SECTION E

Controls on formation of Miocene porphyry and high-sulphidation deposits in the Cajamarca Au District, northern Peru

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E.1 Abstract

This section presents a model for the formation of Miocene mineralised centres in the Cajamarca region. Geochemical data for Miocene mineralised centres indicate metals and hydrous magmas were derived from partial melting of deep, amphibole-rich source, most likely upper mantle to lower crust. These magmas ascended rapidly along deeply tapping faults during brief changes in the tectonic stress and were emplaced in a highly fractured upper crust. The locations of magmatic and hydrothermal centres were controlled by zones of weakness in the upper crust, such as structural intersections between regional-scale faults and superimposed oblique faults. Fracture, vein and fault trends in the mineralised dioritic intrusions developed as a response to a regionally-extensive stress regime. Variations in metal grades at the early Miocene (23-17 Ma) porphyry deposits reflect differences in temperature and oxygen fugacity conditions during the precipitation of early-stage hypogene sulphides. Development of late Miocene (12.5-11 Ma) high-sulphidation deposits coincided with subduction of the Inca plateau, as well as cessation of crustal thickening and uplift. The timing of these Miocene deposits shows no direct correlation with either the Incaic or Quechua orogenic events, but a strong association with high plate convergence rates. It is suggested that porphyry-related and high-sulphidation deposits formed as a result of a combination of geological processes triggered by changes in the tectonic stress.

E.2 Introduction

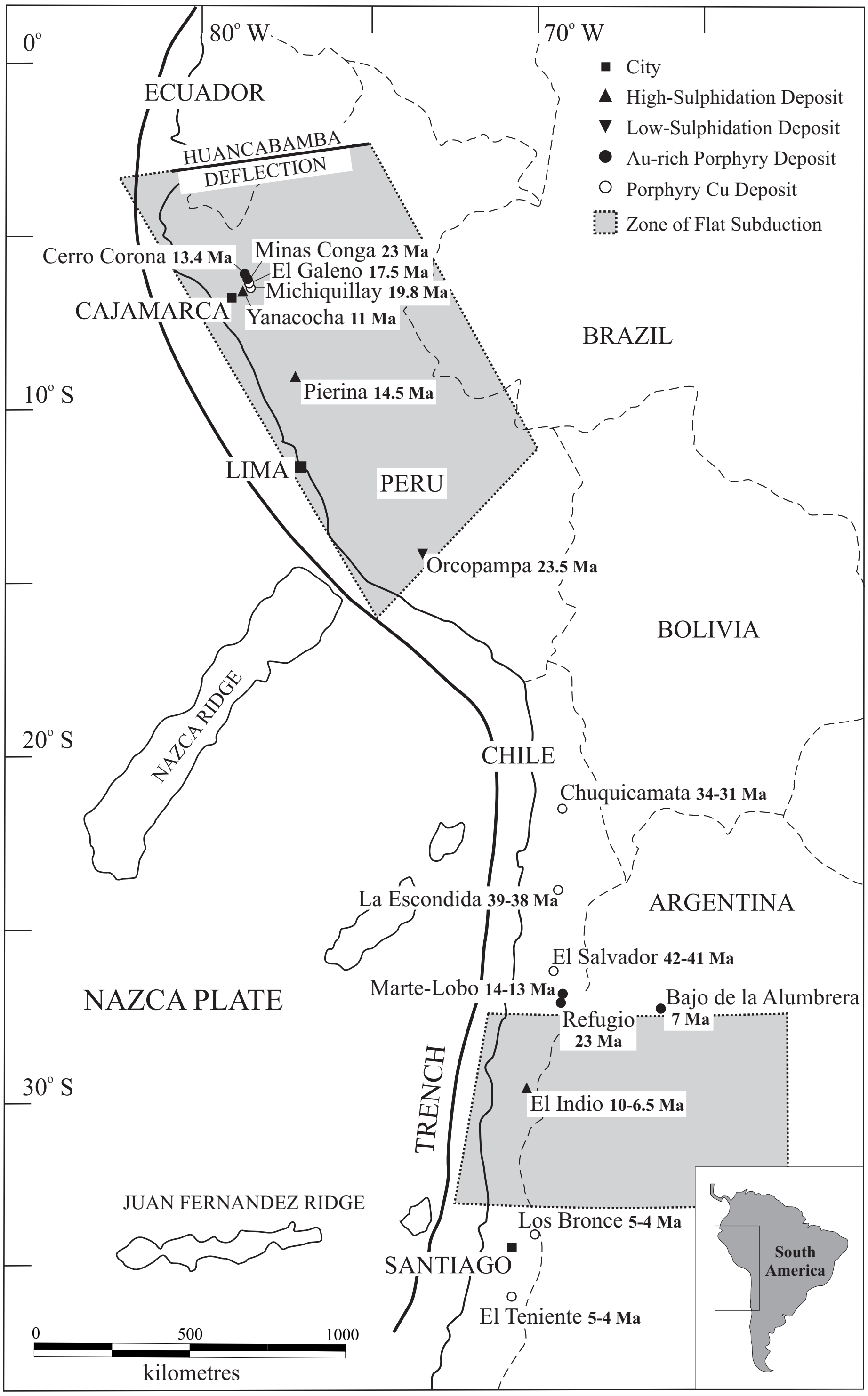
Gold-rich porphyry deposits tend to cluster in geographically restricted belts or districts (Sillitoe, 2000b). The Cajamarca mining district of northern Peru and the Central Andean transect (24^{o} to 30^{o}S), as defined by Sasso and Clark (1998), are two such districts that host an unusually high concentration of Au-rich deposits compared to other Andean metalliferous districts. The Cajamarca district hosts a number of significant late Miocene (12.5-10.9 Ma) high-sulphidation deposits, including South America's largest Au mine at Yanacocha, and early Miocene (23.2-16.5 Ma) porphyry-related deposits (Fig. 1). Porphyry deposits include the Au-rich Minas Conga (Chailhuagon and Cerro Perol) and Cerro Corona deposits, as well as the Cu-Au-Mo Michiquillay and El Galeno deposits. The Au-rich deposits, Minas Conga and Cerro Corona (Hualgayoc region), have amongst the lowest Cu/Au atomic ratios (~8,500-15,500) of known porphyry copper deposits throughout the world (Kesler *et al*., 2002).

