mineralisation styles recognised (sulphide vein infills, disseminated and stringer sulphides, semi-massive to massive sulphide lenses, and shear-zone-hosted sulphides; (Figs. 4 and 5) record progressive modification of an evolving skarn system rather than a series of discrete mineralising events. Their spatial and textural relationships indicate a progressive shift from sulphide deposition within reactive calc-silicate lithologies to increasingly fracture-, breccia-, and shear-zone-controlled mineralisation.

The earliest sulphides occur within scapolite–feldspar–diopside calc-silicates, garnet–diopside–amphibole–carbonate skarn, and diopside–amphibole skarn (Fig. 6). Pyrite, pyrrhotite, and chalcopyrite display overlapping growth relationship, fracture-controlled infill, and local replacement of silicate and carbonate phases. Diopside and calcite occur both as inclusions within sulphides and as minerals enclosing or transected by sulphide aggregates, while Py1 and Py2 commonly preserves euhedral crystal faces against chalcopyrite, pyrrhotite and silicates (Fig. 5a–e). Reciprocal

inclusion relationships between sulphides and diopside, calcite, and other silicates indicate that sulphide precipitation began during, or immediately following, prograde skarn development. The earliest sulphides were therefore entrapped during growth of the high-grade calc-silicate skarn assemblage during or immediately following peak metasomatism. Low dihedral-angle contacts and wetting textures between sulphides and host silicates/carbonate further indicate fluid-assisted grain-boundary infiltration and replacement (e.g., Finch et al. 2024). Lobate sulphide–silicate boundaries are similarly consistent with precipitation from fluids that exploited pre-existing permeability and progressively replaced reactive skarn minerals (e.g. Beyer et al. 2024). These relationships indicate that the earliest sulphide mineralisation was closely coupled to high-temperature metasomatism rather than representing a distinctly later event superimposed on a pre-existing skarn. (cf. Mokhtari et al. 2019). This syn-metasomatism association is not unique to Elaine Dorothy but is recognised in several Paleoproterozoic skarn systems, including Tongon Au, Pant Hill Cu–Au, and Sala Zn–Pb–Ag deposits, indicating that sulphide deposition during prograde skarn formation can be an important component of Proterozoic skarn evolution (Jansson et al. 2022; Keyser et al. 2022; Lawrence et al. 2017).

Subsequent mineralisation was associated with hydrothermal calcite and albite formation (Figs. 4e and 5f–g), indicating continued fluid infiltration after prograde silicate growth. Disseminated sulphides subsequently precipitated throughout the system, replacing earlier skarn assemblages (Fig. 4e & f). Continued influx of hot sulphide-bearing fluids promoted carbonate dissolution, enhancing permeability and facilitating further fluid–rock interaction within reactive calc-silicate units. Dissolution–reprecipitation textures are expressed by calcite and sulphide vein networks developed along foliation planes (Fig. 3g). Replacement and fracture-controlled reprecipitation are expressed by calcite–sulphide networks along foliation planes and fractures in prograde skarn minerals, locally producing sharp reaction fronts and irregular, embayed margins of diopside (Figs. 4a and e and 5a) and dissolution–replacement of diopside with amphiboles during fluid–rock interaction (Fig. 5c). Chalcopyrite locally embays and irregularly replaces diopside along grain boundaries, producing a ragged ‘nibbling’ texture (Fig. 5a), consistent with partial dissolution of diopside and subsequent sulphide precipitation. However, Py1 is locally cross-cut by chalcopyrite- and pyrrhotite-filled fractures, and these later sulphides also occur along pyrite grain boundaries (Fig. 5i), indicating textural replacement and fracture-controlled overprinting of earlier pyrite rather than complete dissolution. This stage marks an important change in the architecture of the mineralising

Fig. 6 Summary of the mineral paragenetic sequence for the Elaine Dorothy deposit. Mineral occurrences are subdivided into host rocks, early and late prograde skarn, early retrograde skarn through the orogenic stage, and late retrograde stages, with corresponding ore textures and the inferred decrease in temperature from >600 °C to 250 °C shown above

