# SECTION B

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Structural evolution of the Cajamarca region, northern Peru: Implications for development of mineralised centres

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## B.1 Abstract

The oldest structural features identified in the Cajamarca region of northern Peru are a series of low-angle thrust faults and near E-W trending folds in Cretaceous sedimentary rocks. The dominant faults in the deformed sedimentary rocks are NE-trending and likely to have developed contemporaneously with the early fold-thrust phase. A series of subvertical Miocene(?) normal faults are superimposed on these older structures. These range from NE- to NW-trending, plus minor near E-trending. Early to middle Miocene intrusive rocks are mostly located in the hanging wall of a regional-scale thrust and are spatially associated with secondary oblique structures. Structural investigations at mineralised porphyry systems reveal that the deposits are typically characterised by NNW fault-fracture trends and subordinate NE-trending structures. Two of the porphyry Cu complexes, Minas Conga and Michiquillay, contain N to NNW deposit-controlling fault-vein arrays that were influenced by tectonic stress. In contrast, the third mineralised porphyry, El Galeno, has both magmatic- and tectonic-controlled fracture arrays. NW deposit-controlling faults and an overall NE district trend characterise the late Miocene Yanacocha high-sulphidation Au district. NE-trending faults throughout the region display dextral movement, whereas NW faults have sinistral displacement. Both of these fault trends also show evidence of late vertical displacement.

Structural investigations in the Cajamarca region suggest the location and formation of Miocene mineralised centres resulted from younger tectonic events superimposed on pre-existing structures. Fault and fracture trends in the region display a counterclockwise rotation in orientation with time, i.e. NE-trending structures in older units compared to NW-trending in the younger units. These changes in fault orientation are temporally linked with clockwise rotation of the Nazca plate. Cretaceous sedimentary rocks preserve a dominant NE fault-fracture trend that formed during NNE-directed oblique plate convergence along the western margin of the South American plate. A near orthogonal plate convergence direction predominated

throughout the Miocene, during which N- to NW-striking faults formed. These oblique to orthogonal fault trends superposed on pre-existing regional structures significantly influenced the emplacement of diorite stocks. Early- to middle Miocene porphyry Cu centres contain N- to NNW deposit-controlling faults, whereas the late Miocene high-sulphidation deposit was controlled by NW- and E-W striking faults. Faults at these Miocene mineralised centres display both horizontal and vertical displacement. This suggests rotation of the principal stress direction occurred during formation of these deposits. Changes in the principal stress direction and observed NW to NE conjugate trends at mineralised Miocene centres provided important dilatant channelways for ascending hydrothermal fluids.

## B.2 Introduction

Porphyry Cu deposits are commonly spatially associated with regional structures or lineaments (Tosdal and Richards, 2001). The orientation and timing of activation or reactivation of these structures is largely controlled by major tectonic events and can significantly influence mineralisation at a deposit (Sibson, 2001). Fault-fracture networks focus ascending magmatic and hydrothermal fluids at porphyry Cu deposits, as well as preserving important information on structural controls of these deposits and regional stress fields. Previous studies and discussions on structural controls at porphyry Cu deposits and districts include work by Gustafson and Hunt (1975), Titley and Heidrick (1978), Heidrick and Titley (1982), Titley *et al*. (1986), Lindsay *et al*. (1995) Richards *et al*. (2001) and Chernicoff *et al*. (2002).

The Cajamarca mining district in northern Peru (Fig. 1a) is characterised by deformed marine Cretaceous sedimentary rocks that have been intruded and overlain by Tertiary porphyritic intrusive and volcanic units. Based on lineaments observed from satellite images, Quiroz (1997) proposed that mineralised systems in the region are restricted to a NE-trending feature, termed the Chicama-Yanacocha structural corridor (Fig. 1a). This incorporates the southern part of the Huancabamba Deflection zone and the world-class Yanacocha epithermal Au deposits. Several mineralised intrusive-related deposits such as Minas Conga (Au-Cu), Michiquillay (Cu-Au) and El Galeno (Cu-Au-Mo) are also located within this corridor (Fig. 1b). Previous regional geological

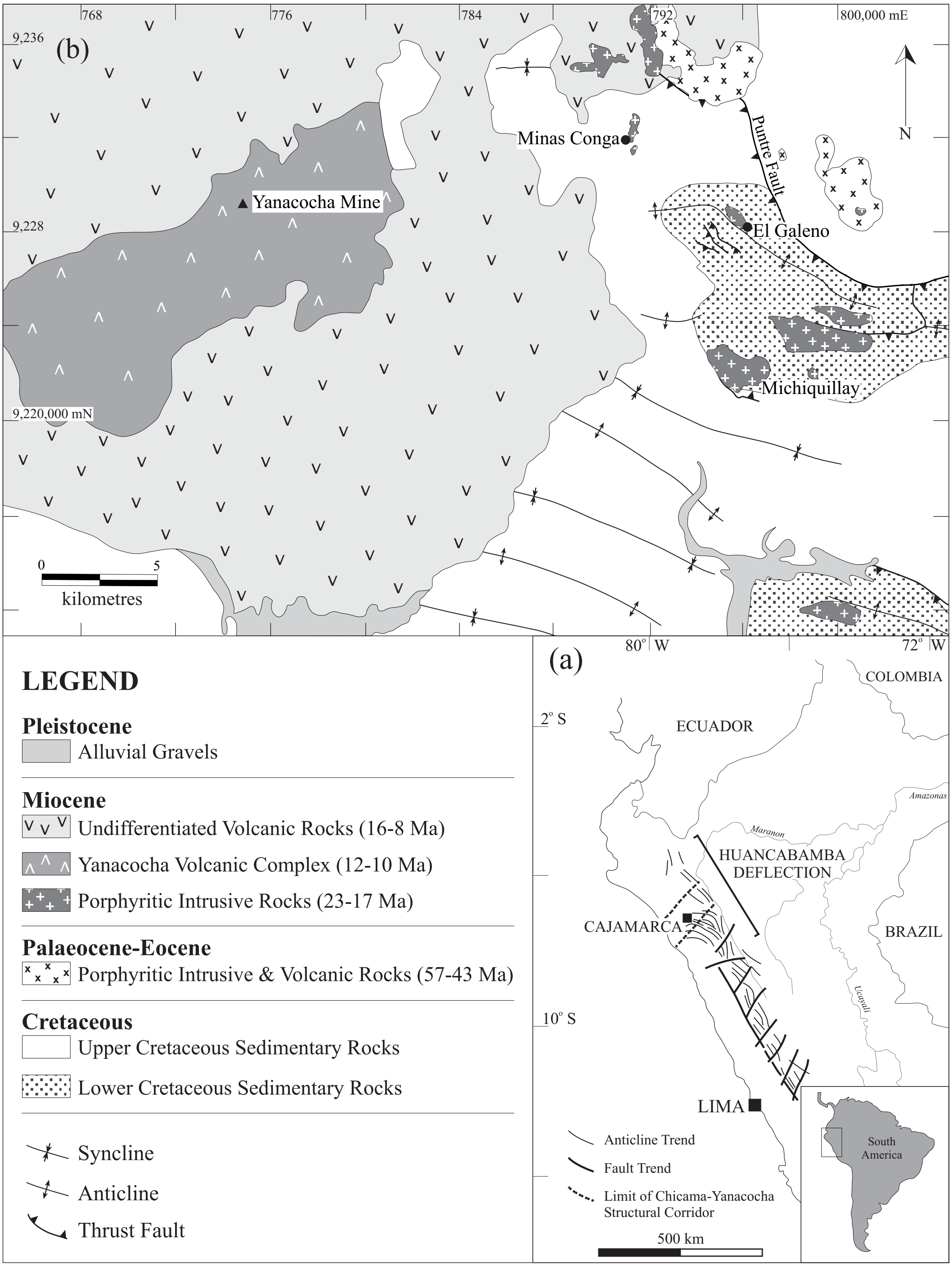



Fig. 1. (a) The Cajamarca district, located in southern part of Huancabamba deflection of northern Peru (modified from Benavides, 1999). (b) The district consists of deformed Cretaceous sediment intruded and unconformably overlaid by Tertiary igneous rocks (modified from Reyes, 1980).

mapping of the Cajamarca district (Reyes, 1980; Wilson, 1985a, 1985b; Bellier *et al*., 1989; Quiroz, 1997) and detailed geological studies at various mineralised centres (Hollister and Sirvas, 1974; Macfarlane and Petersen, 1990; Llosa *et al*., 1996; Turner, 1997; James, 1998; Longo, 2000), combined with palaeomagnetic studies (Laj *et al*., 1989: Mitourad *et al*., 1992) define a complex and protracted tectonic, magmatic, hydrothermal and mineralisation history.

The structural framework of the Cajamarca district during Tertiary times, especially with regards to formation of mineralised complexes is poorly understood. This section presents new fault and fracture data for the deformed Cretaceous sedimentary rocks and Miocene mineralised intrusive centres in the Cajamarca mining district. Structural data were compiled from field mapping, aerial photo interpretation and combined with previously unpublished and published material (MMA, 1975; Longo, 2000; Llosa and Veliz, 2000). A model for the structural evolution of the region, with emphasis on regional influences for formation of Miocene mineralised complexes, is also presented.

## B.3 Tectonic Framework of Northern Peru

The Cajamarca mining district is located in the northern Peruvian Andes at altitudes from 2700m to 4300m where the Huancabamba Deflection marks a significant change in the structural grain from the dominant NW Andean trend to near E-W (Fig. 1a). Cretaceous marine and non-marine sedimentary rocks in northern Peru were deposited in the Western Peruvian Trough (WPT) in a Mariana-type subduction regime (Mégard, 1984). The WPT became the Western Cordillera after later folding and subsequent uplift. From early Tertiary time, a change to Andean-type subduction was marked by repeated episodes of compression, intense magmatism, crustal thickening and uplift (Benavides, 1999; Fig. 2).