Both the Au-rich central Andes and Cajamarca districts host significant Tertiary epithermal and porphyry-related deposits. However, the central Andes also contain a number of giant Tertiary porphyry Cu deposits characterised by economically significant supergene enrichment zones. Clusters of gold-rich and copper-dominated deposits within the Central Andean transect show a common deep-level tectonomagmatic evolution. Geochemical modelling and structural observations reveal magmas formed during mineralisation episodes equilibrated with amphibole- to amphibole-garnet-bearing mineral residues and ascended along deeply tapping structures to shallow crustal levels (Kay *et al*., 1999; Richards *et al*., 2001; Chernicoff *et al*., 2002). Additionally, the geology, alteration and mineralisation styles of these central Andean deposits have been well documented. Compared to the central Andes, the tectonic, magmatic and upper crustal ore-forming processes that operated during the formation of mineralised centres in the Cajamarca district are poorly understood. This section presents a top-to-bottom model for the formation of Miocene deposits in the Cajamarca region based on geochronological, geochemical, structural and deposit geology studies.

E.3 Geological Setting

Cajamarca is located in the Western Cordillera of the northern Peruvian Andes, ~685 km north of Lima. This region is situated in the southern section of the Huancabamba Deflection where there is a significant change in the structural grain from the dominant NW Andean trend to near E-W. Cajamarca is located above a present day zone of flat subduction (Fig. 1). During Tertiary times, Cretaceous sedimentary rocks were folded and thrusted by several compressive orogenic events (Mégard, 1984).

Fig. 1. Location of Miocene deposits in the Cajamarca region of northern Peru, situated at the southern tip of the Huancabamba deflection and above the present day flat subduction zone where the dip of the subducting slab is ~10^{o} (Barazangi and Isacks, 1979). Also shown are some of the significant Tertiary porphyry and high-sulphidation deposits in the central Andean transect (24^{o}S-30^{o}S; adapted from Sillitoe, 1991; Noble and McKee, 1999).


0°
80° W
70° W
City
High-Sulphidation Deposit
Low-Sulphidation Deposit
Au-rich Porphyry Deposit
Porphyry Cu Deposit
Zone of Flat Subduction
ECUADOR
HUANCABAMBA DEFLECTION
Cerro Corona 13.4 Ma
Minas Conga 23 Ma
El Galeno 17.5 Ma
Michiquillay 19.8 Ma
CAJAMARCA
Yanacocha 11 Ma
BRAZIL
Pierina 14.5 Ma
10° S
LIMA
PERU
Orcopampa 23.5 Ma
BOLIVIA
NAZCA RIDGE
20° S
CHILE
Chuquicamata 34-31 Ma
La Escondida 39-38 Ma
ARGENTINA
El Salvador 42-41 Ma
Marte-Lobo 14-13 Ma
NAZCA PLATE
Bajo de la Alumbrera 7 Ma
Refugio 23 Ma
30° S
El Indio 10-6.5 Ma
TRENCH
JUAN FERNANDEZ RIDGE
Los Bronce 5-4 Ma
SANTIAGO
El Teniente 5-4 Ma
South America
0
500
1000
kilometres

Palaeocene-Miocene magmas were channelled along deeply tapping faults and emplaced in zones of weakness in the highly fractured upper crust. Palaeogene igneous rocks commonly crop out in the footwall of the thrust fault, whereas most Neogene rocks are located in the hanging wall.

E.4 Re-evaluation of the Magmatic History of the Cajamarca Region

Tertiary igneous rocks intrude and unconformably overlie a deformed package of Cretaceous sedimentary rocks. The igneous rocks formed over two major magmatic intervals; these include Palaeogene (57.0-35.4 Ma) and Miocene magmatism (23.2-7.2 Ma). Palaeogene magmatic rocks comprise intermediate volcanic rocks belonging to the lower Llama Formation and coeval porphyritic intrusions. Peak Palaeogene magmatism (~43 Ma) roughly coincided with both the Incaic II orogenic event (43-42 Ma, Benavides, 1999) and the end of a high convergence rate period (49-42 Ma, Pardo-Casas and Molnar, 1987). This magmatic interval persisted until middle Oligocene times (~35 Ma, Noble *et al*., 1990), after which low convergence and magmatic quiescence characterised northern Peru. Gabbroic dykes were however emplaced at high crustal levels at *ca*. 29.5 Ma.

Commencement of early Miocene (23.2 Ma) magmatism roughly corresponded with the Incaic IV orogenic pulse (22 Ma, Benavides, 1999) and a change back to high convergence rates (Pardo-Casas and Molnar, 1987). Synmineralisation intrusions at porphyry-related deposits and regional coeval barren stocks were emplaced during the initial 7 m.y. of this magmatic interval (23.2-16.5 Ma; Llosa *et al*., 1996; Section A). Interestingly, no volcanic rocks have yet been dated for this interval. A cluster of age dates between 17.9 and 16.5 Ma signifies the termination of both early Miocene magmatism and prolific porphyry Cu formation. This 1.4 m.y. period coincided with the Quechua I orogenic event (17 Ma, Benavides, 1999). The locus of magmatic activity shifted to the polymetallic Hualgayoc district between 16.8 and 12.5 Ma (Borroden, 1982; Macfarlane *et al*., 1994; James, 1998; Noble and McKee, 1999). Widespread alteration and mineralisation near Hualgayoc occurred from 14.5 to 13.0 Ma (Macfarlane *et al*., 1994). The locus of magmatic activity changed back to near Cajamarca between 12.3 and 8.4 Ma. This late Miocene magmatism was characterised by widespread volcanism and formation of the high-sulphidation Yanacocha Au district (Turner, 1997). Significantly, formation of the Yanacocha Au district correlates with subduction of the Inca plateau (12-10 Ma) and flatting of the subduction dip angle (Gutscher *et al*., 1999). Magmatic activity terminated following the Quechua II orogenic event (7-8 Ma, Benavides, 1999).