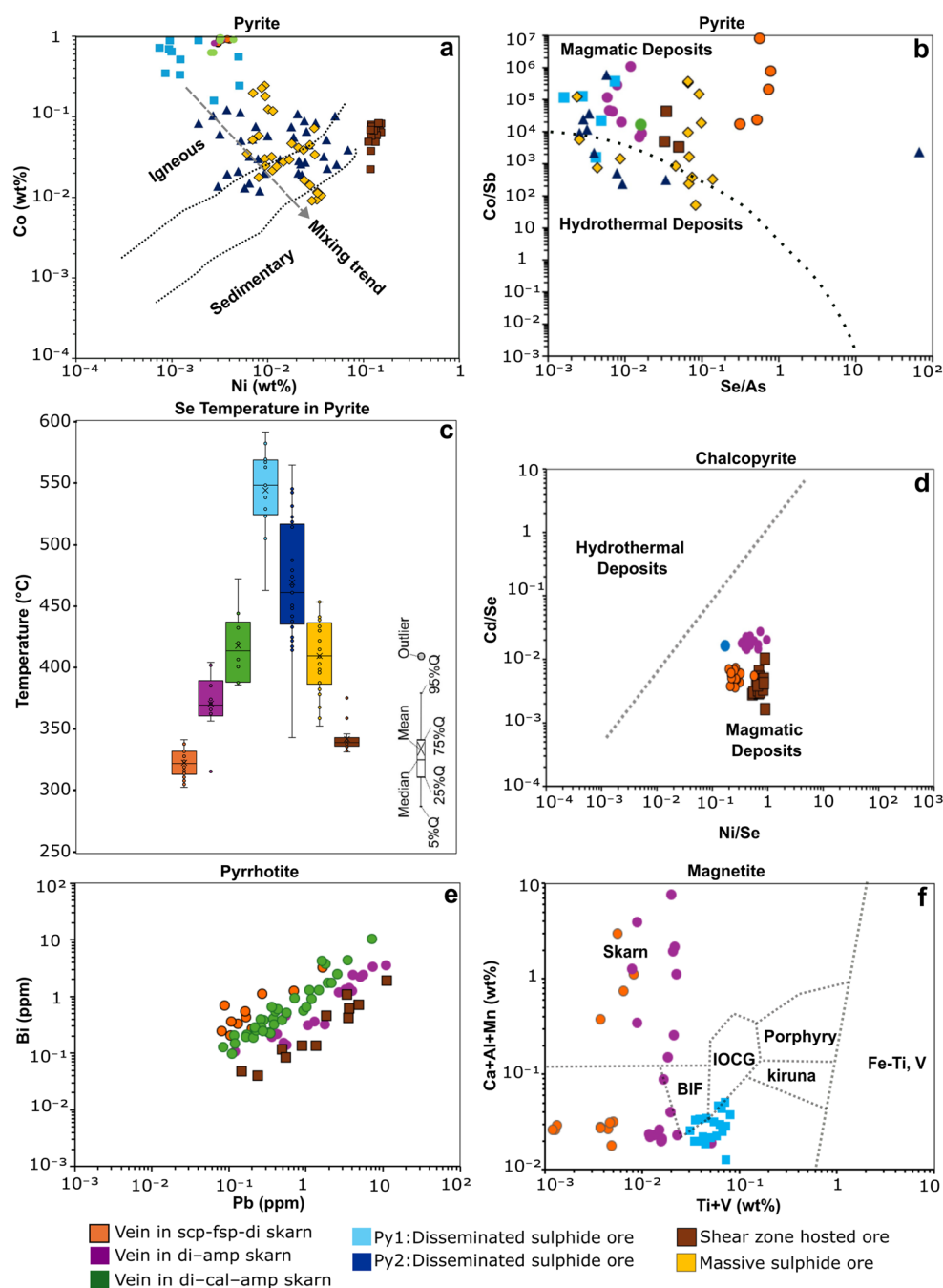


system; permeability was no longer controlled solely by the original carbonate–calc–silicate reaction front but was increasingly generated by dissolution, fracturing and fluid-driven replacement. For example, at Bismark, Mexico, ore occurs as incipient to massive replacement of exoskarn and recrystallised limestone and as open-space infill around breccia fragments, in prograde exoskarn of andradite and diopside overprinted by hedenbergite, from fluids of 8.4–10.9 wt% NaCl equivalent at 351–438 °C (Baker and Lang 2003). Those authors attribute ore deposition to fluid neutralisation during limestone replacement, cooling, and decreasing salinity. At Elaine Dorothy, carbonate dissolution-replacement along diopside boundaries would have raised pH and destabilised metal-chloride complexes, and Se-in-pyrite temperatures record cooling from above ~550 °C to 323–417 °C (Fig. 7c). Fluid pH and salinity are not constrained here, so this mechanism is inferred by

analogy rather than demonstrated. Similar early hydrothermal activation during skarn development is reported from the Mount Colin Cu-Au deposit east of Elaine Dorothy (Cave et al. 2024). This transition reflects fluid evolution from dominantly magmatic to mixed magmatic-hydrothermal conditions (cf. Wang et al. 2026). The term magmatic is used here for fluids exsolved directly from the intrusion, and magmatic-hydrothermal for those fluids after progressive exchange with the host rocks. Comparable relationships have been documented in the Azegour Mo-Cu-W skarn (Baker and Lang 2003; El Khalile et al. 2023) and the Zhuxi W (Cu) skarn in South China (Pan et al. 2020).

With progressive cooling, sulphide mineralisation evolved into semi-massive and massive sulphide lenses, predominantly within diopside–amphibole–carbonate lithologies (Fig. 4g–i, l). Stringer zones locally mark the transition from disseminated to massive sulphide

Fig. 7 Sulphide and magnetite trace-element compositions at Elaine Dorothy. **(a)** Co versus Ni in pyrite, modified after Reich et al. (2016) and Goudarzi et al. (2025). **(b)** Binary diagram of Co/Sb versus Se/As in pyrite for discriminating between pyrite from magmatic and hydrothermal deposits based on Co, Sb, Se, and As concentrations, developed by Duran et al. (2015). **(c)** Average Se concentrations in pyrite vs. temperature after Keith et al. (2018). **(d)** Cd/Se versus Ni/Se concentrations in chalcopyrite for differentiating magmatic and hydrothermal compositional fields after Mansur et al. (2021). **(e)** Bi vs. Pb correlation in pyrrhotite. **(f)** Ca+Al+Mn vs. Ti+V discriminant diagram for magnetite after Dupuis and Beaudoin (2011)



mineralisation and are developed within fracture and cavity networks, recording the progressive concentration of sulphides within structurally controlled sites. Diopside hosts rounded to euhedral inclusions of pyrite and pyrrhotite, whereas pyrite locally contains chalcopyrite, pyrrhotite, native Au, and Bi–Te-rich fracture fills (Fig. 5h–j). The relative contributions of elevated fluid pressure and far-field stress to fracture opening cannot be distinguished from the present dataset. Comparable fracture-controlled sulphide networks have been documented in the Antamina Cu–Zn skarn, where quartz–fluorite–calcite–sulphide

veinlets proximal to the skarn and calcite–sulphide veins distally formed over ~300–600 °C during structurally focused fluid pulses (Escalante et al. 2010). A closer textural analogue is the Terranera magnetite–hematite–pyrite deposit on Elba, which is hosted directly by a regional fault zone and comprises matrix-supported breccias and cataclasites where diopside and clinozoisite are replaced by magnetite, hematite, pyrite and Mg–hornblende at 350–180 °C and 27–125 MPa. Garofalo et al. (2023) interpreted this system as transitional between skarn and epithermal environments and identified faults as preferential

sites for retrograde skarn formation. At Elaine Dorothy, stringer zones consist of anastomosing pyrrhotite–chalcopyrite–pyrite veinlets, millimetres to a few centimetres wide, surrounding medium-grained diopside–garnet skarn and passing laterally into disseminated sulphides within ferruginous K-feldspar–albite alteration (Fig. 4e–f). The local replacement of diopside by sulphide and oxide within a structurally controlled setting is comparable to the textures described at Terranera, although Elaine Dorothy is characterised by Cu–Co mineralisation rather than Fe-oxide-dominated mineralisation. These examples illustrate that fracture-controlled mineralisation is not restricted to IOCG systems, but structurally focused fluid flow is also capable of substantially modifying skarn systems during cooling and deformation. Elaine Dorothy extends this relationship by preserving the transition from lithologically controlled skarn mineralisation to structurally focused, sulphide-rich mineralisation which is consistent with episodic fluid focusing and progressive sulphide accumulation within fractures during cooling and deformation.

The final stage involved deformation-enhanced sulphide redistribution. Shearing concentrated sulphides within amphibole–biotite–quartz–feldspar–calcite–epidote–chlorite alteration zones developed in quartz–feldspar–biotite schists (Fig. 4j–k). Pyrrhotite and chalcopyrite occur along schistosity, grain boundaries, and microfractures, while locally interconnected stringers and fracture-controlled aggregates define heterogeneous sulphide concentrations. Fractured Py1 locally contains chalcopyrite–pyrrhotite fracture fills, and chalcopyrite is concentrated along pyrite grain boundaries and microfractures indicating late sulphide infill following brittle fracturing of the earlier pyrite (Fig. 5i–l). These relationships demonstrate that earlier pyrite remained mechanically and chemically reactive during subsequent sulphide deposition. Rather than representing completely discrete mineralising events, the sulphide textures therefore record repeated fracturing → fluid infiltration → grain-boundary replacement/nibbling → fracture-controlled sulphide infill during continued fluid infiltration. Deformation was therefore not simply a post-mineralisation overprint but a repeatedly regenerated permeability and enabled renewed fluid access to previously mineralised rocks. The paragenesis therefore records a progression from sulphide precipitation associated with prograde skarn formation to increasingly fracture- and deformation-controlled sulphide deposition and remobilisation (Fig. 6). This establishes deformation as an active component of ore formation, linking the early skarn framework to later sulphide redistribution and structural concentration, and provides the textural framework for interpreting the trace-element and redox evolution discussed below.