### *B.3.1 Cretaceous History*

During late Triassic to late Cretaceous times, northern Peru was the depositional site of a major marine sequence and characterised by an extensional regime that caused crustal attenuation or Mariana-type subduction (Benavides, 1999). The

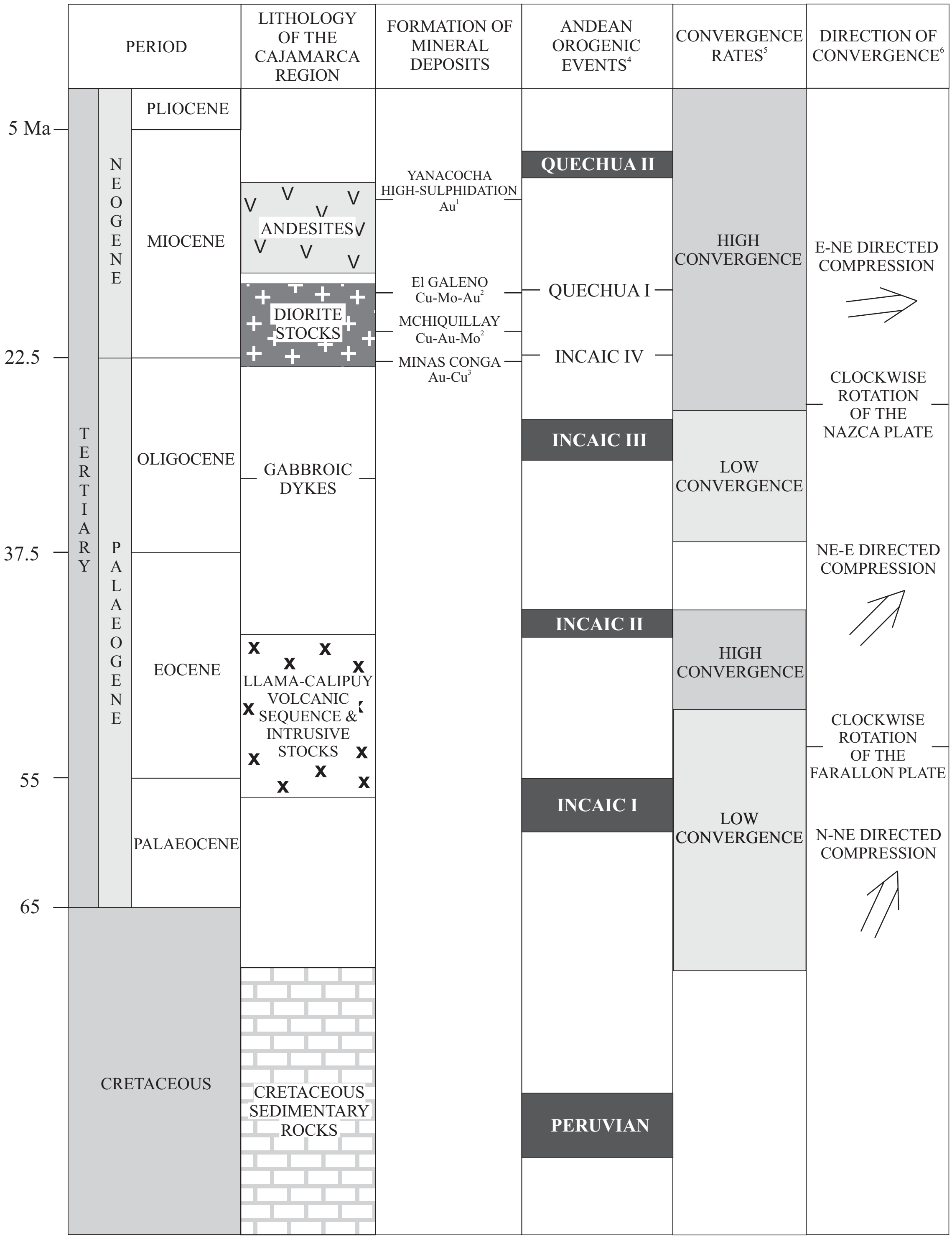



Fig. 2. Tectonic framework of the northern Peruvian Andes and the Cajamarca district. [1] Turner (1997), [2] Section A, [3] Llosa *et al*., (1996), [4] Megard (1984), [5] Pardo-Casas and Molnar (1987), [6] Pilger (1984).

oldest rocks in the Cajamarca region are Lower Cretaceous quartzite, siltstone and shale units (Benavides, 1956). These are overlain by an Upper Cretaceous shallow water marine marl – limestone sequence. Between 90 and 55 Ma, northern Peru underwent a period of weak deformation that was associated with a significant decrease in subsidence rates and resulted in the development of disconformities (Jaillard and Soler, 1996). The first widespread deformation phase observed in Peru is the Peruvian Orogeny that led to the emergence of both the WPT and Eastern Peruvian Trough (Mégard, 1984). In the WPT, this late Cretaceous orogenic event resulted in the emergence of the marine sedimentary rocks, continental red-beds were deposited and initial development of the Western Cordillera occurred. Pardo-Casas and Molnar (1987) suggest a slow plate convergence rate (55 ± 28 mm/a) between the Farallon and South American plates occurred from 70 to 50 Ma.

### *B.3.2 Tertiary History*

Andean-type subduction has occurred along the western margin of the South American plate from the end of the Cretaceous period to the present day. Intense fold and thrust development in the Cretaceous sedimentary rocks is the oldest evidence for Andean-type subduction in the Cajamarca region. This compressional event is known as Incaic I orogenic pulse (Noble *et al*., 1985) and occurred from 59 to 55 Ma. The Llama-Calipuy Volcanic Sequence (54-43 Ma) unconformably overlies the folded Incaic I deformed sedimentary rocks (Noble *et al*., 1985). It is comprised of subaerial basaltic to rhyolitic rocks, but dominated by basalts and andesites. Atherton *et al*. (1985) observed that the Llama-Calipuy volcanic rocks are the most voluminous and characteristic Andean volcanic association. Several intrusive rocks were emplaced contemporaneously with these volcanic rocks (57-43 Ma, Llosa *et al*., 1996; Section A). Peak Eocene magmatism roughly coincided with the first of two major periods of rapid plate convergence (Section A). This occurred between 49.5 and 42.0 Ma at an estimated rate of 154 ± 58 mm/a and corresponded with a clockwise rotation of the subducting Farallon Plate in the northern Andes (Pilger, 1984; Pardo-Casas and Molnar, 1987). Soler and Bonhomme (1990) proposed that a decrease in the dip of the subducting slab resulted in arching, uplift, extension and volcanism in the overriding plate.

The cessation of both rapid plate convergence and deposition of the Llama-Calipuy Volcanic Sequence was marked by the second deformation phase, known as the

Incaic II phase, from 43 to 42 Ma (Benavides, 1999). Folds that developed during the Incaic orogenic events are generally upright, gentle to open, and within the Huancabamba Deflection plunge WNW or ESE. Thrust faults that developed during the same orogenic pulses generally dip SSW. Structures produced during the Incaic phases suggest NE-SW directed compression (Wilson, 2000). Some authors (Benavides, 1999; Mitourad *et al*., 1990; Kissel *et al*., 1992) have suggested that the Cajamarca structural bend and the N-S compression in the Cajamarca region resulted from counterclockwise rotation block movement and oblique convergence. Another characteristic of the Incaic Belt is a series of strike-slip faults trending NE or E-W, with significant vertical and lateral movements that are probably related to basement tectonics (Vidal and Noble, 1994). During Oligocene times (36-24 Ma), the convergence rate decreased to 50 ± 30 mm/a (Pardo-Casas and Molnar, 1987) and there was apparently a lull in magmatic activity in northern Peru. Since late Oligocene times the Peruvian Andes have been subjected to compressional tectonics with shortening occurring in the lowlands and extension restricted to high topographical regions in the Andes (Sebrier and Soler, 1991).

The second phase of rapid convergence (110 ± 8 mm/a) identified by Pardo-Casas and Molnar (1987) occurred from 26 Ma onwards, with possibly higher convergence rates between 20 and 10 Ma. Pardo-Casas and Molnar (1987) suggested rapid convergence coincided with the break-up of the Farallon plate (into the Nazca and Cocos plates) and a clockwise rotation of the subducting plates. Furthermore, Mitourad *et al*. (1992) proposed that the Peruvian margin underwent late Oligocene to early Miocene counterclockwise rotation of the order of 20$^{o}$. Renewed magmatic arc activity following the Incaic IV (22 Ma) orogenic pulse involved emplacement of intermediate, calc-alkaline intrusive stocks and development of mineralised porphyry centres (Llosa *et al*., 1996; Section A). The compressive Quechua I (17 Ma) pulse and extinction of the Pacific-Farallon spreading centre (~18 Ma) appears to have marked the end of this magmatic episode within the Cajamarca region (Benavides, 1999). After the Quechua I pulse, intra-cordillera graben basins developed in the highlands in response to gravitational extension (Benavides, 1999).

North of Cajamarca, major magmatic-hydrothermal activity occurred in the Hualgayoc district between 14 and 10 Ma (Macfarlane *et al*., 1994; James, 1998).

Deposition of andesitic lava flows near Yanacocha represents the initiation of middle- to late Miocene magmatic activity (12.3 Ma, Turner, 1997). Main stage alteration at Yanacocha took place at *ca*. 11 Ma (Turner, 1997), which roughly corresponds to termination of major uplift in the Peruvian Andes (Noble *et al*., 1990). The last magmatic activity in the Cajamarca region involved deposition of rhyodacite tuffs (8 Ma, Turner, 1997) and coincided with the Quechua II orogenic pulse (8-7 Ma) proposed by Mégard (1984). South of Cajamarca, Bellier *et al*. (1989) identified a series of late Miocene to Quaternary extensional and compressional events that were interpreted to reflect changes in the subduction angle.

## B.4 Structural Observations

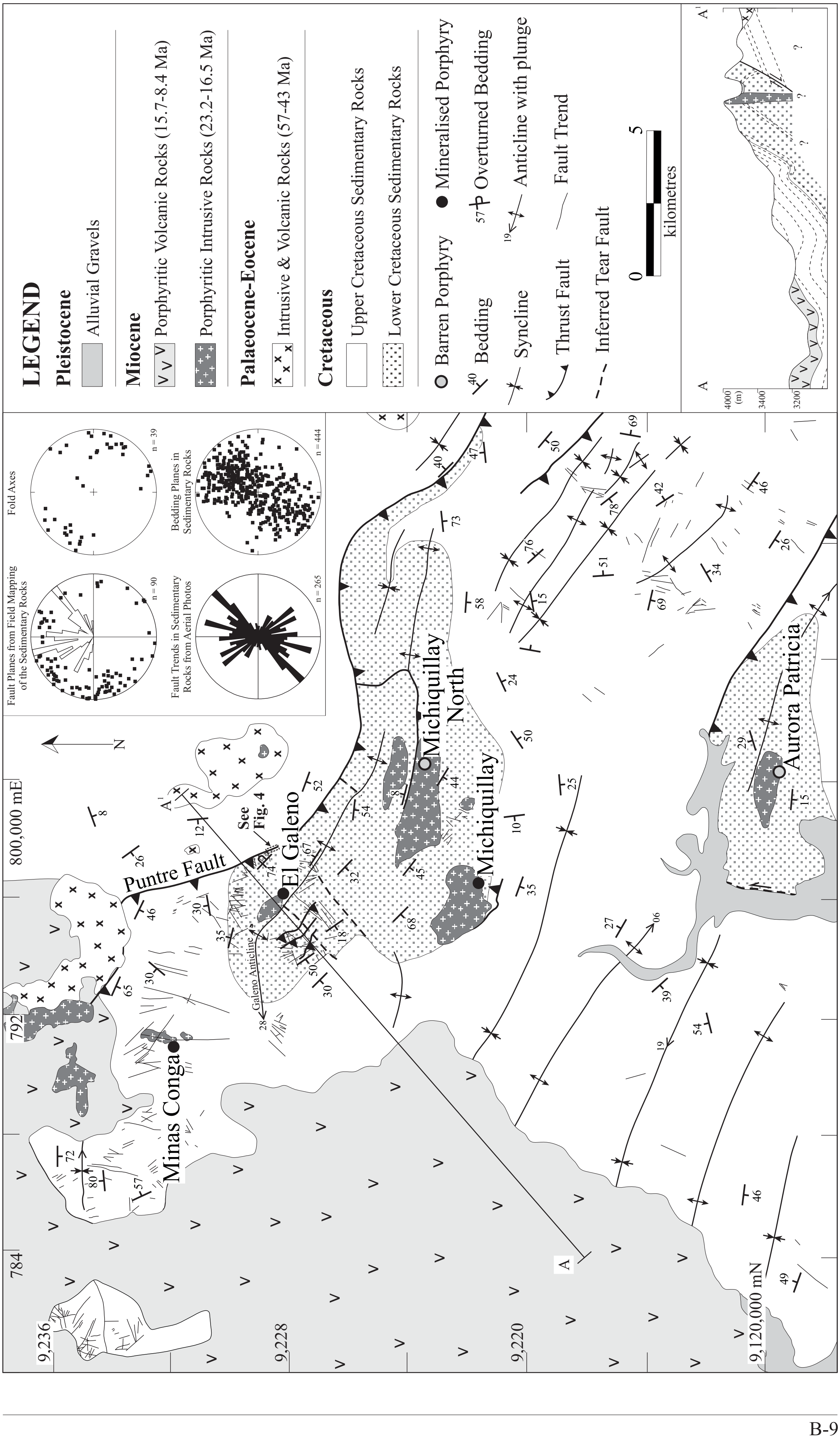
The regional structural analysis of the Cajamarca district presented in this section has been compiled from field mapping, aerial photo interpretation and previously unpublished studies from other sources. The data include fault, fracture and joint orientations observed in a variety of lithological units that range in age from Upper Cretaceous to late Miocene. The data are presented in three main sections that relate to the age of the lithological units in which structural features were observed. These include the Cretaceous sedimentary rocks, early- to middle Miocene mineralised intrusions and late Miocene volcanic rocks.