Based on dates from Miocene mineralised centres in central and northern Peru, Noble and McKee (1999) argued magmatic-hydrothermal activity in the arc occurred over short-lived pulses with periods from 13 to 15.5 Ma and 7 to 10 Ma relating to intervals of increased mineralisation. Geochronological results from this study indicate that both prolonged (~7 m.y. during the early Miocene) and short-lived (at *ca*. 13.5-12.5 and 11.5-10.9 Ma in the middle-late Miocene) mineralisation intervals took place in northern Peru. These new $^{40}Ar/^{39}Ar$ dates also show mineralisation events did not necessarily coincide with the either the Inca or Quechua orogenic events, as previously proposed by Noble and McKee (1999).

E.5 Petrogenesis of Tertiary Igneous Rocks

Tertiary igneous rocks in the Cajamarca region are predominantly medium- to high-K calc-alkaline rocks that show typical magmatic arc affinity with enrichment of large ion lithophile elements (LILE) and light rare earth elements (LREE) relative to high field strength elements (HFSE). The oldest of these are Palaeocene-Eocene intrusive and volcanic rocks (57-43 Ma) of intermediate composition with moderate to flat REE profiles (average La_N/Yb_N ratio of 9). These rocks have primitive isotope compositions (Fig. 2a, Table 1), although some appear to have been contaminated by material with a low ε_{Nd} and high Sr_i, possibly seawater. Partial melt modelling suggests these melts were derived from a garnet-poor residue dominated by pyroxene and olivine, whilst mineral assemblages indicate magmas were dry melts (<3 wt % H_2O). Oligocene gabbroic dykes (29 Ma) have tholeiitic compositions and relatively flat REE profiles (La_N/Yb_N ratios of 4 to 11). Rare earth element modelling indicates these gabbros were derived from partial melting of a primitive mantle that was in equilibrium with olivine and pyroxene residue minerals. The dykes have primitive isotopic ratios (Fig. 2a) and display no clear evidence of upper crustal contamination. At present, no

Fig. 2. (A) Sr and Nd isotope plot of Tertiary igneous rocks in the Cajamarca-Hualgayoc region and Miocene mineralised districts in Chile. Igneous rocks from Cajamarca display limited evidence of upper crustal contamination. Note that synmineralisation rocks from Cajamarca and the Los Bronce-El Teniente regions have relatively primitive isotope compositions compared to other deposits of similar age. (B) Sulphide Pb isotope trends from mineralised Miocene intrusions in Cajamarca compared to Pb isotope trends of Au-rich and Ag-rich deposits in northern Chile and southern Peru (adapted from Tosdal *et al*., 1999). Tosdal (1995) proposed Au-rich deposits in northern Chile contained lower $^{208}Pb/^{204}Pb$ at any given $^{206}Pb/^{204}Pb$ value than Ag-rich deposits indicating greater crustal influence. Sulphides from Cajamarca plot to the right of the Chilean Au-rich deposits, suggesting even greater crustal influence. These isotope compositions and trends are consistent with deposits in the Pb isotope province II defined by Macfarlane *et al*. (1990) and suggest an upper mantle to lower crustal source. S/K = average crustal growth curve of Stacey and Kramers (1975).