Fluid evolution recorded by sulphide and magnetite chemistry

The trace-element composition of pyrite, pyrrhotite, chalcopyrite, and magnetite provide complementary evidence for progressive modification of the mineralising fluids. These minerals can preserve variations in fluid composition, temperature, redox state, metal availability, and fluid–rock interaction and have widely been used as proxies for fluid composition, redox state, temperature, and metal source (Keith et al. 2018; Kumar et al. 2024; Reich et al. 2016; Xie et al. 2020; Zhang et al. 2022). At Elaine Dorothy, the distinction between Py1 and Py2, together with systematic differences among pyrrhotite, chalcopyrite, and magnetite, records changes in the physicochemical conditions of mineralisation through time.

Early magmatic-hydrothermal fluid signature

The first generation of pyrite (Py1) is enriched in Co (average ~1.1 wt%) and As (average. ~3,000 ppm), together with relatively elevated Se and low Sb. Its trace-element characteristics and occurrence within prograde skarn assemblages are consistent with an early magmatic-hydrothermal contribution (Fig. 7a–b). Comparable Co-rich pyrite associated with early mineralisation has been reported from the Middle-Lower Yangtze River metallogenic belt (Zhang et al. 2025), the Pusangguo Cu–Pb–Zn deposit (Wang et al. 2022), Mamuniyeh deposit in the Urumieh-Dokhtar Magmatic Arc (Goudarzi et al. 2025), and Linglong gold deposit (Wang et al. 2024). Co enrichment is therefore not necessarily evidence for a discrete Co mineralisation event but can be incorporated into early pyrite during high-temperature hydrothermal mineralisation. The Co/Sb versus Se/As discrimination diagram developed by Duran et al. (2015), which distinguishes magmatic from hydrothermal pyrite further supports a dominantly magmatic affinity (Fig. 7b). Py1 from Elaine Dorothy predominantly occupies the relatively high-Co–Se, low-Sb–As field, consistent with an early magmatic-dominated fluid contribution as opposed to pyrite associated with lower-temperature hydrothermal systems that would otherwise show lower Co and Se and higher Sb and As.

The Se contents of pyrite vary systematically among ore types, with the lowest average concentration in Py1 from disseminated sulphide zones (3.5 ppm; Table 1), compared with 41.2, 22.2, and 14.4 ppm in Py1 from vein infills hosted in scapolite-feldspar-diopside, diopside-amphibolite, and diopside-carbonate-amphibolite skarns, respectively. Se-in-pyrite geothermometer after Keith et al. (2018), using the equation: $\text{Se}_{\text{pyrite}} = 5 \times 10^{13} \times T^{-4.82}$ yields calculated temperatures

ranging from 323 ± 11 to 544 ± 36 °C (Fig. 7c, Supplementary Material S3), with the highest temperature recorded in the disseminated sulphide zones. Py1 from scapolite–feldspar–diopside, diopside–amphibolite, and diopside–carbonate–amphibolite vein infills yields temperatures of 323 ± 11 , 370 ± 25 , and 417 ± 28 °C, respectively.

The calculated temperatures overlap the high-temperature conditions expected for prograde skarn formation and are compatible with contact metamorphic temperatures of ~ 500 – 600 °C reported from the Mary Kathleen area (Cartwright and Oliver 1992). The temperature range recorded by Py1 is compatible with the high-temperature skarn-forming environment inferred from the mineral assemblages at Elaine Dorothy which is consistent with the stability of garnet, pyroxene, wollastonite, and scapolite during high-temperature skarn formation (Einaudi and Burt 1982; Einaudi et al. 1981; Meinert et al. 2005). Prograde garnet and pyroxene fluid inclusions in Fe–Cu skarns span approximately 370 – 700 °C and 300 – 690 °C, respectively (Meinert 1992), whereas grandite garnet and wollastonite are stable above approximately 550 °C (Gustafson 1974; Taylor and O’Neil 1977). Although individual estimates should be treated cautiously, their distribution is consistent with a high-temperature skarn-forming system followed by cooling towards lower-temperature hydrothermal conditions. The temperature variation among lithological settings further suggests that host-rock composition influenced fluid–rock interaction, with carbonate-rich units potentially buffering infiltrating fluids (e.g., Cartwright and Oliver 1992; Meinert et al. 2005), whereas scapolite–feldspar–diopside domains provided a different chemical environment for sulphide precipitation, promoting Py1 precipitation at comparatively lower temperatures during early skarn formation (Fig. 7c). Thus, the temperature estimates are better interpreted as reflecting spatially variable fluid–rock interaction during the broader high-temperature stage rather than a simple monotonic cooling sequence.

Redox and sulphur-fugacity evolution

The paragenetic relationships and mineral chemistry record systematic changes in sulphide assemblages during the evolution of the Elaine Dorothy system. Early Py1 formed at temperatures up to 544 ± 36 °C (Fig. 7c) and occurs with magnetite and prograde skarn assemblages. Euhedral pyrite, pyrrhotite, and chalcopyrite are intergrown with or enclosed by prograde diopside, whereas later chalcopyrite–pyrrhotite assemblages cross-cut earlier mineralisation and Py1 is commonly strongly fractured (Fig. 5i–j). Between approximately 417 ± 28 and 323 ± 11 °C, pyrrhotite becomes increasingly abundant and locally replaces earlier pyrite. Pyrrhotite also commonly contains > 600 ppm Co, except in vein-infill

samples from diopside–carbonate–amphibolite units, where the average Co concentration is only 15.5 ppm (Table 2). The association of Co-rich pyrrhotite with fractured and locally replaced Py1 suggests redistribution of Co from earlier pyrite into newly formed pyrrhotite. In contrast, the low Co content of pyrrhotite in carbonate-rich domains coincides with limited evidence for Py1 dissolution, suggesting that carbonate buffering may have restricted Co mobilisation in these domains (cf. Meinert et al. 2005).

Late Py2 formed at approximately 342 ± 11 °C (Fig. 7c) and is compositionally distinct from Py1, with lower Co (< 650 ppm average) and elevated Ni ($\sim 1,300$ ppm average). Py2 coexists with pyrrhotite, indicating that sulphide stability continued to change during late fluid circulation rather than following a simple unidirectional sequence. Taken together, the early association of Py1 and magnetite, followed by increasing pyrrhotite abundance, replacement of earlier pyrite, and redistribution of Co into pyrrhotite, records a shift from comparatively higher oxygen and sulphur activities toward conditions more favourable for pyrrhotite stability. The predominance of pyrrhotite during the intermediate stage is consistent with relatively reduced, low- f_{O_2} conditions documented in Au–Cu-bearing skarn systems (El Khalile et al. 2023; Sun et al. 2025). The contrasting Co–Ni compositions of Py1 and Py2 further indicate subsequent modification of the sulphide-forming environment. Thus, the sulphide assemblages record progressive but non-monotonic changes in redox state, sulphur activity, and metal partitioning during continued deformation-enhanced fluid circulation.