### *B.4.1 Cretaceous Sedimentary Rocks*

Structural mapping of the deformed Cretaceous sedimentary rocks involved field mapping and aerial photograph interpretation. Analysis of the sedimentary rocks covered an area of ~1250 km$^2$ (Fig. 3). In general, these are characterised by small-scale extensional faults superposed on a regional-scale fold and thrust fabric. Bedding planes throughout the area have an average orientation of near NW-SE (23$^o$→213$^o$; Fig. 3).

*Puntre Thrust Fault*: The Puntre Thrust Fault is defined by Lower Cretaceous quartzites in the hanging wall juxtaposed against Middle-Upper Cretaceous limestones indicating several hundred metres of reverse offset. In the study area, the fault changes from near E-W trending and shallowly-dipping to NW-trending and steeply-dipping

Fig. 3. Structural map and cross section of the northeastern Cajamarca district displaying the major structural features in the deformed Cretaceous sedimentary rocks. Insert: Stereoplots and rose diagrams of folds, faults and bedding planes from field mapping. Fault trends picked from aerial photos have also been plotted.



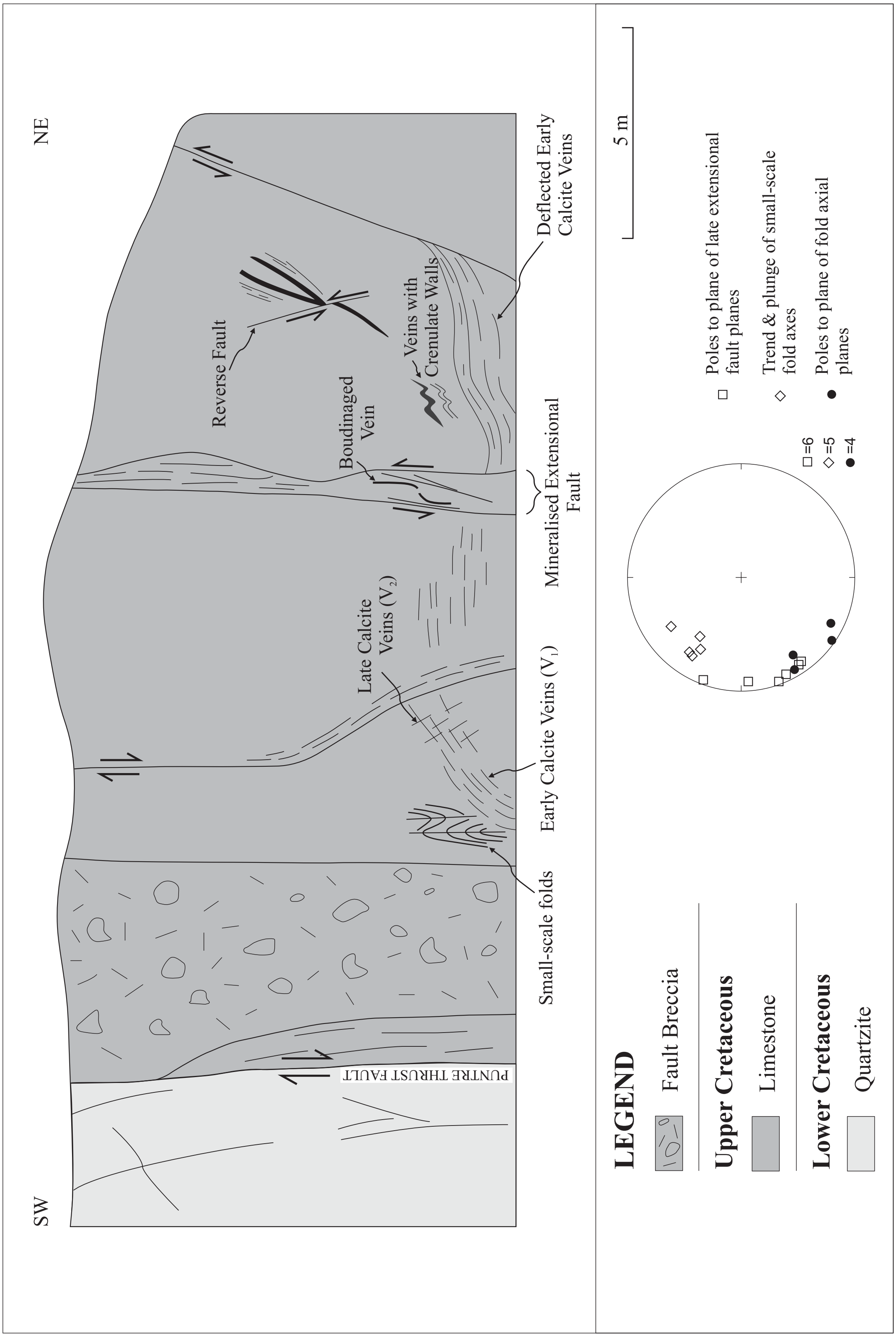
LEGEND
Pleistocene
Alluvial Gravels
Miocene
Porphyritic Volcanic Rocks (15.7-8.4 Ma)
Porphyritic Intrusive Rocks (23.2-16.5 Ma)
Palaeocene-Eocene
Intrusive & Volcanic Rocks (57-43 Ma)
Cretaceous
Upper Cretaceous Sedimentary Rocks
Lower Cretaceous Sedimentary Rocks
Barren Porphyry
Mineralised Porphyry
Bedding
Overturned Bedding
Syncline
Anticline with plunge
Thrust Fault
Fault Trend
Inferred Tear Fault
0
5
kilometres
Fault Planes from Field Mapping of the Sedimentary Rocks
n = 90
Fold Axes
n = 39
Fault Trends in Sedimentary Rocks from Aerial Photos
n = 265
Bedding Planes in Sedimentary Rocks
n = 444
N
800,000 mE
784
792
9,236
9,228
9,220
9,120,000 mN
Puntre Fault
El Galeno
See Fig. 4
Galeno Anticline
Minas Conga
Michiquillay North
Michiquillay
Aurora Patricia
A
A'
4000 (m)
3400
3200

(Section D.5.2). To the northeast of El Galeno, argillic altered limestones situated within the NW-trending zone of the thrust display polyphase deformation (Fig. 4). The earliest structures observed in the altered limestone are small-scale folds (50 cm amplitude) that dominantly have fold axes at $23^{o} \rightarrow 304^{o}$ and subvertical axial planes (Fig. 4). Early planar veins with calcite infill ($V_1$) have a general orientation of $30^{o} \rightarrow 268^{o}$. However, some minor veins have crenulate vein walls. These early structures are crosscut by subvertical normal faults that displace and disrupt early $V_1$ veins (Fig. 4). The fault planes have an average strike of 342$^{o}$ and dip steeply (83$^{o}$) to the east. Steeply-dipping calcite veins ($V_2$) crosscut the early flat lying $V_1$ veins. Weak pyrite mineralisation was observed in the fault breccia matrix of the extensional faults.

*Folds*: Regional-scale folds are upright and have a wavelength >5 km (Fig. 3). Quartzite units commonly define hanging wall anticlines (Fig. 3) due to detachment occurring along competency boundaries, such as between quartzite and limestone units. Fold axes display a dominant ESE-WNW orientation with modes near $16^{o} \rightarrow 115^{o}$ and $19^{o} \rightarrow 295^{o}$ (Fig. 3). Some large-scale folds in the southern sector of the study area have a moderate plunge (>40$^{o}$) to the SW. Minor, small-scale folds (wavelengths of a few metres) that have NE and SE trends were also observed. The abundance of these folds is low and possibly represents different stress fields on a localised scale.

*Normal Faults*: Faults in the Cretaceous sedimentary rocks are mostly subvertical and contain cataclastic rocks with oxidised breccia textures. The majority display normal displacement ranging from a few, to tens of metres. A stereoplot (Fig. 3) indicates these subvertical faults have three dominate orientations, namely, (a) 175/77E, (b) 045/78SE and (c) 109/71S. Faults identified during aerial photo analysis over an area of ~1250 km$^2$ were mostly within deformed Cretaceous sedimentary units (Davies, 2000). The faults range from NE- to NW-striking, have an average strike of between 010$^{o}$-015$^{o}$ and a mode of 040$^{o}$-045$^{o}$. The ages of the majority of faults identified in the field and aerial photo analysis are poorly constrained due to a lack of crosscutting relationships.

Fig. 4. Outcrop sketch of deformed limestone and quartzite rocks located in the Puntre Thrust Fault to the NE of El Galeno. In the limestones, flat calcite veins (V1) and upright small-scale folds are crosscut by steeply dipping calcite veins (V2) and normal faults that contain minor pyrite mineralisation.


SW
NE
PUNTRE THRUST FAULT
Small-scale folds
Early Calcite Veins ($V_1$)
Late Calcite Veins ($V_2$)
Mineralised Extensional Fault
Boudinaged Vein
Reverse Fault
Veins with Crenulate Walls
Deflected Early Calcite Veins
5 m
LEGEND
Fault Breccia
Upper Cretaceous
Limestone
Lower Cretaceous
Quartzite
□ =6
◇ =5
● =4
Poles to plane of late extensional fault planes
Trend & plunge of small-scale fold axes
Poles to plane of fold axial planes

### *B.4.2 Cretaceous Sedimentary Rocks Summary*

Thrust faults have near E-W trends and contain hanging wall anticlines with similar orientations. Regional-scale folds also have a near E-W trend that suggests fold and thrust structures developed contemporaneously. The geometries of both folds and thrusts suggest the structures developed during subhorizontal, N-NE directed compression. This is consistent with early NNE-SSW compression during the Eocene fold-thrust event (Incaic I) proposed by Wilson (2000). It is inferred that initial development of regional-scale folds and thrusts occurred during the same compressional event.

The deformed Cretaceous basement rocks are intruded and overlain by Tertiary diorite stocks and andesite volcanic rocks. The oldest magmatic rock dated in the Cajamarca region was emplaced *ca*. 57 Ma (Section A). Recent $^{40}Ar/^{39}Ar$ age data indicate major Eocene magmatism in the region ceased *ca*. 42.5 Ma (Section A). This age also possibly marks the end of the Palaeogene fold-thrust events in the region.