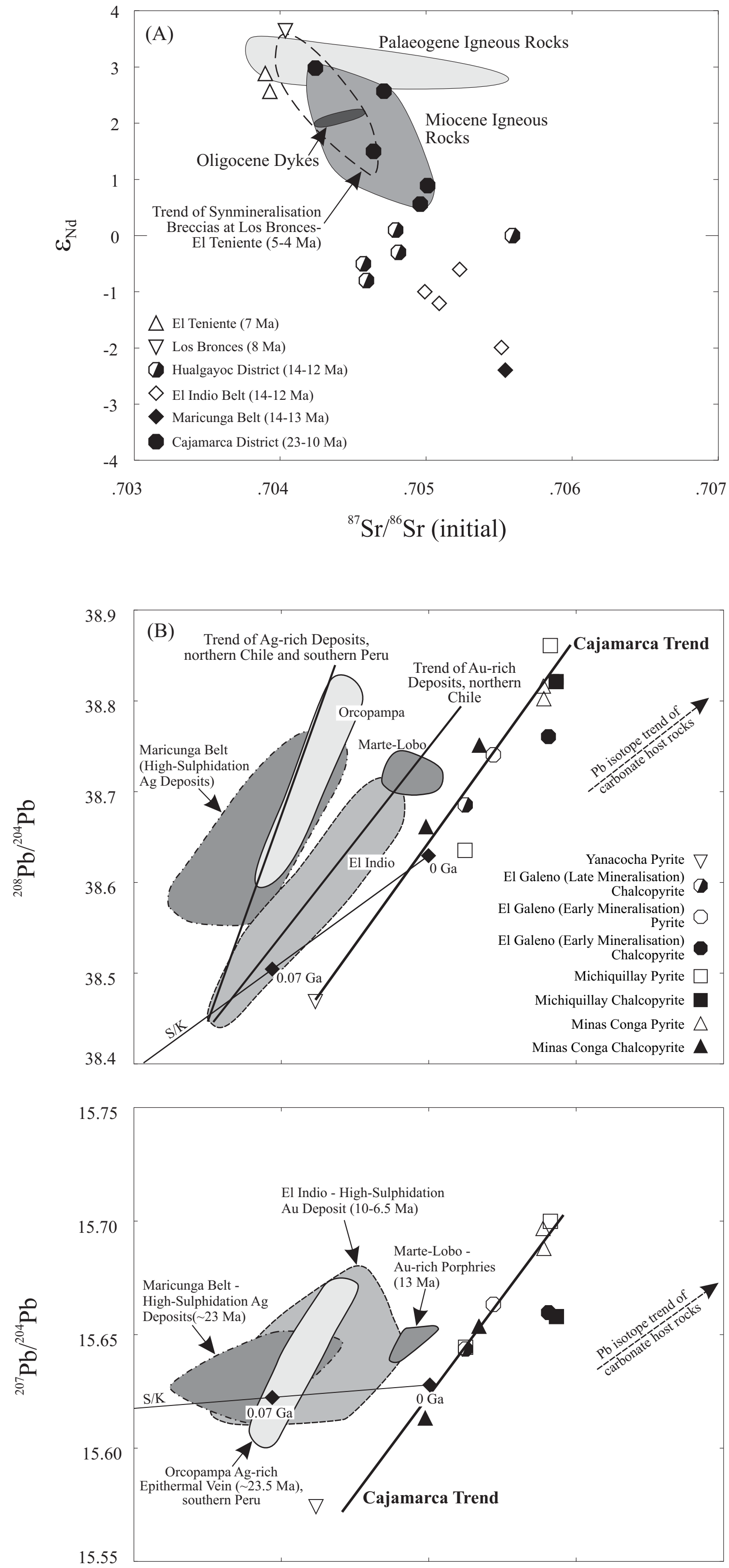

(A)
Palaeogene Igneous Rocks
Miocene Igneous Rocks
Oligocene Dykes
Trend of Synmineralisation Breccias at Los Bronces-El Teniente (5-4 Ma)
El Teniente (7 Ma)
Los Bronces (8 Ma)
Hualgayoc District (14-12 Ma)
El Indio Belt (14-12 Ma)
Maricunga Belt (14-13 Ma)
Cajamarca District (23-10 Ma)
ε_{Nd}
$^{87}Sr/^{86}Sr$ (initial)
4
3
2
1
0
-1
-2
-3
-4
.703
.704
.705
.706
.707
(B)
Trend of Ag-rich Deposits, northern Chile and southern Peru
Trend of Au-rich Deposits, northern Chile
Cajamarca Trend
Orcopampa
Marte-Lobo
Maricunga Belt (High-Sulphidation Ag Deposits)
El Indio
0 Ga
0.07 Ga
S/K
Pb isotope trend of carbonate host rocks
Yanacocha Pyrite
El Galeno (Late Mineralisation) Chalcopyrite
El Galeno (Early Mineralisation) Pyrite
El Galeno (Early Mineralisation) Chalcopyrite
Michiquillay Pyrite
Michiquillay Chalcopyrite
Minas Conga Pyrite
Minas Conga Chalcopyrite
$^{208}Pb/^{204}Pb$
38.9
38.8
38.7
38.6
38.5
38.4
El Indio - High-Sulphidation Au Deposit (10-6.5 Ma)
Marte-Lobo - Au-rich Porphries (13 Ma)
Maricunga Belt - High-Sulphidation Ag Deposits(~23 Ma)
S/K
0.07 Ga
0 Ga
Orcopampa Ag-rich Epithermal Vein (~23.5 Ma), southern Peru
Cajamarca Trend
Pb isotope trend of carbonate host rocks
$^{207}Pb/^{204}Pb$
15.75
15.70
15.65
15.60
15.55
18.5
18.6
18.7
18.8
18.9
$^{206}Pb/^{204}Pb$

Table 1. Results from radiogenic Sr, Nd (Section C) and Pb (Section D) analyses. Sample numbers in bold represent intrusions from mineralised centres

Sample No.	Location	Rock Type	Age (Ma)	Rb ppm	Sr ppm	$(^{87}Rb/^{86}Sr)_m$	$(^{87}Sr/^{86}Sr)_m$	$(^{87}Sr/^{86}Sr)_i$	Sm ppm	Nd ppm	$(^{147}Sm/^{144}Nd)_m$	$(^{143}Nd/^{144}Nd)_m$	$\varepsilon_{Nd(0)}$		$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
S-46	Co Perol East	Intrusion	57.0	56.2	699	0.233	0.70422	0.70403	3.29	14.43	0.1361	0.512779	2.76				
S-31	Co Montana	Intrusion	47.0	58.1	1246	0.135	0.70556	0.70547	4.51	21.07	0.1294	0.512781	2.79				
S-32	Cruz Conga	Volcanic	43(?)	82.5	925	0.258	0.70399	0.70383	2.95	14.89	0.1197	0.512814	3.44				
S-21	La Carpa	Volcanic	42.6	67.6	938	0.209	0.70483	0.70470	2.38	12.17	0.1180	0.512803	3.22				
S-16	South Galeno	Dyke	29.4	23.4	322	0.211	0.70465	0.70455	1.12	3.74	0.1812	0.512751	2.20				
S-57	South Galeno	Dyke	29.4	29.9	516	0.168	0.70436	0.70428	2.54	11.24	0.1364	0.512742	2.03				
S-Chail	Minas Conga	Intrusion	23.2	54.9	693	0.229	0.70472	0.70464	1.21	5.65	0.1291	0.512715	1.50	ccp	18.6980-18.7342	15.6132-15.6536	38.6605-38.7507
														pyr	18.7778-18.7781	15.6878-15.6968	38.8013-38.8161
S-11	Aurora Patricia	Intrusion	21.3	59.8	559	0.310	0.70482	0.70473	1.42	5.98	0.1436	0.512691	1.04				
S-H22	Michiquillay	Intrusion	19.8	42.8	672	0.184	0.70429	0.70424	2.37	11.87	0.1205	0.512791	2.98	ccp	18.7865	15.6577	38.8215
														pyr	18.7248-18.7826	15.6439-15.7000	38.6349-38.8608
S-59	Michiquillay North	Intrusion	20.6	62.4	392	0.461	0.70458	0.70445	1.75	8.89	0.1189	0.512695	1.10				
S-T2	El Galeno	Intrusion	17.5	53.4	530	0.291	0.70508	0.70501	0.44	2.87	0.0916	0.512684	0.89	ccp	18.7813	15.6597	38.7608
S-38	La Carpa	Intrusion	17.9	80.1	784	0.296	0.70463	0.70456	1.06	6.01	0.1061	0.512728	1.76				
S-T4	El Galeno	Intrusion	16.5	56.8	586	0.281	0.70478	0.70471	2.89	13.87	0.1261	0.512770	2.57	ccp	18.7071	15.6348	38.6853
S-CLL5	Yanacocha	Intrusion	10.0	84.4	881	0.278	0.70500	0.70496	0.92	7.60	0.0728	0.512667	0.56	pyr	18.6234	15.5742	38.4688
S-MC4	South Minas Conga	Volcanic	9(?)	75.1	632	0.344	0.70472	0.70468	1.79	8.90	0.1212	0.512728	1.75				