Evidence for fluid–rock interaction and chemical modification

On the Co–Ni diagram (Fig. 7a), pyrite compositions span the igneous and sedimentary fields, with several analyses distributed along the defined mixing trend. Py2 is characterised by lower Co and elevated Ni relative to Py1, consistent with modification of the sulphide-forming system through interaction with Ni-bearing lithologies and changing metal partitioning during fluid–rock interaction (Li et al. 2018; Van Ryt et al. 2020; Xie et al. 2020). Although the Co–Ni distribution is consistent with variable contributions from igneous- and sedimentary-associated components, it does not independently constrain the proportions or timing of such mixing.

The Co/Sb versus Se/As diagram provides complementary evidence (Fig. 7b). Most pyrite analyses plot within the field defined for magmatic deposits, characterised by relatively high Co and Se and low Sb and As, whereas some analyses, particularly from shear-zone-hosted ores and massive sulphide zones, extend into the field defined for hydrothermal deposits. Rather than representing discrete fluid

types, this distribution is interpreted as evidence for modification of an initially magmatic-dominated signature during continued fluid–rock interaction and structural reworking, consistent with the textural evidence for sulphide replacement and remobilisation (e.g., Wang et al. 2024).

Chalcopyrite from massive sulphide domains displays Ni enrichment and Cd depletion (Fig. 7d), consistent with a magmatic sulphide affinity (Mansur et al. 2021), but its composition was subsequently modified during hydrothermal evolution. Pyrite, chalcopyrite, and particularly pyrrhotite show a strong positive Bi–Pb correlation (Fig. 7e), indicating coherent redistribution of these elements among sulphide phases. This relationship may reflect remobilisation during fluid–rock interaction and incorporation of a sedimentary-derived component into an initially magmatic-hydrothermal system, as proposed by Sun et al. (2025). However, Bi–Pb systematics alone do not uniquely establish a sedimentary source and are therefore interpreted as evidence for fluid modification rather than definitive source discrimination.

Collectively, these trace-element relationships in Co–Ni, Co/Sb–Se/As, Ni–Cd, and Bi–Pb suggests progressive chemical modification of the mineralising system, involving fluid–rock interaction, variable metal partitioning, and possible mixing between compositionally distinct components during deformation. The trace-element data independently support the textural evidence for progressive reworking: early pyrite preserves a relatively high-temperature, Co–Se-rich signature, whereas later sulphides record changing Co–Ni partitioning, redox–sulphur conditions and increasing structural control.

Timing and magmatic affinity of skarn formation

No intrusive body has been dated directly at Elaine Dorothy, and the deposit is not centred on an exposed pluton. Consequently, the age and genetic relationship between magmatism and skarn formation cannot be established from local intrusive contacts alone. Regional relationship nevertheless constrains the timing of skarn development. At Mount Burstall, folded skarn is cut by a dolerite porphyry dyke dated at 1739 ± 4 Ma, indicating that skarn formation and subsequent folding predate this event (Spence et al. 2021). The broader temporal association with the Wonga–Burstall Igneous Event, together with the high-temperature prograde calc-silicate assemblages and sulphides enclosed within and intergrown with prograde diopside (Fig. 5d–e), supports a magmatic–hydrothermal contribution to skarn formation at Elaine Dorothy.

Local cross-cutting relationships further constrain the sequence of events. Prograde garnet–diopside–calcite assemblages replace scapolite–feldspar and overprint the regional foliation (Fig. 3g), indicating that skarn formation

postdates the earlier fabric-forming metamorphism. The skarn was subsequently folded and later modified by hydrothermal alteration and deformation. Younger ages reported for late hydrothermal minerals, including titanite from a carbonate vein, constrain subsequent hydrothermal overprinting rather than the primary skarn-forming event (Spandler et al. 2016). This interpretation is consistent with regional evidence that younger mineralisation ages in the Mary Kathleen Domain may record remobilisation of older mineralisation during the ca. 1550–1490 Ma Williams Igneous Event (Cocker et al. 2025), as also proposed for the Burstall Granite (Cave et al. 2024; Page 1983; Spandler et al. 2016) and Tick Hill system where gold deposited at ~1790–1770 Ma was subsequently remobilised during metasomatism at ~1525–1520 Ma (Le et al. 2021, 2022).

Thus, the available evidence supports an early skarn-forming event during the broader Wonga–Burstall magmatic–tectonic interval, followed by prolonged hydrothermal modification. The absence of a directly dated causative intrusion at Elaine Dorothy prevents assignment of the skarn to a specific plutonic body, but the temporal association with regional magmatism and the high-temperature prograde assemblages are consistent with a magmatic–hydrothermal contribution.

Structural framework and deformation-enhanced fluid flow

The structural relationships provide the physical mechanism for the chemical and mineralogical variability described above. Brecciation, veins, fracture-controlled sulphides, and shear-zone-hosted mineralisation demonstrate repeated development and destruction of permeability during deformation (Figs. 3, 4, 5 and 6). Earlier sulphides and magnetite were fractured, replaced, and locally remobilised, whereas later pyrrhotite and chalcopyrite occupy fractures, grain boundaries, and breccia networks. These relationships indicate progressive redistribution of metals within an already metasomatised rock volume and explain the spatial association of sulphide mineralisation with both favourable carbonate–calc-silicate lithologies and high-strain structural zones. Deformation therefore did not simply provide a pathway for a new mineralising event but repeatedly reactivated an existing skarn framework. Lithological reactivity and structural permeability consequently operated together, with carbonate and calc-silicate rocks providing favourable chemical environments for metasomatism and sulphide precipitation, while deformation enhanced permeability and promoted fluid transfer, partial replacement, and reprecipitation.

The persistence and textural modification of pyrite provide further evidence for repeated fluid flow through the mineralised system. Py1 occurs as fractured and locally

deformed grains within vein-hosted and massive sulphide assemblages and is locally crosscut by chalcopyrite–pyrrhotite fracture fills and Au–Bi–Te-bearing phases occupying fractures and fracture margins (Fig. 5j). In contrast, Py2 forms euhedral grains associated with later sulphide precipitation and is locally enclosed by chalcopyrite (Fig. 5b). These relationships indicate that pyrite formed early and remained mechanically and chemically reactive during subsequent sulphide deposition and remobilisation. Pyrite therefore records not only the chemistry of individual mineralising stages but also the mechanical reactivation of the ore system. Repeated fracturing and infilling of pre-existing sulphides therefore records continued fluid circulation during deformation.