## *B.5. Early Miocene Mineralised Centres*

Early to middle Miocene magmatism (23.2 to 16.5 Ma) produced a number of barren and mineralised diorite intrusive rocks with steep contacts (Llosa *et al*., 1996; Section A), as well as the upper Llama Formation volcanic rocks (15.8 Ma; Turner, 1997). The Minas Conga, El Galeno and Michiquillay porphyry systems have related Cu-Au-Mo mineralisation. Fault, fracture and/or vein data from these mineralised systems are presented and used to help determine stress conditions that prevailed during this 7 m.y. interval. Field mapping was conducted at El Galeno, whilst previous mapping at the Minas Conga by Llosa and Veliz (2000) and Michiquillay by the Metal Mining Agency (MMA) plus Japan International Cooperation Agency (1975) is presented in combination with structural features observed from the both aerial photo analyses and field mapping.

### *B.5.1 El Galeno*

El Galeno is a Cu-Au-Mo porphyry centre hosted in multiple diorite stocks (Cordova and Hoyos, 2000; Section D.5). In outcrop, the main porphyry body is approximately 1.25 km by 0.6 km, oval in shape and has a general NW trend (Fig. 5). The diorite porphyry complex is hosted within folded Lower Cretaceous sedimentary rocks and was emplaced in the NW-trending El Galeno Anticline (Fig. 5). The porphyry stock is located at the intersection of the El Galeno Anticline and a NE-striking tear fault, which displays an overall dextral shear sense. Local folds and faults are inferred to have controlled localisation of the porphyry complex (Section D.5.2). Emplacement, alteration and mineralisation of the porphyry complex occurred between 17.5 and 16.5 Ma (Section A).

Southwest of the mineralised complex, several gabbroic dykes have intruded fault and bedding planes in the quartzite units (Fig. 5). The dykes intruded the deformed quartzite units prior to emplacement of the El Galeno porphyry system (29.4 Ma; Section A). The dykes are commonly located along fault planes that are subvertical and NNW- to N -trending. One of the dykes contains a series of cooling joints that are mostly subvertical (~80$^{o}$) and have a dominant trend of 028/80E with a subordinate 120/83NE to 150/84NE trend (Fig. 5). The average orientation of the cooling joints (010/81E) is oblique to the geometry of the host fault plane (167/80W).

Fracture orientations in the El Galeno intrusive complex were measured to assess the degree of magmatic versus tectonic stress during cooling and solidification of the complex. The fractures offset early quartz veins and in turn are crosscut by later quartz veins. Some fracture planes also display post-alteration movement with steep slickenlines, thereby indicating fractures were active both during and following alteration. A stereoplot (Fig. 5) shows the fractures display a large amount of scatter with orientations ranging from E- to WNW-striking and dip varying from subhorizontal to subvertical. The average orientation of the fractures in the intrusive complex is approximately 003/57E. Overall, fractures display a random orientation across the entire intrusive complex and no spatial trends were observed. However, a rose plot of the fracture data suggests three common fracture trends, which include 045$^{o}$-055$^{o}$, 170$^{o}$-140$^{o}$ and 115$^{o}$-105$^{o}$.

In the southwestern part of the intrusive complex, crosscutting fracture sets were observed in the upper part of the exposed P1 intrusion (Fig. 6). The earliest fracture set ($F_1$) has strongly oxidised planes that are planar to slightly undulose. These fractures are

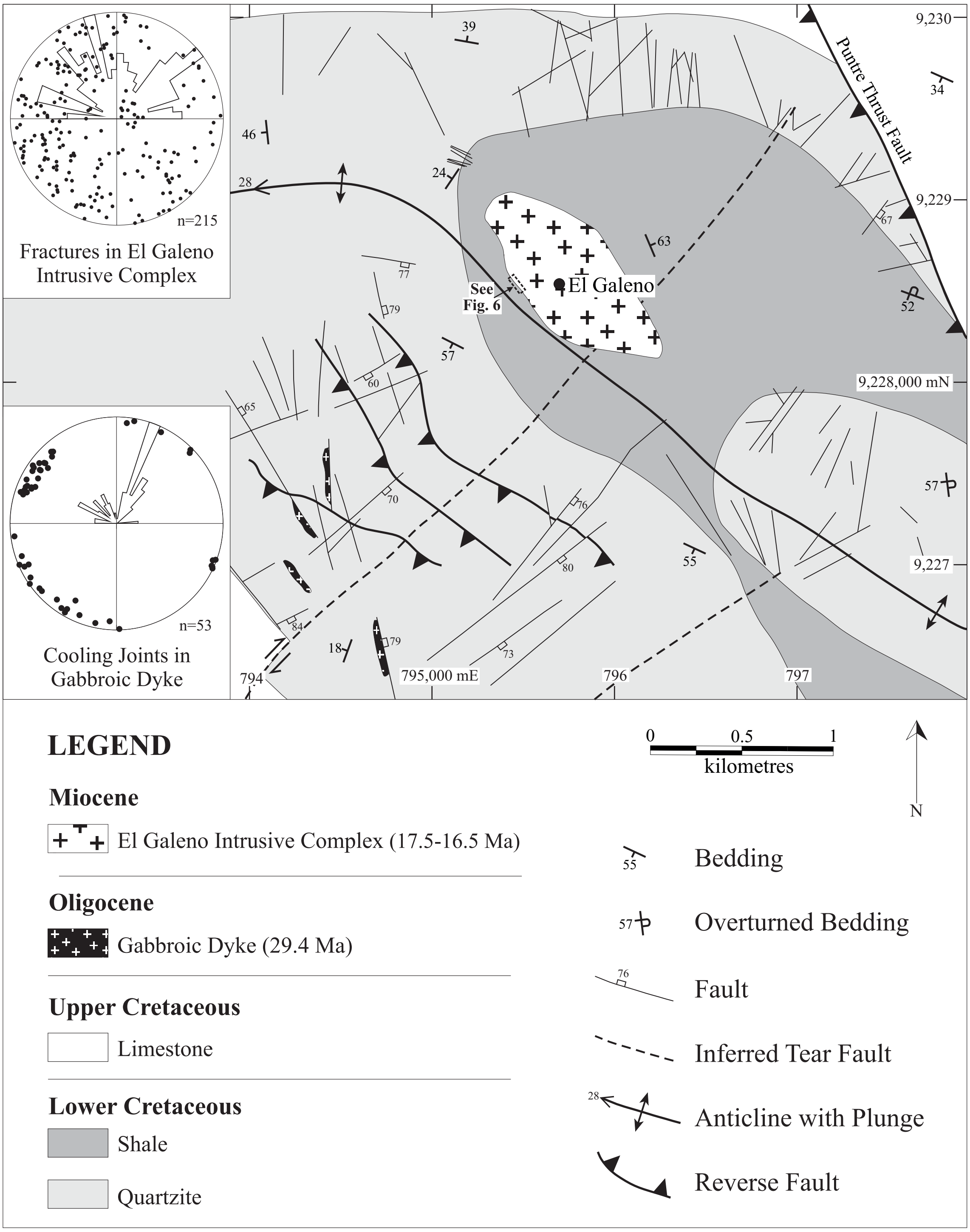



Fig. 5. Structural geology of the El Galeno prospect. Stereoplots and top-half rose diagrams of the subvertical cooling joints in Oligocene dykes display a dominant N-NE trends, whereas fractures in the Miocene El Galeno intrusive complex have a random orientation. However, the most common fractures have NE and NNW-NW trends.

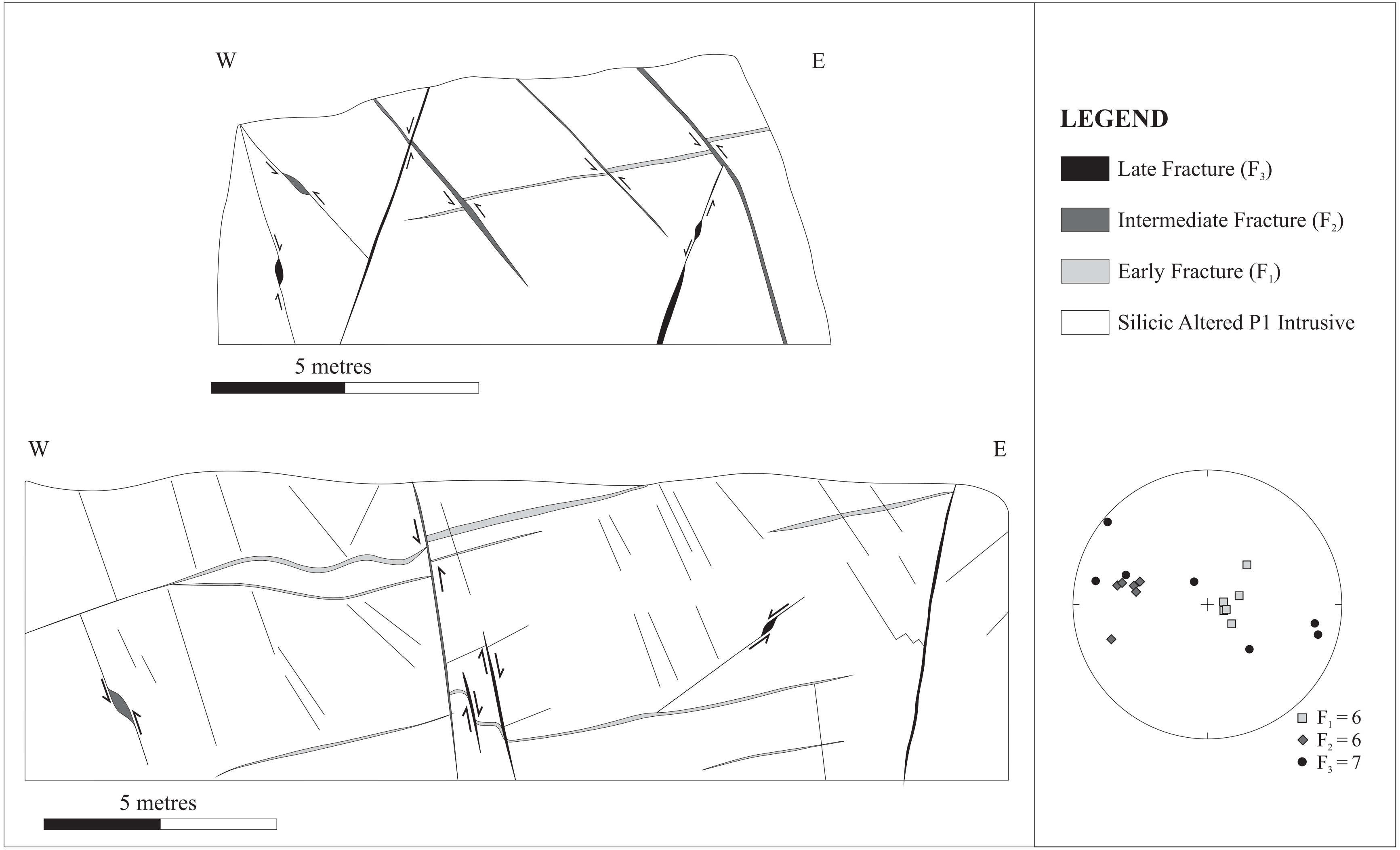



Fig. 6. Fracture patterns in the southwestern part of the El Galeno intrusive complex (location shown in Fig. 5). Early flat fractures ($F_1$) are crosscut by steep $F_2$ fractures that have a reverse movement. Steep extensional $F_3$ fractures postdate both of these

flat-lying and have a predominant N-S strike (174/15W). The flat-lying fractures are crosscut by a second set ($F_2$) of near N-striking, moderate-dipping planar fractures (008/51E) that display reverse displacement. $F_2$ fractures contain both strong oxidisation and clay alteration along the planes. The third fracture set ($F_3$) crosscuts both of these, has a NNE strike and is moderately- to steeply-dipping (022/65E). $F_3$ fractures are planar and also contain clay minerals. The wide range in fracture orientations and crosscutting relationships observed at El Galeno are typically of porphyry copper deposits characterised by multiple phases of intrusive and hydrothermal activity (Tosdal and Richards, 2001).