All $^{143}Nd/^{144}Nd$ are relative to La Jolla-Nd = 0.511860; all $^{87}Sr/^{86}Sr$ are relative to SRM987-Sr = 0.71024; m = measured; i = initial

$\varepsilon_{Nd(0)}$ calculated for present-day CHUR = 0.512638

Pb isotope reactor of 0.15% based on muliple analyses of NBS981 standard lead, and the values in Thrilwall (2000) mineralisation is known to have been associated with Palaeogene magmatism.

Miocene intrusive and volcanic rocks (23-7 Ma) are intermediate to acidic in composition and have steep, HREE-depleted profiles (La_N/Yb_N ratios ranging from 7-21). Miocene synmineralisation intrusions have similar geochemistry to coeval barren stocks indicating a common origin. However, synmineralisation stocks are slightly enriched in Th suggesting greater fractionation. Partial melting models and isotope compositions (Fig. 2a) indicate early-middle Miocene magmas were derived from partial melting of an amphibole-rich source that was in equilibrium with minor amounts of garnet (possibly upper mantle to lower crust). These magmas assimilated minimal upper crustal material. Two early Miocene intrusions (S-T4 and S-H22) have considerably less radiogenic Nd and Sr compositions than intrusions of similar age. Sulphide Pb isotope compositions from mineralised deposits form steep trends consistent with an upper sub-Andean mantle source (Fig. 2b, Table 1). Late Miocene igneous rocks have more evolved Sr and Nd isotope compositions that are interpreted to signify crustal thickening. Partial melting models of these rocks also imply higher garnet content (up to 17%) in the residue than the early-middle Miocene magmas. Differences in isotopic compositions and modelled residual mineralogy between early and late Miocene rocks are inferred to reflect an evolving magmatic arc undergoing extensive uplift, rapid increase in crustal thickness and deepening of the mantle-crust boundary. Similar modelled changes in residual mineralogy (clinopyroxene $\Rightarrow$ amphibole $\Rightarrow$ garnet) have been linked with periods of crustal thickening and formation of Miocene hydrothermal deposits in the Central Andes (Kay *et al.*, 1991; Kay and Mpodozis, 2001).

E.6 Structural Controls at Mineralised Centres

Structural investigations reveal the dominant fault arrays in the Cajamarca region have progressively rotated in a clockwise direction from NE-trending during Eocene times to NNW-trending in the early-middle Miocene and finally NW in the late Miocene. Rotation of these fault arrays was temporally related to counterclockwise rotation of the subducting Nazca plate relative to the South America plate. This suggests changes in plate motion induced rotation of the horizontal principal stress field from

SW-oriented during most of the Palaeogene to near E-oriented since early Miocene times. Rotation of the principal stress direction resulted in NNW and NW-trending Miocene faults superimposed on Eocene NE-trending faults. Fault intersections generated by superimposed faults on pre-existing structures provided important channelways for later magmatic and hydrothermal fluids.

Both mineralised and barren Miocene intrusions are elliptical in plan with the long axes roughly parallel to local large-scale structure(s). Similar alignment of pre-existing local structures and the long axes of elliptical intrusions suggest the stocks intruded a highly fractured, anisotropic crust (Nakamura, 1977; Takada, 1994). The majority of these Miocene intrusions are spatially associated with the Puntre Thrust Fault. Structural observations along sections of the fault suggest normal displacement along the fault plane during the flow of mineralising fluids. During periods of relaxation or extension in subvolcanic environments, structural intersections between deeply-tapping faults and subordinate oblique faults provide favourable channelways for ascending magma melt and hydrothermal fluids (Gow and Ord, 1999; Tosdal and Richards, 2001; Richards *et al*., 2001). Since late Oligocene times, the high Peruvian Andes have been dominated by an extensional regime (Sebrier and Soler, 1991) providing favourable conditions for ascent of magmas. Though Bellier *et al*. (1989) showed that the maximum principal stress direction in the high Andes oscillated from vertical to horizontal throughout Neogene times. Plate tectonic data combined with field relationships indicate that Miocene intrusions were emplaced at structural intersections in a highly fractured upper crust during changes in the tectonic stress.

Fracture arrays at porphyry Cu deposits are influenced by either regional and/or localised tectonic stresses that result in linear fracture-vein arrays, or by magmatic influenced stress that produces concentric and radial fracture-vein arrays (c.f. Tosdal and Richards, 2001). Three distinct fault-fracture-vein arrays (NE, N-S and NW striking) have been identified at Minas Conga and Michiquillay (Llosa and Veliz, 2000; Section B). These regular array orientations are interpreted to have resulted from a tectonic influenced stress regime. In contrast, fractures at El Galeno have a random orientation and no clear preferred orientation. These arrays may have resulted either from overprinting of multiple fracture events, or alternatively indicate a dominantly magmatic stress field. Significantly, the most common fractures at El Galeno (NNW-trending) are subparallel to arrays at Minas Conga and Michiquillay. These results suggest a regionally extensive stress field influenced fault-fracture arrays at all three porphyry complexes. In the Laramide region of North America, similar regional systematic fracture patterns in plutons and their wall rocks have been related to regional stress fields (Heidrick and Titley, 1982).