This interpretation is consistent with structurally controlled mineralisation recognised in Proterozoic IOCG systems, where regional-scale shear corridors can facilitate large-scale fluid circulation and metal redistribution (Groves et al. 2010; Hitzman et al. 1992; Williams et al., 2005). Similar relationships occur in structurally controlled skarn systems in Archean and Paleoproterozoic terranes, where metasomatism may be coupled to deformation, granitoid magmatism, and regional fluid flow rather than being restricted to shallow intrusive contact aureoles (Mueller et al. 2004; Mueller 1997). Comparable deformation-related fluid circulation and overprinting of earlier metasomatic assemblages have also been documented in the Eastern Fold Belt and the greenstone belts of the Fennoscandian Shield (Duncan et al. 2011; Niiranen et al. 2005; Oliver et al. 2009). Marshall and Oliver (2008) demonstrated that brecciation, Na–Ca alteration and local shear strain-controlled fluid flow, with skarn-like assemblages marking high-fluid-flux corridors near IOCG mineralisation within the Mark Kathleen domain. The Island Dam prospect in South Australia also further demonstrates skarn-style alteration within the Olympic Cu–Au Province and specifically addresses the problem of distinguishing primary skarn features from later IOCG-related hydrothermal overprinting (Keyser et al. 2022). These examples demonstrate that skarn-style alteration can develop within regionally metamorphosed and deforming crust where structural permeability provides pathways for metasomatic fluids. At Elaine Dorothy, the transition from prograde calc-silicate development through retrograde hydrothermal alteration to shear-zone-hosted sulphide concentration similarly indicates that deformation was an important control on the continued evolution and redistribution of the mineralising system.

Together, the field, textural, and paragenetic relationships indicate that sulphide mineralisation at Elaine Dorothy evolved from high-temperature sulphide-bearing metasomatism associated with prograde skarn growth, through retrograde hydrothermal alteration and progressive sulphide concentration, to deformation-enhanced remobilisation and structural focusing. The resulting mineralisation styles

therefore reflect progressive modification of an evolving skarn system by repeated fluid infiltration and deformation.

Magnetite and the skarn–IOCG transition

Magnetite chemistry provides an additional constraint on the evolution of the system. Magnetite compositions vary substantially between and within samples (Fig. 7f), indicating that magnetite did not form during a single chemically homogeneous event. Vein-hosted magnetite in scapolite–feldspar–diopside and brecciated diopside–amphibolite skarns plot within skarn fields and toward low-trace-element BIF compositions. In contrast, magnetite from disseminated sulphide zones plots below the BIF field on the Ca+Al+Mn versus Ti+V diagram and contains very low Ca+Al+Mn and up to at least 0.1 wt% Ti+V. Elevated Ca in some grains may reflect interaction with Ca-rich fluids during metasomatism (Garofalo et al. 2023; Xie et al. 2022). The textural relationships further indicate that magnetite predates at least part of the later sulphide mineralisation: magnetite is commonly brecciated, with chalcopyrite and pyrrhotite occupying fractures and voids (Fig. 5a). Thus, the chemical variability and cross-cutting relationships indicate subsequent modification of the magnetite assemblage during continued fluid circulation and deformation rather than a single-stage Fe-oxide event.

These observations help evaluate the relationship between Elaine Dorothy and IOCG systems. Classical calcic skarns are characterised by prograde garnet–pyroxene assemblages generated during high-temperature interaction between magmatic fluids and carbonate-bearing rocks (Meinert et al., 2005; Page 1983), whereas IOCG systems commonly exhibit strong structural control, Fe-oxide alteration, Na–Ca alteration, and Fe–Cu±Au mineralisation associated with oxidised saline fluids (Groves et al. 2010; Hitzman et al. 1992). Elaine Dorothy contains characteristics for both. The prograde garnet–diopside–scapolite–feldspar assemblages and sulphides enclosed within or intergrown with prograde silicates are consistent with calcic skarn formation, whereas strong structural control, magnetite brecciation and chemical variability, the Fe–Cu–Co±Au association, Na-bearing alteration, and evidence for changing redox and sulphur-fugacity conditions demonstrate substantial later modification.

Importantly, Elaine Dorothy does not contain the volumetrically dominant magnetite–hematite assemblages characteristic of many IOCG end members. Its IOCG-like component is therefore expressed primarily through structural architecture, alteration, metal association, fluid evolution, and hydrothermal overprinting rather than through Fe-oxide abundance alone. This supports interpretation of Elaine Dorothy as a transitional system rather than an unambiguous classical calcic-skarn or IOCG end member, without requiring a universal skarn–IOCG genetic continuum.

Elaine Dorothy in the context of Paleoproterozoic skarn and IOCG systems

The integrated geological, petrographic, structural, geochemical, and geochronological observations indicate that Elaine Dorothy preserves an early Paleoproterozoic calcic skarn framework that was subsequently modified during deformation and repeated fluid flow. The earliest alteration comprises prograde garnet–diopside–scapolite–wollastonite assemblages developed within reactive carbonate–calc–silicate lithologies, together with pyrite, pyrrhotite, and chalcopyrite that locally occur intergrown with or enclosed by prograde silicates. These relationships establish the initial calcic skarn character of the deposit and indicate that sulphide mineralisation commenced during or closely accompanied skarn development rather than being restricted to a later retrograde stage. The mineral assemblages and textural relationships with reactive carbonate-bearing lithologies are consistent with calcic skarn systems (Einaudi et al. 1981; Meinert et al., 2005; Page 1983) and are comparable with the range of skarn assemblages recognised elsewhere in the Mary Kathleen Domain and other Paleoproterozoic terranes (Oliver et al. 1999; Page 1983). Paleoproterozoic skarn systems commonly record multiple episodes of metasomatism, subsequent deformation and hydrothermal overprinting (Dieng et al. 2015; Hellingwerf 1984), although their mineralogical characteristics vary regionally (Table 5). The Island Dam Cu–Au skarn in South Australia provides an additional example of carbonate-related skarn-style alteration dominated by actinolite/phlogopite, K-feldspar, and magnetite, reflecting a different tectono-magmatic setting from Elaine Dorothy (cf. Keyser et al. 2022).

The later evolution of Elaine Dorothy is characterised by increasing structural control on fluid access and mineralisation. Sulphides occur within fractures, breccias, veins, grain boundaries, foliation-parallel domains, and high-strain zones associated with the Mary Kathleen Shear Zone and contacts between contrasting lithologies (Figs. 3, 4, 5 and 6). Earlier sulphides and magnetite are locally fractured and overprinted by later pyrrhotite, chalcopyrite, and pyrite, demonstrating repeated modification of pre-existing mineralisation. The distribution and textures of these minerals indicate that deformation influenced the availability and geometry of permeability, allowing subsequent fluids to access and modify earlier mineral assemblages. Corresponding changes in sulphide and oxide chemistry, including the contrasting trace-element characteristics of Py1 and Py2 and the Co–Ni, Co/Sb–Se/As, Ni–Cd, and Bi–Pb systematics identified in the analysed minerals, further indicate chemical modification and variable metal partitioning during continued fluid evolution.

The significance of Elaine Dorothy lies in the preservation of these relationships within a single hydrothermal system. Rather than representing simply the coexistence of skarn and IOCG characteristics, the deposit records progressive modification of an early lithologically controlled skarn framework through deformation, renewed fluid access, and sulphide redistribution. Deformation therefore influenced not only the location of mineralisation but also the pathways through which later fluids interacted with and chemically modified pre-existing mineral assemblages. Elaine Dorothy is consequently interpreted as a deformation-modified Paleoproterozoic calcic skarn that progressively developed IOCG-affinity characteristics during subsequent hydrothermal and structural reworking, rather than as a classic IOCG end member.