### *B.5.2 Michiquillay*

Michiquillay is a diorite Cu-Au-Mo porphyry system and was previously mapped by Metal Mining Agency (MMA, 1975). The intrusive complex is elongate, ~5 km in length by 1.5 km wide, and roughly parallel to the local NW structural trend (Fig. 7). Intrusions were emplaced in the hanging wall of a NW-trending back-thrust, the Michiquillay Fault, that dips moderately (~60$^{o}$) to the NE. Hollister and Sirvas (1974) suggest the Michiquillay complex is located the intersection of the Michiquillay and the NE-trending Encanada faults. Laughlin *et al*. (1968) used the K-Ar method to date biotite from a quartz-biotite monzonite at the Michiquillay prospect and obtained an age of 20.6 ± 0.6 Ma. Llosa *et al*. (1996) dated biotite from the Michiquillay prospect at 18.8 ± 1.6 Ma also using the K-Ar method. New $^{40}$Ar/$^{39}$Ar age dates indicate barren intrusions (20.6 ± 0.1 Ma) to the north of the Michiquillay region were emplaced slightly prior to the Michiquillay mineralised porphyry (19.8 ± 0.05 Ma; Section A).

Prospect-scale faults that crosscut the Michiquillay mineralised centre were previously mapped by MMA (1975) and were reviewed in this study. The faults dominantly occur toward the centre of the intrusive system and were recognised by an increased density of fractures toward the central part of the fault zones. Very few kinematic indicators were identified along fault planes, but where observed these displayed late steeply-plunging slickenlines (Fig. 16 in Section D). The prospect-scale faults have a dominant NNW-NW trend and a subordinate NNE-NE trend (Fig. 7). The faults have an average NNW strike and dip steeply to the E (167/79E). NNW-trending faults that crosscut both the Michiquillay Fault and mineralised intrusive complex have

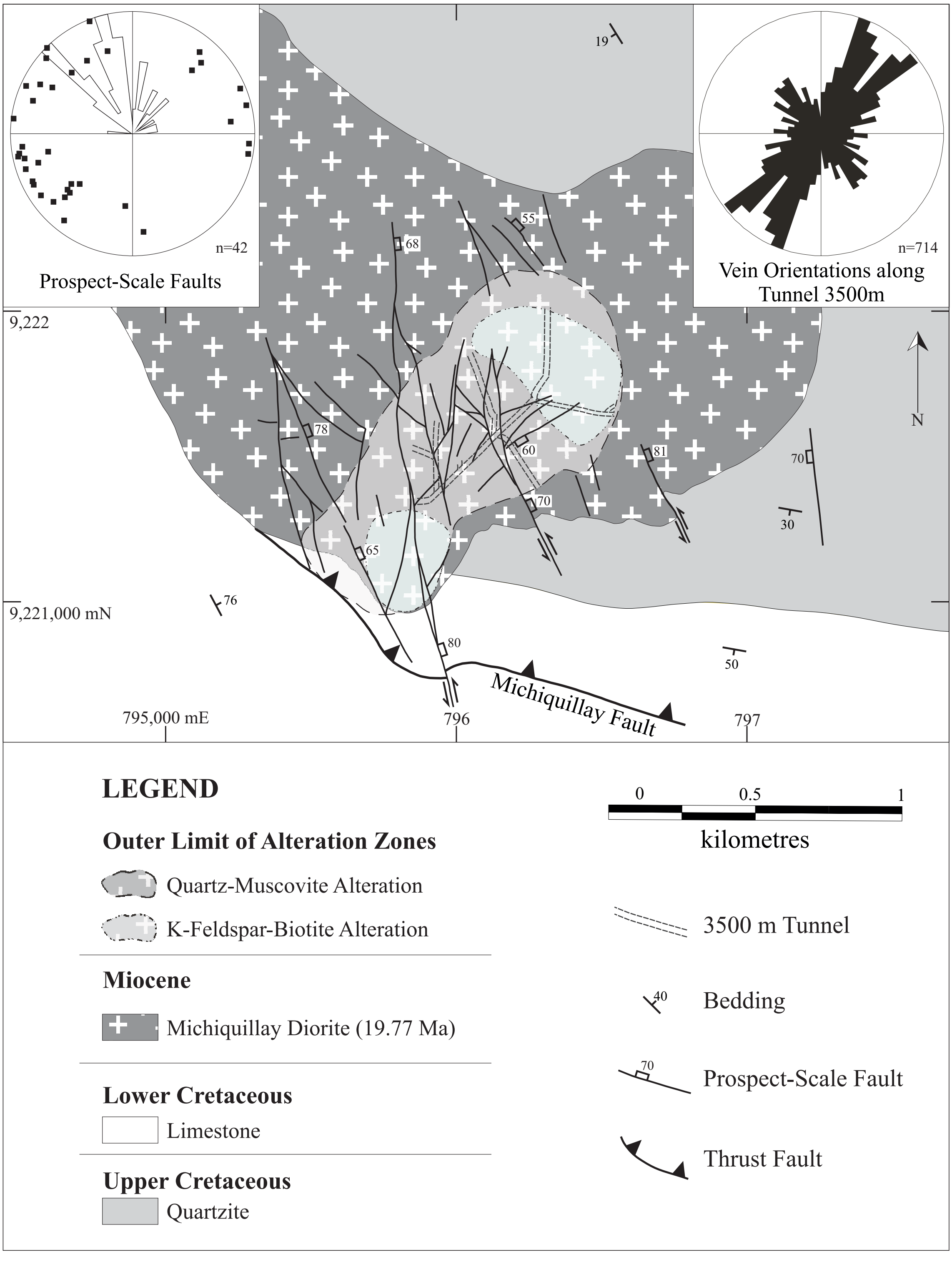



Fig. 7. Structural map of the Michiquillay prospect showing prospect-scale faults and the trend of the alteration zones (MMA, 1975). Top left insert, stereoplot illustrates the preferred NNW to NW trend of the subvertical prospect-scale faults. This is further highlighted by the top-half of a rose diagram. Top right, rose diagram showing veins have a dominant NE trend and a weak secondary NW trend. Note the oblique relationship of the vein and alteration trends compared to the prospect-scale fault trend.

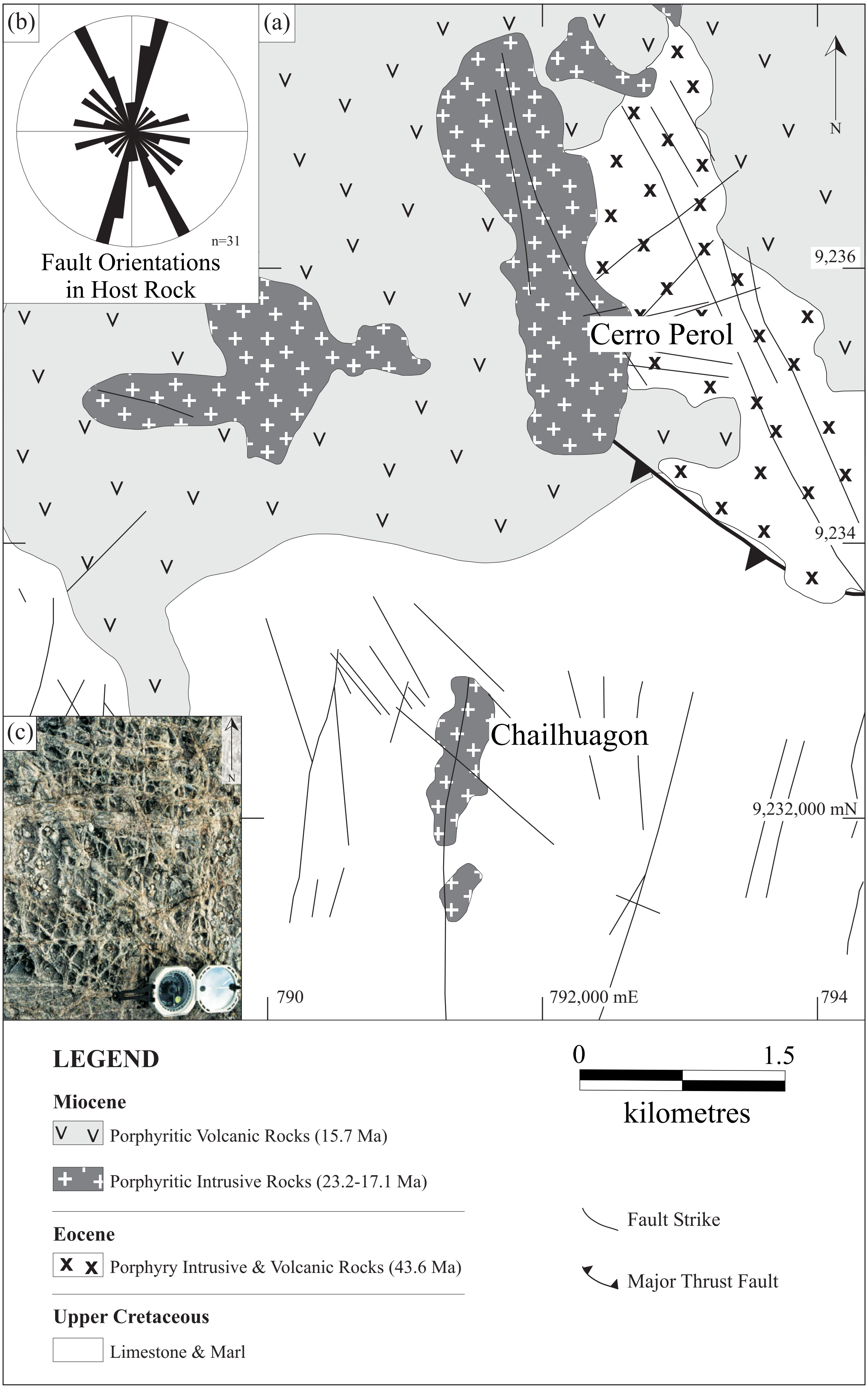
a sinistral displacement (Fig. 7). In outcrop and drill core, K-feldspar-biotite and quartz-muscovite alteration assemblages display a NE trend. Metal grades are spatially associated with these alteration zones (Section D.6.3). The prospect-scale faults define the outer limit of strong quartz-muscovite alteration and divide K-silicate alteration zones in the NE and SW of the system. It is inferred that the NNW-trending faults controlled the distribution of quartz-muscovite alteration and possibly mineralisation.