Conjugate structural relationships are observed in both early Miocene porphyry-related and late Miocene high-sulphidation deposits. Both the Michiquillay and Yanacocha deposits have overall NE trends that are crosscut by ore-controlling NW-striking faults. At these deposits, subvertical NW-striking faults display sinistral movement whereas NE-trending faults are dextral, with both fault orientations also displaying late vertical movement (Longo, 2000; Section B). This implies the maximum principal stress direction during formation of this deposit rotated, possibly numerous times, between horizontal E-directed (strike-slip) and vertical (extension). Tosdal and Richards (2001) suggest episodic rotations of the regional stress field are unlikely during short time spans in which porphyry Cu deposits form (<1 m.y.). Therefore, rotations of the stress direction during hydrothermal activity are inferred to result from a low-differential stress field and fluctuating fluid pressures.

E.7 Deposit Geology

Porphyry-related deposits near Cajamarca formed during early to middle Miocene times (23.2 to 16.5 Ma) are associated with dioritic intrusions. These deposits are mostly located in the hanging wall of Puntre Thrust Fault. Synmineralisation intrusions share similar geochemical and sulphide Pb isotope compositions indicating a common origin (probably upper mantle to lower crust) for both the intrusions and metals. Mineralisation at the porphyry deposits occurs as both disseminated and in stockwork. However, despite these similarities the deposits display a number of significant differences that include variations in the Au/Cu ratio.

The Au-rich Minas Conga (23.2 Ma) and Minas Carpa (~17.5 Ma?) deposits are hosted in limestones, contain abundant hydrothermal magnetite, display a strong Au-Cu association with bornite-chalcopyrite mineralisation, lack a well-developed phyllic alteration and have preserved quartz-alunite lithocaps. These deposits have characteristics consistent with generalised Au-rich porphyry models (Sillitoe, 2000b, Kesler *et al*., 2002), and close similarities to Au-rich dioritic porphyries in the Maricunga Belt in Chile (Vila and Sillitoe, 1991). In contrast, Michiquillay (19.8 Ma) and El Galeno (17.5-16.5 Ma) are Cu-Au-Mo deposits hosted in quartzites ± limestones and contain modest (45-100 m thick) supergene enrichment zones with Cu grades of >1 %. Hypogene pyrite-chalcopyrite mineralisation was associated with potassic alteration. Late, pyritic phyllic alteration zones that are slightly gold depleted overprint the potassic alteration zones. These Cu-Au-Mo deposits have characteristics typical of generalised porphyry Cu systems (Titley and Beane, 1981).

Deposits with high-sulphidation systems in the region include Tantahuatay (12.4 Ma; Macfarlane *et al*., 1994), Sipán and Yanacocha (11.5-10.9 Ma, Turner, 1997). These formed *ca*. 10-5 m.y. after development of the major porphyry Cu deposits. A synmineralisation intrusion beneath the Yanacocha epithermal systems has slightly elevated SiO_2 (69 wt% SiO_2) compared to early Miocene synmineralisation stocks (avg. 65 wt% SiO_2). These deposits are characterised by acid-sulphate (alunite) alteration, but their settings and mineralisation styles vary significantly (Turner, 1999). In contrast to the structurally controlled caldera-related Sipán and La Zanja deposits, Yanacocha displays a greater degree of brecciation, lithological control and resurgent magmatic-hydrothermal activity (Turner, 1999). Intriguingly, pyrite from a mineralised intrusion at the Yanacocha Au mine has a less radiogenic Pb isotope composition than sulphides from early Miocene porphyry deposits reflecting an enriched mantle source (Fig. 2b).

Tosdal (1995) showed Au-rich deposits in northern Chile generally contained lower $^{208}Pb/^{204}Pb$ at any given $^{206}Pb/^{204}Pb$ value than Ag-rich deposits, which he interpreted to indicate a higher crustal influence (Fig. 2b). Sulphide Pb isotope results from this study show even lower $^{208}Pb/^{204}Pb$ values than the Chilean Au-rich deposits suggesting even greater crustal influence or alternatively mixing with subducted sediments (Macfarlane, 1999). Cajamarca is located within a Pb isotope province defined by a mantle source region mixed with either subducted sediment or crustal rocks (province II, Macfarlane *et al*., 1990), compared to the Chilean deposits that are situated in province I characterised by a mantle-dominated source. Additionally, metamorphic basement rocks in northern Peru have much higher $^{206}Pb/^{204}Pb$ values than their equivalents in southern Peru and northern Chile (Macfarlane, 1999). Pb isotope compositions from Cajamarca might be expected to display higher $^{206}Pb/^{204}Pb$ had they been crustally contaminated. However, Sr-Nd-Pb isotope compositions from the Cajamarca-Hualgayoc region provide limited evidence of crustal contamination (Macfarlane, 1999; Section C). Therefore, Au enrichment in the Cajamarca region does not appear to have been influenced by crustal contamination.