Broader implications of deformation-driven transformation of skarn mineral systems

The significance of Elaine Dorothy extends beyond its classification as a Cu–Au skarn or its comparison with IOCG deposits. The deposit provides a process-based example of how an initially lithologically controlled calcic skarn can be progressively modified by deformation, fluid–rock interaction, and repeated hydrothermal reactivation to produce a structurally focused sulphide-rich system with IOCG-affinity characteristics. Importantly, the geological record at Elaine Dorothy does not require a separate, discrete IOCG-forming event to account for these characteristics. Instead, they developed through progressive modification of an established skarn framework, as deformation repeatedly generated and reactivated permeability, redirected fluids, fractured earlier mineralisation, and promoted local sulphide redistribution. This relationship highlights deformation as an active component of hydrothermal mineralisation rather than simply a post-mineralisation overprint.

The transformation is recorded at several scales. At the lithological scale, carbonate-bearing horizons provided favourable reactive sites for the development of garnet–diopside–scapolite±wollastonite assemblages and associated early sulphides. At the mineral scale, inclusion, intergrowth, and wetting relationships indicate that sulphide precipitation overlapped with prograde silicate growth, whereas subsequent replacement, fracturing, brecciation, and fracture infill record renewed fluid access during later stages. At the structural scale, sulphides became concentrated within fractures, breccia networks, foliation-parallel domains, lithological contacts, and structures associated with the Mary Kathleen Shear Zone. The transition from Co- and Se-rich Py1 to relatively Co-poor, locally Ni-enriched Py2, together with chemical modification of pyrrhotite and magnetite, indicates that structural reactivation was accompanied by

Table 5 Summary of known Paleoproterozoic skarn deposits and associated alteration and mineralisation style

Deposit/ area	Main metals	Age (approx.)	Tectonic setting	Host rocks	Alteration stages from prograde to retrograde	Mineralisation style/ Temp	Reference
Daginggou (China)	Fe-Cu	1.9 Ga	Arc-continent collision orogeny in the JLJB	Microcline granite and carbonate rocks (marble)	-Diopside-epidote alteration followed by magnetite-hematite -Quartz-chalcocopyrite-azurite-chalcocite-pyrite-pyrrhotite -Late quartz-sulphide-sphalerite -Quartz-carbonate: chlorite-calcite-sericite±pyrite	Structurally controlled, Hosted in ductile–brittle shear zones 395–466 °C	(Liu et al. 2023)
Sala, Bergslagen (Sweden)	Zn-Pb-Ag	1.89 Ga	Marine back-arc or intra- arc basin on extended continental crust during the Svecokarelian orogeny	Marble and calc-silicate with garnet clinopyroxene skarn	-Seawater-brine-driven alteration, limestone dolomitisation -Clinopyroxene-diopside, and andradite-grossular garnet -Magnetite-sulphide enrichment -Hydrolytic alteration: sphalerite-galena, phlogopite, tremolite-actinolite-chlorite - calcite	Calcic and magnesian Fe-skarn controlled by lithological con- tacts and faults. 280 to 300 °C	(Jansson et al. 2022)
Gruvaasen (Sweden)	Cu-Zn-Fe-Pb-As	1.9 to 1.8 Ga	Rift basin	Metatuff, dolomitic limestone	-Potassic alteration-sulphide enrichment -Amphibolite-pyroxene skarn formation -Recrystallisation of pyrite, late sulphide remobilisation	Potassic-structural controlled, 550 °C	(Hellin- gwerf 1984)
Island Dam, Pant Hill (Australia)	Cu-Au, (Pb-Zn)	1.6 Ga	Arc Magmatism-hydrothermal	Hiltaba Suite granites and Wallaroo metasediments of the Gawler craton	-Actinolite/phlogopite, minor K-feldspar, magnetite, quartz -Disseminated chalcocopyrite-pyrite-bornite and veinlets -Carbonate + quartz + late sulphide veining	Alkali-calcic skarn, fault controlled 300 to 550 °C	(Keyser et al. 2022)
Tongon (Côte d'Ivoire)	Au	2.1Ga	Senoufo greenstone belt in West African Craton	Greenstone sequence (basaltic- andesitic tuffs), calc-silicates	-Potassic (biotite-K-feldspar-actinolite) -Clinopyroxene±grossularitic garnet -Calc-silicate-albite-carbonate-quartz-pyrrhotite-pyrite-arsenopyrite-Au as disseminated and stringer veinlets -Late chlorite-sericite-quartz±gold	Fault controlled, orogenic event 500 to 600 °C	(Law- rence et al. 2017)
Mount Elliot, (Australia)	Cu-Au (Co-Ni-Fe), U-REE	1.5 Ga	Magmatic-hydrothermal system, arc- or post arc magmatism in the Mount Isa Inlier	Carbonaceous metapelites of the Soldiers Cap Group	-Early albittisation (K-Fe-Mg depletion) -Diopside-scapolite-actinolite -Brecciation, chalcocopyrite-actinolite-scapolite alteration -Andradite-tourmaline-allanite-apatite-magnetite-pyrite-pyrrhotite and late calcite	Structurally controlled mineralisation along shear zones 400 to 600 °C	(Wang and Williams 2001)
Mount Colin, Mary Kathleen, & Elaine Dorothy (Australia)	Cu-Au (Co-Ni-Fe), U-REE	1.75 to 1.5 Ga	Back-arc tectonic setting associated with syn- to post-rift magmatism in the Mary Kathleen Domain.	Calc-silicates, marble	-scapolite-feldspar-diopside progressive to garnet-diopside- wollastonite-magnetite-amphibole-calcite skarn assemblages -Prograde metasomatism: allanite-sulphide vein infills -Amphibole-biotite-quartz-calcite-epidote-albite-alteration and structurally controlled sulphide remobilisation. -Epidote-actinolite-tremolite-calcite-malachite-azurite	Calcic skarn alteration, Magmatic- hydrothermal transition from 600 to 350 °C, structurally controlled sulphide remobilisation	(Cave et al. 2024), (Oliver et al. 1999; Page 1983)
Azegour (Moroco)	Mo-Cu-W Skarn		Magmatic activity linked to its volcanic arc	Metasediments and limestone	-Wollastonite-andradite-diopside -Hedenbergite- grossular-scheelite -Vesuvianite-quartz-k-feldspar-albite-calcite-amphibole-epidote-molybdenite-chalcocopyrite-pyrite -Amphibole-quartz-calcite-chlorite-mica	Intrusive, magma- carbonate rock, 600 to 150 °C	(El Khalile et al. 2023)
Misi Region (Finland)	Fe-Skarn	2.0 Ga	Greenstone and schist belts of the Fennoscandian shield	Gabbroic rocks and Raajärvi Formation marbles	-Actinolite/tremolite±biotite -Chlorite, calcite, apatite, ± magnetite -Serpentine±chlorite, talc, apatite, magnetite, and hematite	Sodic alteration at 450 °C controlled by structure and litho- logical contacts,	(Niiranen et al. 2005)

changes in the chemical conditions and metal partitioning behaviour of the hydrothermal system. Thus, deformation influenced not only where fluids migrated, but also how the evolving fluids interacted with and chemically modified pre-existing mineralisation.