Vein trends along the presently abandoned Tunnel 3500 m have been compiled from previously data (MMA, 1975) with the objective to compare variations between vein and prospect-scale fault trends. The vein data incorporate measurements from the central quartz-muscovite and northern K-feldspar-biotite alteration zones. These data display a very strong $020^{o}$-$055^{o}$ trend and a subordinate trend of $150^{o}$-$140^{o}$ (Fig. 7). The veins have a dominant NE strike that is roughly parallel to the NE alteration trend, but oblique to near orthogonal with the major NNW-striking prospect-scale faults.

### *B.5.3 Minas Conga*

The Minas Conga (Au-Cu) prospect comprises two mineralised centres, known as Chailhuagon and Cerro Perol, with only the former being discussed in this paper. Previous mapping by Llosa *et al*. (1996) and Llosa and Veliz (2000) has defined the elongate Chailhuagon porphyry as a microdiorite stock that in plan is oriented N-S and 2 km long by 0.5 km wide (Fig. 8a). K-Ar age dating of hornblende from the Chailhuagon main intrusive body yielded an age of 23.2 ± 2.1 Ma (Llosa *et al*., 1996). The porphyry complex located at the intersection of a N-S trending fault and a NW-striking fault that has an apparent sinistral sense of shear. Fault trends observed from aerial photo analysis of the Minas Conga region have a dominant N and NW strike (Fig. 8b). Llosa and Veliz (2000) documented three major vein trends that strongly influenced mineralisation at Chailhuagon. These include $005^{o}$-$020^{o}$, $140^{o}$-$120^{o}$ and an E-W trend. In outcrop, veins are predominantly subvertical (~75-$80^{o}$) and sheeted (Fig. 8c).

Fig. 8. (a) Structural map of the Minas Conga prospect (modified from Llosa and Veliz, 2000). (b) The Chailhuagon centre is hosted in deformed limestone rocks that contain NNE and NNW faults, as illustrated in the rose diagram. (c) Outcrop photo of vein stockwork illustrating three dominant trends N-S, NW and E-W.


(a)
(b)
(c)
Fault Orientations in Host Rock
n=31
N
Cerro Perol
Chailhuagon
9,236
9,234
9,232,000 mN
790
792,000 mE
794
LEGEND
Miocene
Porphyritic Volcanic Rocks (15.7 Ma)
Porphyritic Intrusive Rocks (23.2-17.1 Ma)
Eocene
Porphyry Intrusive & Volcanic Rocks (43.6 Ma)
Upper Cretaceous
Limestone & Marl
0
1.5
kilometres
Fault Strike
Major Thrust Fault

### *B.6 Late Miocene Mineralised Centre*

The late Miocene magmatic interval was characterised by deposition of andesitic volcanic rocks and formation of the Yanacocha epithermal system. Structural features that developed or were reactivated during this interval have been recognised at the Yanacocha mine.

#### *B.6.1 Yanacocha*

The Yanacocha high-sulphidation Au deposit is located within a complex N60$^{o}$E trending structural corridor that is defined by the alignment of deposits and alteration in the Yanacocha Volcanic Complex (YVC; Harvey *et al*., 1999). Andesitic rocks that form the YVC were initially deposited at 11.8 Ma (Turner, 1997). Main stage alteration took place shortly afterwards, between 11.5 and 10.9 Ma (Turner, 1997). Previous work by Harvey *et al*. (1999) and Longo (2000) documented the major deposit-controlling faults at the mine (Fig. 9). A rose diagram of these faults illustrates the major fault trends define the Yanacocha mine are 140-130$^{o}$, 045-050$^{o}$ and 080-090$^{o}$ (Fig. 9). Harvey *et al*. (1999) documented that several deposits were located at the intersection of NE and NW structural zones, and NW-trending structures spatially related to other deposits. Longo (2000) suggested sinistral displacement occurred along some of the NW- and N-trending faults, and dextral sense of shear along the NE-trending faults. Late N- and W-trending fracture zones appear to postdate the major structural trends. All structural trends are associated with late normal displacement or lateral movement, although the overall displacement along the faults in the mine is unknown (Turner, 1997; Longo, 2000).

## B.7 Structural Evolution of the Cajamarca Region

The Cretaceous sedimentary rocks are the oldest exposed rocks in the Cajamarca district and are structurally the most complex (Table 1). The earliest deformation phase manifests as a fold-thrust fabric related to the Incaic I (59-55 Ma) orogenic event. Regional-scale fold axes are dominantly horizontal or plunge gently to the W-NW or ESE. Thrust faults mostly strike ENE and dip SSW. Anticlines located in the hanging wall of thrusts indicate folds and thrust faults developed contemporaneously. It is

Fig. 9. Geological map of the late Miocene Yanacocha district showing the major lithological units, ore deposits and faults identified at the mine (modified from Longo, 2000). The mine is characterised by an overall NE trend, although individual deposits are mostly controlled by NW-oriented faults.

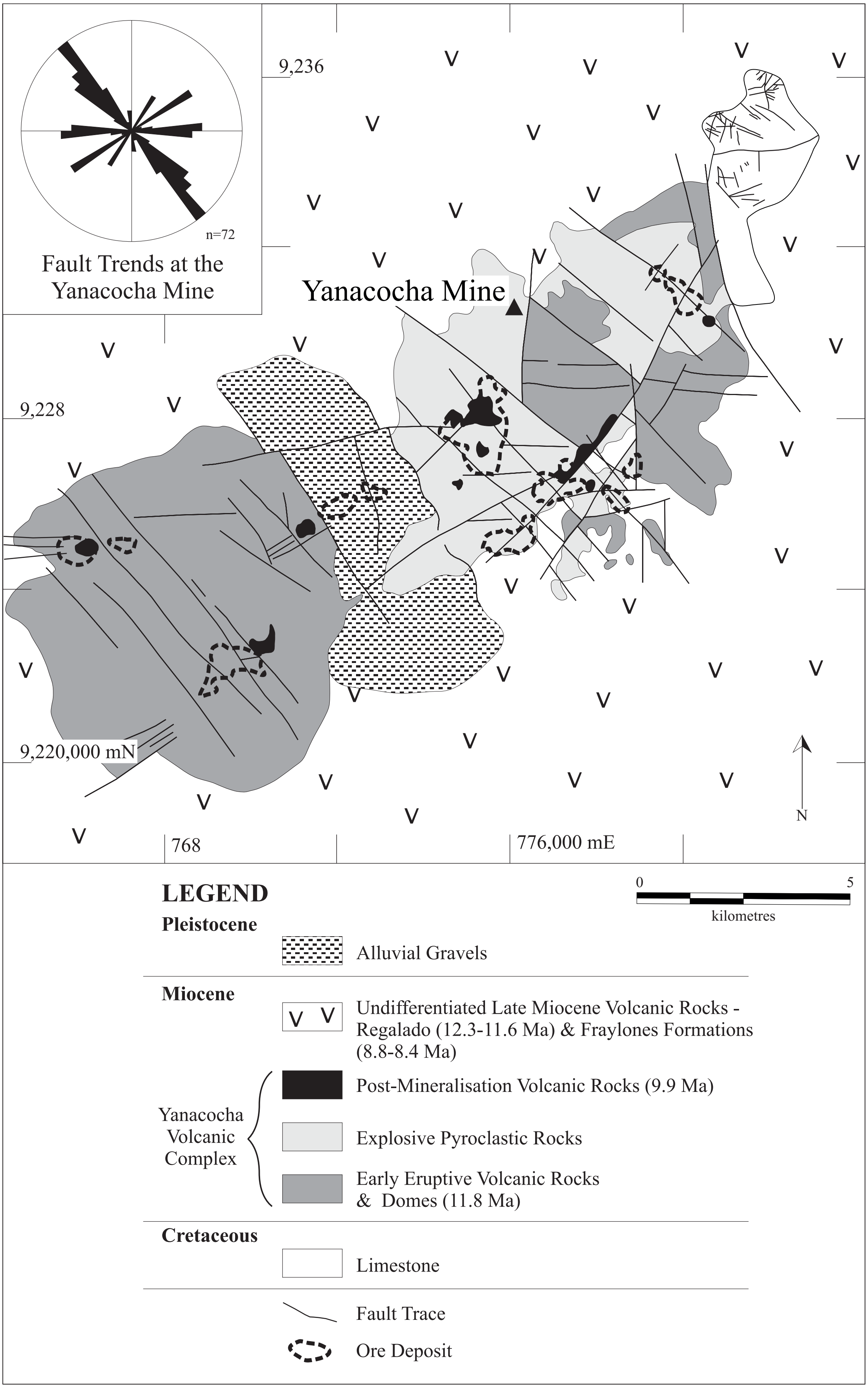
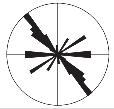
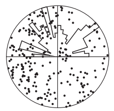
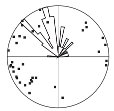
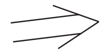
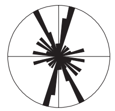
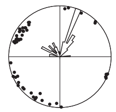
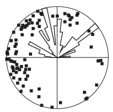
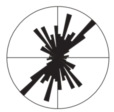
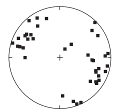

n=72
Fault Trends at the Yanacocha Mine
Yanacocha Mine
9,236
9,228
9,220,000 mN
768
776,000 mE
N
0
5
kilometres
LEGEND
Pleistocene
Alluvial Gravels
Miocene
Undifferentiated Late Miocene Volcanic Rocks - Regalado (12.3-11.6 Ma) & Fraylones Formations (8.8-8.4 Ma)
Yanacocha Volcanic Complex
Post-Mineralisation Volcanic Rocks (9.9 Ma)
Explosive Pyroclastic Rocks
Early Eruptive Volcanic Rocks & Domes (11.8 Ma)
Cretaceous
Limestone
Fault Trace
Ore Deposit

Table 1. Compilation of structural data from this study and previous work. [1] Pardo-Casas and Molnar (1987)

| Location | Age of Complex (Ma) | Trend of Magmatic Complex | Alteration Trend | Faults | | Fractures | Fault/ Fracture Plots | Veins | Rose Diagram of Vein Trends | Reference | Plate Convergence Direction[1] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | *Major* | *Minor* | | | | | | |
| **Yanacocha** | 12-10 | NE | Fault Controlled | 140°-130° | 045-050°, 080-090° | Late N-S & E-W |  | - | - | Harvey *et al*. (1999), Longo (2000) | |
| **Sipan (La Zanja District)** | 13(?) | WNW | NE | NE | | | | - | - | Turner (1999) | |
| **El Galeno** | 17.5-16.5 | NW | - | NE-striking Tear Fault | - | 040°-055°, 170°-140°, 115°-105° |  | - | - | This study | |
| **Michiquillay** | 19.8 | NW | NE | 170°-160° | 140°-135°, 005°-010° | |  | 020°-055°, 150°-140° |  | MMA (1975), this study |  |
| **Minas Conga (Chailhuagon)** | 23-17 | N-S | - | N-S, 145°-140° | - | |  | 005°-020°, 140°-120°, E-W | - | Llosa *et al*. (1996), Llosa and Veliz (2000) | |
| **Gabbroic Dykes (El Galeno)** | 29.4 | NNW | - | 010°-015° | | **Cooling Joints** 020°-025° |  | - | - | This study | |
| **Cretaceous Sedimentary Rocks** | | | | | | | **Faults from Aerial-photo Analysis** | **Folds** | **Stereoplot of Folds** | |  |
| *Field & Aerial Photo* | 120-80 | - | - | 045°-050° | 170°-165°, 120°-115°, 000°-005° |  |  | 16°–>115°, 19°–>295° |  | This study | |

inferred that NNE-directed compression took place during development of the early fold-thrust fabric. These orientations are consistent with a NNE-directed oblique plate convergence direction proposed by Pilger (1984).