E.8 Tectonomagmatic Model for Formation of Miocene Deposits

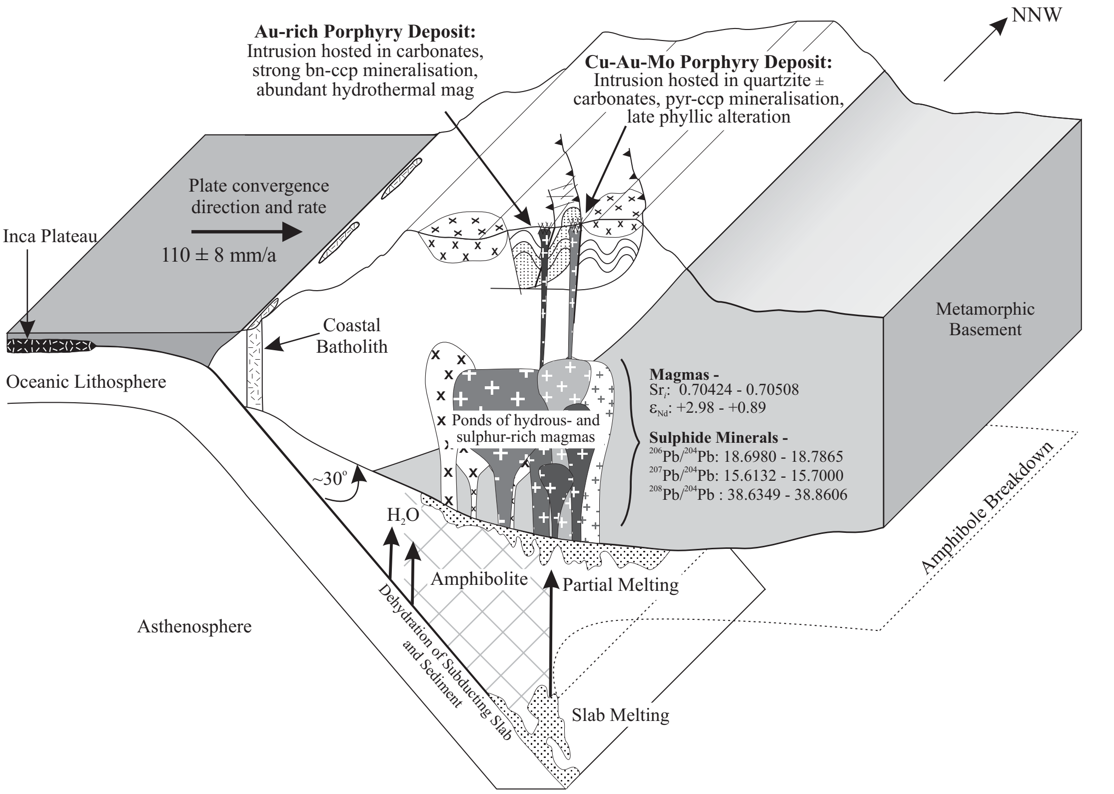
Recently, Shatwell (2002) proposed that Miocene Au-Cu deposits in the Cajamarca region formed due to subduction of the Inca Plateau (12-10 Ma). He proposed this led to shallowing of the slab dip angle and rapid erosion that caused fluctuations in the lithostatic-hydrostatic pressure boundaries. However, this argument ignores the fact that the early Miocene porphyry-related deposits formed 5-11 m.y. earlier. In addition, erosion surfaces observed in central Peru are noticeably absent in the Cajamarca region.

Initiation of mineralisation during early-middle Miocene times was triggered by an increase in plate convergence rates that resulted in the generation of hydrous (>3 wt % H_2O) melts from the breakdown of an amphibole-rich upper mantle (Fig. 3). Highly oxidised, H_2O-rich mafic melts have high sulphur solubility and are effective carriers of chalcophile elements (Burnham, 1979). In contrast, Palaeogene melts derived from an olivine-pyroxene residuum were relatively dry (<3 wt % H_2O) and poor carriers of chalcophile elements. This change from a pyroxene- to amphibole-dominated magma source occurred in the Cajamarca region is unclear. A similar correlation between periods of prolific mineralisation and magmas derived from an amphibole-rich source has also been proposed for formation of Miocene deposits in Chile (Kay *et al*., 1991; Kay *et al*., 1999; Kay and Mpodozis, 2001).

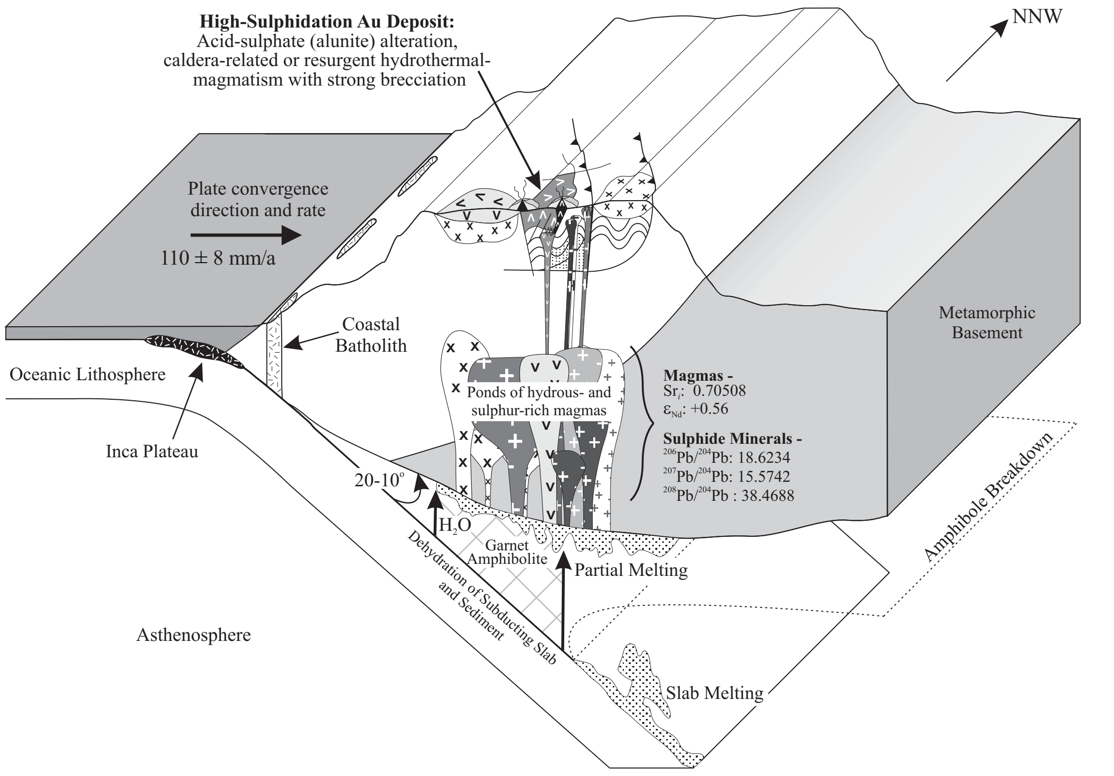
Commencement of high convergence rates in early Miocene times would have induced an E-W directed horizontal maximum principal stress on the magmatic arc. The lower crust would have been characterised by horizontal compression, whilst principal stress directions in the upper crust rotated between horizontal and vertical. Hydrous