Comparable relationships occur in other Proterozoic Cu–Au systems in which skarn-style alteration, structural permeability, and later hydrothermal overprinting are spatially associated. The Island Dam system in the Olympic Cu–Au Province of South Australia, for example, contains skarn-style alteration within a broader Cu–Au hydrothermal system and illustrates how carbonate-related alteration can form part of a more extensive mineralising architecture (Keyser et al. 2022). Within the Mary Kathleen Domain, skarn-like assemblages are also associated with zones of intense fluid–rock interaction, brecciation, Na–Ca alteration, and structural permeability. More broadly, structural controls, superposed alteration assemblages, and reactivated shear zones and lithological contrasts are widely recognised as important controls on fluid circulation and metal redistribution in IOCG systems (e.g., Dieng et al. 2015; Groves et al. 2010; Oliver et al. 1999). In this context, Elaine Dorothy provides a particularly useful example because the early calcic-skarn framework and its subsequent structural and hydrothermal modification are preserved together, allowing the evolution between these stages to be examined directly.

These observations have a broader implication for the interpretation of Proterozoic mineral systems. The distinction between skarn and IOCG mineralisation may, in some systems, partly reflect the stage of hydrothermal evolution represented by the preserved mineral assemblages and structures rather than requiring fundamentally separate mineralising processes. This does not imply that skarn and IOCG deposits form a universal genetic continuum. Rather, Elaine Dorothy demonstrates that an early calcic-skarn architecture can be substantially reorganised during subsequent deformation and hydrothermal reactivation, such that later mineralisation acquires characteristics commonly associated with IOCG systems. The important process is therefore not a simple conversion of one deposit type into another, but progressive modification of permeability, fluid pathways, mineral stability, and metal partitioning during the lifetime of a hydrothermal system. Recognition of this process provides a framework for interpreting mineral systems in which later deformation and alteration have partially obscured the characteristics of their earlier stages.

This interpretation also has implications for exploration in Proterozoic terranes. Calcic-skarn assemblages developed around carbonate-rich horizons or intrusive contacts may not necessarily represent isolated, intrusion-centred mineral systems, particularly where they occur adjacent to major structures or within regions affected by repeated deformation.

The coexistence of skarn assemblages with brecciation, Na-bearing alteration, structurally controlled sulphide networks, modified magnetite, and systematic changes in sulphide trace-element chemistry may indicate that the skarn forms part of a larger, structurally reactivated hydrothermal system. Consequently, exploration models that rely primarily on conventional intrusive-contact relationships may overlook structurally modified skarn systems in which later hydrothermal processes have redistributed Cu–Au–Co mineralisation away from the original skarn-forming sites. Elaine Dorothy demonstrates the potential value of integrating lithological, structural, alteration, textural, and mineral-chemical criteria when evaluating such systems.

Genetic model for the Elaine Dorothy skarn–IOCG system

The integrated data support a five-stage evolution of the Elaine Dorothy system (Fig. 8).

Stage 1: Prograde skarn formation and early sulphide precipitation

High-temperature magmatic–hydrothermal fluids infiltrated reactive carbonate and calc-silicate horizons, producing garnet–diopside–scapolite±feldspar assemblages. Early sulphides precipitated during or shortly after prograde silicate growth. Co-rich Py1 and the high-Se/low Sb–As pyrite characteristics indicate a dominant magmatic contribution, while the highest calculated pyrite temperature of 544 ± 36 °C records the high-temperature stage of the system (Fig. 7a–c).

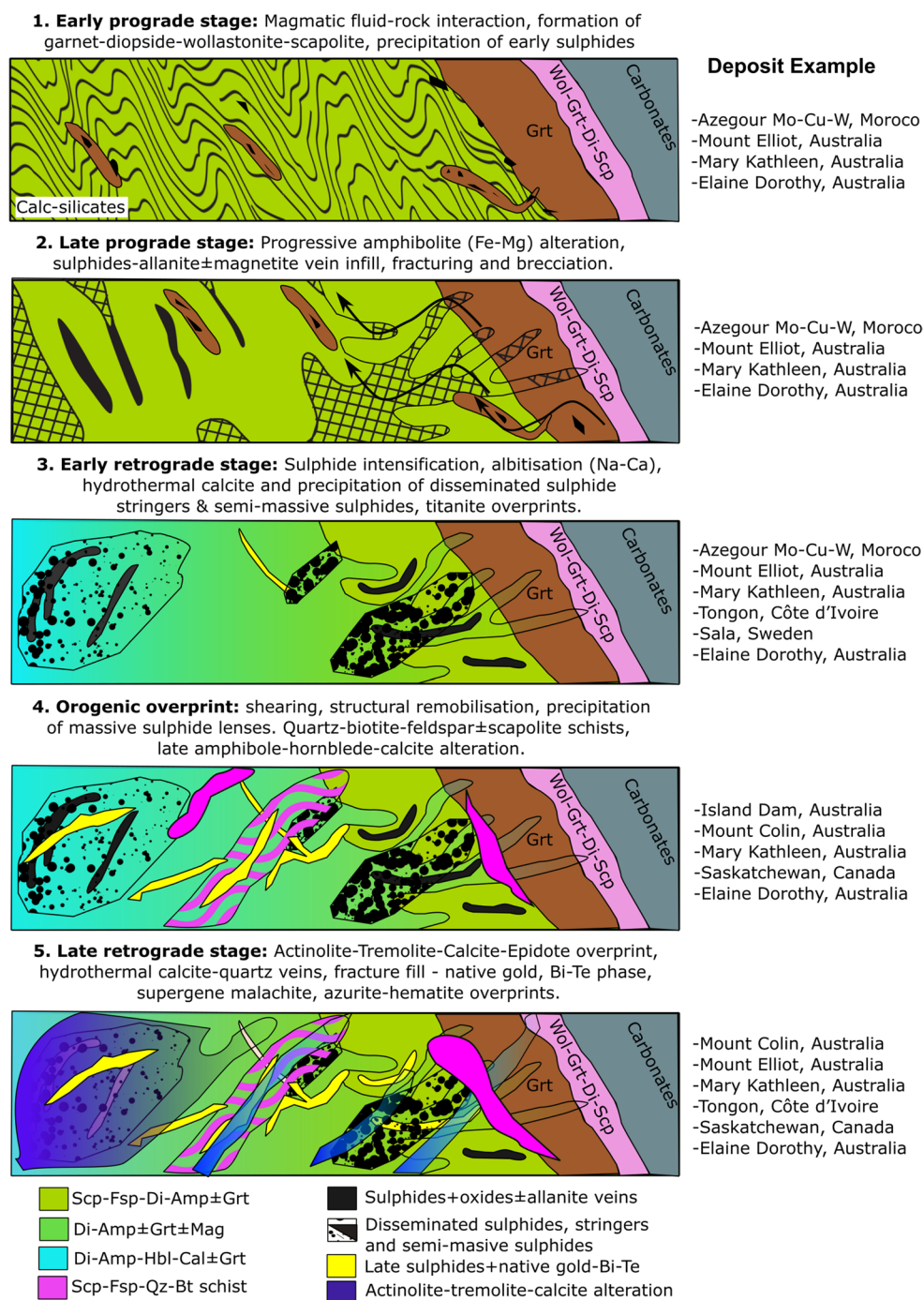
Stage 2 Late prograde stage, development of sulphide-vein infill

Progressive Fe–Mg amphibole alteration, fracturing, and brecciation accompanied the development of Fe–Cu sulphide±garnet–magnetite–allanite vein infills within scapolite–feldspar–diopside calc-silicate, diopside–amphibolite–carbonate, and moderately brecciated diopside–amphibolite±garnet skarns.