Observed NE-trending faults in all lithological units generally display dextral displacement, whereas N- to NW-trending faults have a dominant sinistral sense of shear. Fault planes in Cretaceous rocks display the largest range of fault orientations for all lithological units, ranging from NE- to NW-striking. The exact age of faults in these rocks is difficult to constrain due to a lack of overprinting or crosscutting relationships. The dominant fault orientation observed in the sedimentary rocks is steeply dipping and NE-striking, whereas NE-striking faults are rarely observed in the younger lithological units. It is inferred that the NE-striking faults initially developed as tensional faults contemporaneous with the early fold-thrust fabric. Tear faults observed near El Galeno have a NE-trend, display dextral displacement and inferred to have developed during the fold-thrust event. In the south of the study area, a N-S striking tear fault near the Aurora Patricia intrusion (Fig. 3) has a sinistral sense of displacement.

Most Palaeogene magmatic rocks in the Cajamarca region were deposited or emplaced during a change in the plate convergence rate, from low to high, and following a change in the direction of plate convergence (Fig. 2; Pardo-Casas and Molnar, 1987; Section A). This magmatic interval was characterised by widespread volcanism and emplacement of minor intrusive stocks. The majority of Palaeogene magmatic rocks in the region are spatially associated with the Puntre Thrust Fault and mostly located within the footwall of this thrust (Fig. 3). No secondary structures that may have influenced the location of these rocks were observed. At El Galeno, gabbroic dykes of middle Oligocene age (29.5 Ma) intruded subvertical NW-trending fault and bedding planes. Despite emplacement of these dykes, Oligocene times appear to have been mostly characterised by a lack of significant deformation and magmatism.

Renewed magmatic activity in the Cajamarca region during early to middle Miocene times (23.2-15.8 Ma) is represented by numerous diorite stocks and minor volcanic sequences. Initiation of major uplift (Noble *et al.*, 1990) and formation of porphyry Cu deposits also occurred during this period. Most Miocene intrusions are spatially associated with the same regional-scale structure as the Palaeogene units, i.e.

the Puntre Thrust Fault, but dominantly located within its hanging wall. Field relationships indicate that most Miocene stocks were emplaced at structural intersections, commonly between a major fault and oblique secondary fault(s), such as El Galeno (Section D.5.2). In plan view, mineralised stocks are generally elliptical in shape with the long axis roughly parallel to the local structural fabric. El Galeno and Michiquillay intrusive complexes have NW orientations, whilst Chailhuagon (Minas Conga) has a N-S trend. The Chailhuagon and Michiquillay mineralised systems both contain NNW- to NW-striking faults that display sinistral displacement. Fracture and vein trends at these mineralised centres have a dominant NE, N-S or NW strike. In contrast, El Galeno is characterised by numerous fracture arrays of varying orientation and timing. However, faults in the host sedimentary rock and fractures in the El Galeno intrusive complex display a dominant NNW and NE trend.

Major uplift in the Andes had ceased by middle to late Miocene times (Noble *et al*., 1990). In the Cajamarca region, this time was marked by renewed volcanic activity (12-8 Ma) and the formation of the Yanacocha high-sulphidation Au deposit. A NE-striking structural fabric defines the Yanacocha district, but conjugate NW-striking faults are the dominant deposit-controlling structures (Harvey *et al*., 1999). At the mine, NW-striking faults display a sinistral sense of shear as opposed to NE-trending faults that have a dextral slip component (Longo, 2000). Recent work by Turner (1999) suggested a WNW-trending structural corridor controlled known mineralisation at the La Zanja deposit, with Sipán being located at the southeastern end of the structural corridor (Fig. 10). At the Sipán deposit, mineralisation was localised along a NE-striking fault that is nearly orthogonal to the WNW structural corridor (Compañia Minera Sipán, unpubl. data).

### B.8 Discussion

At the current level of exposure, magmatic episodes in the Cajamarca region appear to have been characterised by either a high or low volcanic/intrusive ratio. Palaeogene and late Miocene magmatic intervals were characterised by widespread volcanism and minor subvolcanic stocks, whereas emplacement of abundant diorite stocks and porphyry Cu formation largely defines early Miocene magmatism.

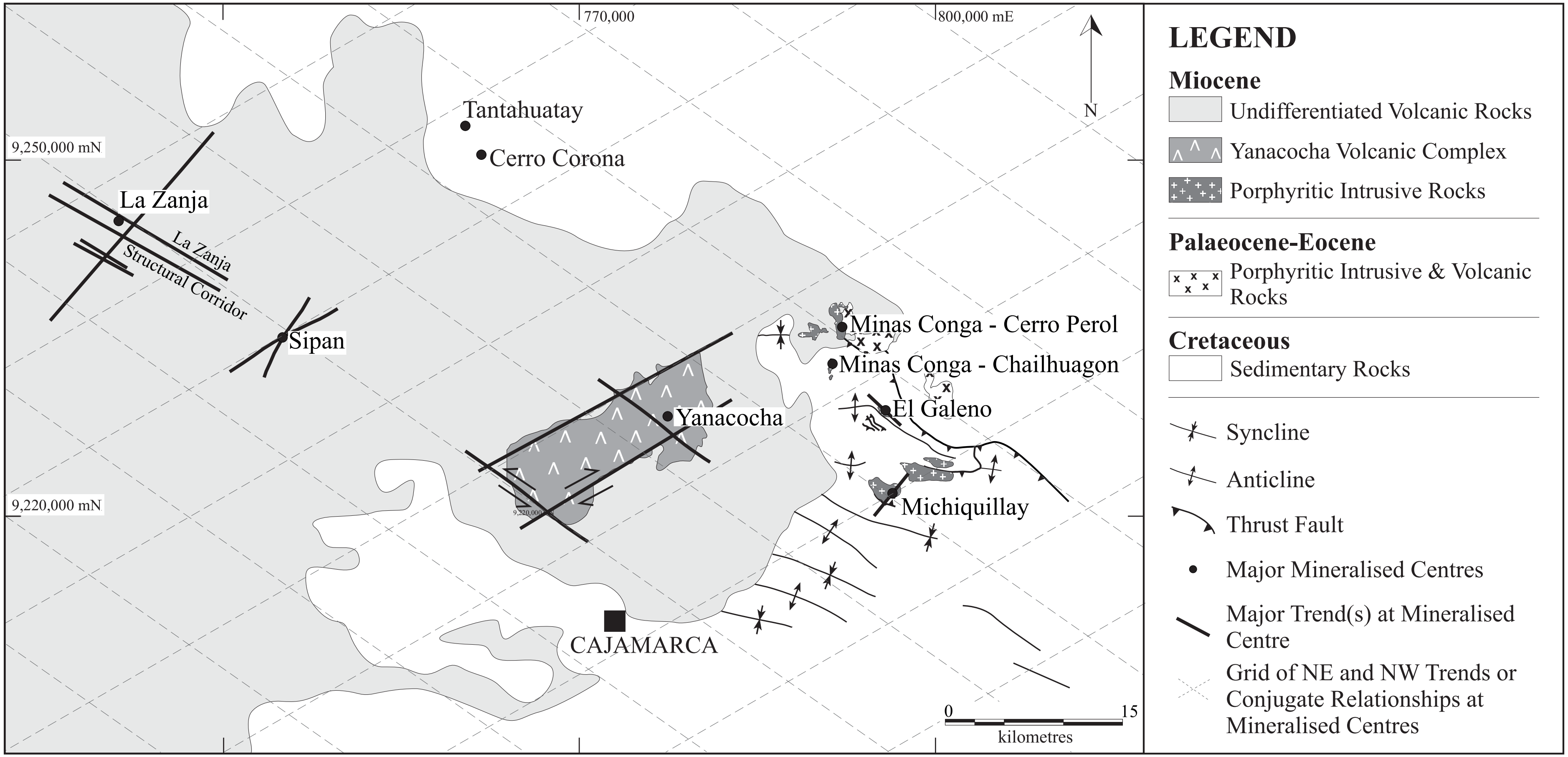



Fig. 10. Simplified geological map of the Cajamarca district displaying the major mineralised centres and the dominant structural trends (thick black lines) observed at the centres. The NE and NW trends identified at deposit-scale for most of the centres also trends to the regional-scale with the spatial location of the deposits. The deposits are roughly aligned in a NE and NW trend with respect to the other centres.

Numerous hypotheses have been proposed to explain periods dominated by volcanism or plutonism in magmatic arcs (Glazner, 1991; Takada, 1994; McNulty *et al*., 1998). In the Cordillera Blanca region of central Peru, coeval Miocene plutonic and volcanic activity occurred during periods of high convergence rates and transtensional tectonics (Petford and Atherton, 1992). Glazner (1991) and McNulty *et al*. (1998) suggest volcanism dominates during orthogonal convergence or compressional pulses within a magmatic arc, whereas strike-slip partitioning due to oblique convergence favours plutonism. Furthermore, Takada (1994) proposed that widespread volcanism and minor plutonism occurs during periods of large differential horizontal stress and high to intermediate magma input rates. Additionally, Tosdal and Richards (2001) suggested that near-surface magma chambers related to porphyry Cu centres result from intermediate to large magma input rates combined with small to intermediate differential horizontal stress. A low volcanic/intrusive ratio would dominate during such conditions.

Palaeogene igneous rocks in the Cajamarca region are mostly located within the footwall of the Puntre Fault. The volcanic-dominated interval occurred during periods of both low and high plate convergence rates, plus between two major orogenic compressive episodes, i.e. Incaic I and II, and within an oblique convergent setting (Mégard, 1984; Pardo-Casas and Molnar, 1987). Sebrier and Soler (1991) proposed that since late Oligocene times the high topographic regions in the Peruvian Andes have been dominated by extensional tectonics due to topographic forces. Therefore, Palaeogene magmatic rocks are proposed to have formed within a horizontal maximum principal stress regime, where $\sigma_1$ was probably parallel to the plate convergence direction, i.e. N-NE directed (Fig. 11a-b).