Fig. 3. Schematic cross section through the northern Peruvian Andes illustrating the proposed tectonomagmatic model for Miocene deposits in the Cajamarca Au district. (A) Early-middle Miocene magmas developed beneath a thickening crust during the breakdown of amphibole-bearing mineral assemblages in the upper mantle. Deep level ponds of hydrous- and sulphur-rich magmas developed and were recharged by melts with primitive isotope compositions. Magmas ascended rapidly along deeply tapping faults, underwent minimal contamination and emplaced in a highly fractured upper crust. Host rock type, temperature and oxygen fugacity conditions during early potassic alteration, and presence of late-stage fluids strongly influenced the type (Au-rich vs. Cu-Au-Mo) of porphyry deposits formed. (B) Late Miocene high-sulphidation deposits formed during termination of crustal thickening and uplift, as well as the onset of a flattening of the subduction zone due subduction of the Inca plateau. Late Miocene magmas have slightly more evolved isotope compositions and modelling indicates higher garnet mineral residue content than the early Miocene magmas. Intriguingly though, ore pyrite from the Yanacocha deposit has less Pb isotope compositions than sulphides from early Miocene deposits. The high-sulphidation deposits all contain acid-sulphate alteration but show significantly different settings and mineralisation styles.

(A) Early-Mid Miocene Magmatism (23.2-16.5 Ma)



(B) Late Miocene Magmatism (12.5-10.9 Ma)



parental melts generated from partial melting of the amphibolite mantle ascended into deep levels of the thickening crust and formed large magma ponds (Fig. 3). Under compressional conditions, magmas would not easily migrate upwards and would have evolved at depth (Campos *et al*., 2002). Behn *et al*. (2001) suggest batholithic, deep crustal ponds of mafic to intermediate melts underlie metalliferous regions in Chile. Primitive isotopic compositions of some early Miocene magmas and late Miocene sulphides suggests these deep crustal ponds were replenished with newly generated oxidised melts that contributed significant amounts of magmatic water and sulphur. Or alternatively, primitive zones in an isotopically zoned pond or deep magma chamber were tapped during magma release. Water-rich primitive magmas were released from the ponds and ascended rapidly along deeply tapping faults during brief changes in the tectonic stress. Rapid ascent of the magmas minimised upper crustal contamination or mid-upper crustal ponding, thereby preventing potential loss of their Au and Cu content (c.f. Clark, 1993; Zentilli and Maksaev, 1995; Oyarzun *et al*., 2001). These uncontaminated magmas were emplaced in the hanging wall of the Puntre Thrust Fault (Fig. 3), commonly at structural intersections and during normal displacement along the fault plane.

Country rock type influenced the duration of solidification or development of an outer shell for the dioritic stocks. Highly fractured quartzite host rocks had a high permeability and metal-bearing hydrothermal fluids flowed both laterally and vertically. In contrast, contacts of carbonate rocks were marbleised thereby lowering permeability. Rocks with low permeability inhibit lateral fluid and heat flow thereby focussing metalliferous fluids within the intrusion and minimising metal loss into the host rock (Sillitoe, 2000b). Synmineralisation intrusions hosted in carbonates, such as Minas Conga (Au-Cu) and Minas Carpa (Au-Cu), have well-developed potassic alteration zones with high hydrothermal magnetite content. Bornite and chalcopyrite are the dominant sulphides associated with main stage mineralisation at these Au-rich deposits. These features suggest both high temperature and oxygen fugacity conditions during mineralisation. This is consistent with recent analytical and experimental data on Au-rich porphyry deposits (Kesler *et al*., 2002). In contrast, Cu-Au-Mo deposits (e.g. El Galeno and Michiquillay) are mainly hosted in quartzite rocks and have relatively magnetite-poor potassic alteration zones. Pyrite, chalcopyrite and molybdenite dominate hypogene mineralisation at these deposits. The deposits also contain well-developed phyllic alteration zones that are noticeably absent from the Au-rich deposits.

High-sulphidation deposits, such as Yanacocha (12-10 Ma) and Sipán (Miocene), are hosted by andesitic to dacitic rocks and exhibit intense acid-sulphate alteration (Fig. 3; Turner, 1999). Formation of these deposits was temporally linked to the cessation of uplift, crustal thickening and subduction of the Inca Plateau (Noble *et al*., 1979; Gutscher *et al*., 1999). Uplift and thickening caused lowering of the crust-mantle boundary to present day depths, i.e. ~45 km for northern Peru (Fukao *et al*., 1989), resulting in a significant change of the mantle mineralogy from amphibole+clinopyroxene to amphibole + clinopyroxene + garnet (Fig. 3). The onset of flat subduction, possibly due to subduction of the Inca plateau (12-10 Ma, Gutscher *et al*., 1999), also coincided with formation of the epithermal systems. An association between crustal thickening, shallowing of the subduction angle and changes in the residual mineral assemblage has also been suggested for formation of the El Indio and Los Bronce-El Teniente districts in Chile (Skewes and Stern, 1994; Kay *et al*., 1999).

E.9 Conclusion

In contrast to central Andean Miocene deposits, no extraordinary tectonic changes or features, such as slab rupture (Sasso and Clark, 1998) or change in slab inclination (Kay *et al*., 1999), are directly linked to the formation of the Miocene porphyry-related deposits in the Cajamarca region. Instead, these deposits formed due to a combination of rapid plate convergence, partial melting of a deep source containing amphibole – clinopyroxene ± garnet, short residence time in the deep crustal magma ponds that were recharged by newly generated oxidised melts, and rapid ascent of uncontaminated hydrous magmas along deeply tapping faults. Hypogene mineralisation at these deposits was strongly influenced by temperature and oxygen fugacity conditions during early potassic alteration.

Late Miocene epithermal deposits in the Cajamarca region share similar tectonic and magmatic histories to central Andean deposits. Formation of the high-sulphidation deposits occurred during periods of the cessation of crustal thickening and uplift, which was possibly related to increased garnet in the magma source. These features appear to be temporally linked to shallowing the slab angle and subduction of an oceanic plateau.