Stage 3 – Cooling, fluid–rock interaction, and sulphide-rich mineralisation

Continued fluid circulation produced calcite and albite alteration and modified the prograde assemblages. Cooling and changes in redox–sulphur-fugacity conditions favoured pyrrhotite over pyrite, with subsequent pyrrhotite–chalcopyrite precipitation along grain boundaries and fractures. Brecciation and fracture development facilitated the transition from disseminated to semi-massive and massive sulphide mineralisation.

Fig. 8 Schematic illustration of the five-stage genetic model for the evolution of Elaine Dorothy sulphide mineralisation, compared with selected Paleoproterozoic skarn systems listed in Table 5, including Azegour, Morocco (El Khalile et al. 2023); Tongon, Cote d'Ivoire (Lawrence et al. 2017); Sala, Sweden (Jansson et al. 2022), Saskatchewan, Canada (Dieng et al. 2015); and Mount Elliot, Mary Kathleen, Mount Colin, and Island Dam, Australia (Cave et al. 2024; Keyser et al. 2022; Wang and Williams 2001). Abbreviations: Scp – scapolite; Fsp – feldspar; Di – diopside; Amp – amphibole; Wol – wollastonite; Grt – garnet; Mag – magnetite; Hbl – hornblende; Cal – calcite; Qz – quartz; Bt – biotite



Stage 4: Deformation-enhanced fluid flow and chemical modification

Progressive deformation along the Mary Kathleen Shear Zone and associated lithological contacts repeatedly generated permeability, fracturing earlier magnetite and sulphides and concentrating later pyrrhotite and chalcopyrite within fractures, breccias, and shear zones. Continued fluid flow modified the earlier mineral assemblages and promoted local redistribution of Fe–Cu–Co±Au.

Stage 5 – Late retrograde overprinting and sulphide remobilisation

Continued deformation and cooling produced amphibole–biotite–albite–epidote–calcite alteration and late fracture-controlled sulphide deposition. Py2 formed at 342 ± 11 °C and records lower Co and elevated Ni relative to Py1, while Bi–Pb enrichment records continued chalcophile-element mobilisation. Late alteration was followed by retrograde and supergene modification.

The Elaine Dorothy system is therefore interpreted as a progressively overprinted Paleoproterozoic calcic skarn–IOCG transitional system. An early lithologically controlled calcic skarn framework was progressively modified by fluid–rock interaction, changing redox–sulphur–fugacity conditions, deformation-enhanced permeability, and structural fluid focusing, resulting in sulphide redistribution and local Fe–Cu–Co $\pm$ Au enrichment.

Conclusion

The Elaine Dorothy Cu–Au deposit records a multi-stage Paleoproterozoic mineralising history involving prograde calcic skarn formation, progressive fluid–rock interaction, changing redox and sulphur–fugacity conditions, and deformation-enhanced fluid flow and sulphide redistribution within the Mary Kathleen Domain of the Mount Isa Inlier. Field relationships, mineral textures, and mineral chemistry demonstrate that mineralisation developed through progressive overprinting rather than as a single discrete event. The earliest stage involved high-temperature interaction of magmatic–hydrothermal fluids with reactive carbonate and calc-silicate lithologies, producing garnet–diopside–scapolite–wollastonite $\pm$ amphibole assemblages and associated pyrrhotite–chalcopyrite–pyrite mineralisation. Co- and Se-rich Py1 and Se-in-pyrite temperatures of up to 544 ± 36 °C further support a high-temperature magmatic–hydrothermal component during this stage.

Subsequent cooling and changes in redox–sulphur–fugacity conditions promoted pyrrhotite-dominated sulphide mineralisation and redistribution of Ni and Co between sulphide phases. Co–Ni and Co/Sb–Se/As systematics indicate progressive modification of an initially magmatic-dominated signature, while contrasting Py1 and Py2 compositions and Bi–Pb relationships record continued trace-element redistribution during fluid evolution. Variability in magnetite trace-element compositions and its cross-cutting relationships with later sulphides further indicate that Fe-oxide mineralisation was modified during subsequent fluid circulation.

Brecciation, fracturing, veins, and shear-zone-hosted sulphides demonstrate that deformation repeatedly enhanced permeability and focused later fluid flow. Early lithologically controlled skarn mineralisation was consequently overprinted by structurally focused alteration and sulphide redistribution, producing local concentration of Fe–Cu–Co $\pm$ Au within retrograde alteration zones. Deformation therefore acted as an active control on the continued evolution and redistribution of the mineralising system rather than simply representing a post-mineralisation overprint.

Taken together, the geological, mineralogical, structural, and geochemical evidence indicates that Elaine Dorothy represents a deformation-enhanced Paleoproterozoic calcic skarn that evolved toward a skarn–IOCG transitional system. Its IOCG affinity is expressed principally by the superposition of structural fluid focusing, Fe–Cu–Co $\pm$ Au enrichment, Na–Ca alteration, magnetite modification, and evolving redox–sulphur–fugacity conditions on an earlier calcic-skarn framework, rather than by the presence of volumetrically dominant magnetite–hematite assemblages. Elaine Dorothy demonstrates how deformation can progressively transform an initially lithologically controlled calcic skarn into a structurally focused sulphide-rich hydrothermal system with IOCG-affinity characteristics, without requiring a discrete IOCG-forming event.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00126-026-01485-w>.

Acknowledgements This is part of a PhD project conducted by Catherine Nyakecho at James Cook University, Townsville, Australia. We acknowledge funding from the Economic Geology Research Centre (EGRU) and JCU Postgraduate Research Scholarship, as well as support from Dr Huiqing Jeffrey Huang, Dr Shane Askew, and Dr Kevin Blake at the Advanced Analytical Centre, JCU for aiding LA-ICP-MS & SEM sulphides analyses.

Author contributions Catherine Nyakecho - Field investigation, sample preparation and analysis, manuscript conceptualisation, methodology, visualisation, and writing and editing. Avish Kumar - Sample preparation and analysis supervision, manuscript conceptualisation, methodology, writing - review and editing. Ioan V. Sanislav - Field investigation, supervision, validating manuscript conceptualisation and methodology, funding acquisition, review and editing. Melanie Finch - Field investigation, supervision, review and editing. Helen A. Cocker - Supervision, manuscript review and editing.

Funding This research received no specific grant funding but was supported by EGRU, under Dr. Ioan V. Sanislav my Primary Supervisor and James Cook University Postgraduate Research Scholarship.

Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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