Miocene porphyry Cu centres and barren stocks of similar age (23.2 to 16.5 Ma) are also spatially associated with the Puntre Fault, but these igneous rocks are dominantly situated within the hanging wall of the thrust fault. The majority of Miocene stocks were emplaced between two orogenic episodes, i.e. the Incaic IV (22 Ma) and Quechua I (17 Ma), during high to moderate-high plate convergence with an E-NE direction (Fig. 11a; Mégard, 1984; Pardo-Casas and Molnar, 1987). Based on current data, no coeval volcanic rocks have been identified or dated between the 23.2 and 16.5 Ma intrusive interval. The mineralised porphyry stocks at Michiquillay, El Galeno and

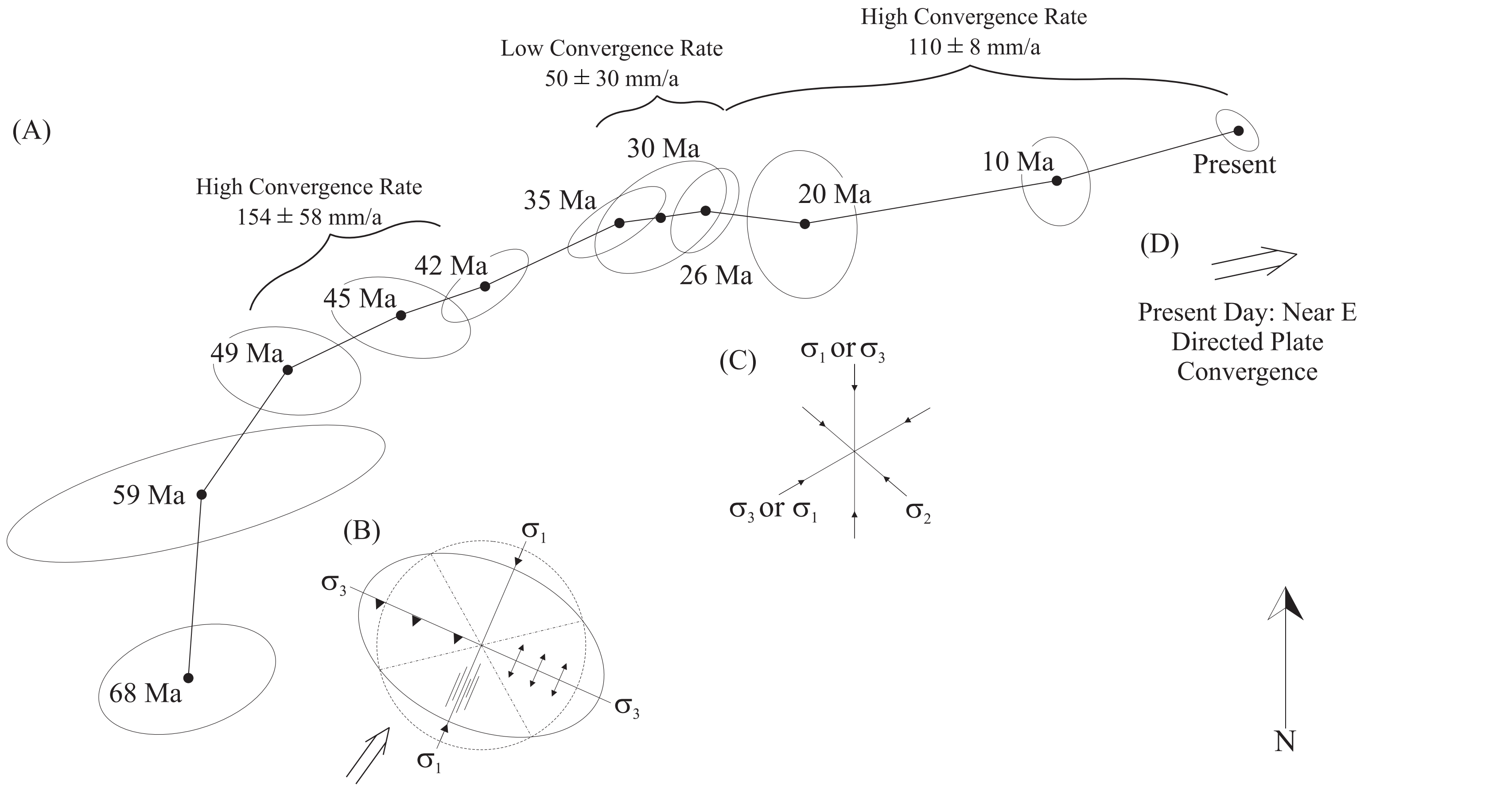



Fig. 11. (A) Plate motion direction of the Nazca Plate (Pardo-Casas and Molnar, 1987). (B) Horizontal principal stress directions for development of the fold-thrust fabric and tensional NE-trending faults during NE directed compression of the Incaic orogenic events (59-42 Ma). (C) Principle stress directions in the Andean Highlands since Late Oligocene (ca 26 Ma) to present day with possible rotations of $\sigma_1$ and $\sigma_3$ between horizontal and vertical. (D) Direction of the present day plate convergence along the South Amercian western margin .

Minas Conga are located at structural intersection zones defined by large-scale faults crosscut by second-order faults. To the NE of El Galeno, the Puntre Fault is crosscut by steep extensional faults that contain minor pyrite mineralisation. This suggests reactivation with normal movement along the regional-scale structure possibly took place during ascent of magmatic and hydrothermal fluids associated with the El Galeno complex. In plan view, the Miocene stocks are elliptical 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 that the stocks intruded highly fractured, anisotropic crust with a high to possibly intermediate differential horizontal stress (Nakamura, 1977; Takada, 1994). Plate tectonic data combined with observed field relations indicate Miocene stocks were emplaced during periods of extension in the upper crust and localised at the intersection of large-scale faults crosscut by oblique subordinate faults.

Large-scale, deeply penetrating conduits or faults that are favourably oriented for dilation provide channelways for ascending fluids (Sibson, 1985; Petford *et al*., 1994; Pitcher, 1997). The close spatial association between the deposits and regional scale faults indicate that ascending early to middle Miocene melts and hydrothermal fluids were preferentially channelled along structural intersection zones. Field- and geophysical-based studies in Chile and Argentina have also documented significant magmatic and hydrothermal centres located at the loci of major structural intersections (Abels and Bischoff, 1999; Richards *et al*., 2001; Chernicoff *et al*., 2002). These authors also suggest porphyry Cu formation was optimised during periods of arc relaxation. This is supported by numerical models for deformation and fluid-flow in a subvolcanic compressive environment that indicate structural intersections are dilatant permeable zones that are favourable for porphyry emplacement (Gow and Ord, 1999).

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Following initial solidification of the porphyry stock, the outer shell of the intrusion and its host rocks undergo brittle fracturing as a result of resurgent hydrothermal-magmatic activity or tectonic stresses (Fournier, 1999; Tosdal and Richards, 2001). In porphyry Cu deposits, regionally- and/or localised tectonically-influenced stresses result in linear fracture arrays, whereas concentric and radial fracture arrays are a product of magmatically-influenced stresses (Tosdal and Richards, 2001). The Minas Conga and Michiquillay mineralised systems are both characterised by deposit-controlling NNW- to NW-striking faults with sinistral displacement. Fracture and vein trends at the mineralised centres have a dominant NE, N-S or NW strike. These similar trends imply a regional stress field largely influenced fault-fracture-vein trends at these centres. In contrast, El Galeno is characterised by numerous fracture patterns of varying orientation and timing. It is inferred that the various fracture patterns at El Galeno were mostly influenced by magmatic stresses. However, faults in the host rock and fractures in the El Galeno intrusive complex display similar trends to those at Minas Conga and Michiquillay, i.e. dominantly NNW- and NE-trending. This suggests fractures at El Galeno formed in response to both magmatic and tectonic stresses, as well as indicating a regional control of fault-fracture systems. Elsewhere, regionally-extensive, systematic fracture patterns in plutons and their wall rocks in the Laramide region of North America have been related to regional stress fields (Heidrick and Titley, 1982).

Middle to late Miocene volcanism and formation of the Yanacocha Au deposit coincided with high convergence rates, near orthogonal E-NE directed convergence (Fig. 11d) and termination of major uplift. Longo (2000) argued subvertical NW-striking faults display sinistral movement, whereas NE faults are dextral (Fig. 10). Faults may also display vertical movement that is dominantly late. This implies the maximum principal stress direction has changed, possibly numerous times between horizontal E-directed (strike-slip) and vertical (extension) during formation of the deposit (Fig. 11c). Such episodic rotations of the regional stress field are unlikely during the short time span in which the Yanacocha deposit formed (<1 m.y.). Tosdal and Richards (2001) suggested rotations in the stress direction imposed on subvolcanic stocks during hydrothermal activity result from a low-differential stress field and fluctuating fluid pressures.

Tectonically-influenced fault-fracture arrays display both temporal and spatial relationships with various lithological units. The Cretaceous sedimentary rocks have a preferred NE fault trend that is inferred to have developed during Eocene SW-directed compression. NNW- and NE-trending faults characterise early Miocene mineralised stocks, whilst the late Miocene Yanacocha district is defined by NW and NE trends. Conjugate relationships between NW and NE structural trends are observed at the majority of mineralised Miocene deposits in the Cajamarca district, as well as to the north in the La Zanja district. The conjugate NE and NW structural trends at Yanacocha are broadly similar to trends observed at Michiquillay where NNW faults with a sinistral sense of shear are near orthogonal to the NE trend of alteration zones and the dominant vein orientation. Similar conjugate shear zones, with NE dextral and W-NW sinistral fault patterns, are observed in many regions and mining districts throughout the Peruvian Andes, e.g. Cerro de Pasco, Marcona and Toquepala (Petersen and Vidal, 1996). Intersections of conjugate zones are highly dilatant and act as channelways that both draw fluids up from a plutonic source (magmatic fluids), and meteoric fluids down during periods of intense horizontal compression in subvolcanic environments (Gow and Ord, 1999).

The dominant orientation of fault arrays in the Cajamarca district display a progressive rotation with time, i.e. early Miocene NNW and late Miocene NW dip-slip faults are superimposed on Eocene NE tensional faults. Two possible scenarios may explain the cause for the change in fault orientation with time. Firstly, counterclockwise rotation of the Cajamarca region in late Oligocene to early Miocene times (Mitourad *et al*., 1992) may have caused the apparent change in preferred fault orientation. Or alternatively, proposed clockwise rotations of the subducting Farallon/Nazca plate throughout Tertiary times (Fig. 11a, Pilger, 1984; Pardo-Casas and Molnar, 1987) are roughly consistent with the changes of the dominant fault orientation. Changes in the direction of plate convergence would induce a rotation in the horizontal principal stress fields from SW-directed during most of the Palaeogene to near E-directed since early Miocene times. This later scenario is consistent with work by Petersen and Vidal (1996) who suggested conjugate shear zones throughout the Peruvian Andes are a result of near E-directed plate convergence along western Peruvian margin. Despite these temporal relationships, structural evidence suggests both of these dominate fault trends (i.e. NE and NW) were active during Miocene times and strongly influenced the development of mineralised centres in the Cajamarca district.

## B.9 Conclusion

Based on results from this study and previous work, several important structural relationships are inferred to have strongly influenced the development of the Cajamarca district and mineralised centres:

- An apparent counterclockwise rotation of the dominant fault orientation occurred with time.
- During changes in the tectonic stress or periods of relaxation structural intersection zones were focal points or favourable channelways for ascending magma and subsequent hydrothermal fluids. On a deposit-scale, periods of extension or rotations of the principal stress direction may have been facilitated by low-differential stress or fluid flow along fault planes.
- Faults and fracture data indicate two of the porphyry Cu complexes contain fault-vein patterns that were controlled by tectonic/regional stress fields, whereas the third mineralised porphyry complex has both magmatic and tectonic influenced fracture arrays.
- Conjugate structural relationships are evident at most of the Miocene mineralised centres in the Cajamarca and La Zanja districts, including both porphyry Cu and high-sulphidation centres.

Recognition of structural intersection zones between regional and oblique secondary faults is of fundamental importance for understanding controls on pluton emplacement and possible subsequent mineralisation in the Cajamarca region. Investigation of regional- and deposit-scale fault arrays and their relative timing suggests conjugate structural trends influenced formation of Miocene porphyry and high-sulphidation deposits in the Cajamarca region. A combined understanding of regionally significant structural trends and their relative timing combined with plate motions provides a powerful tool for exploration in hidden terrains or extending exposed structures beneath volcanic cover for exploring potentially hidden mineralised stocks.