SECTION A

New $^{40}Ar/^{39}Ar$ age constrains on the geological evolution of the Cajamarca mining district

Section A. New $^{40}Ar/^{39}Ar$ age constrains on the geological evolution of the Cajamarca mining district.

A.1 Abstract

New $^{40}Ar/^{39}Ar$ incremental-heating dates were determined for ten samples from intrusive and volcanic rocks in the Cajamarca mining district of northern Peru. A revised magmatic and hydrothermal history of the region is presented based on these new dates. A microdiorite stock east of the Minas Conga (Au-Cu) prospect was the oldest igneous rock dated (57 ± 3 Ma) and suggests magmatism in the region initiated at least during late Palaeocene times. An intrusion from Cerro Montana (47 ± 3 Ma) and a volcanic rock from the La Carpa region (42.55 ± 0.12 Ma) were also dated as middle Palaeogene in age. Hornblende phenocrysts from a mafic dyke yielded a plateau date of 29.4 ± 1.4 Ma.

Magmatic biotite from a synmineralisation intrusion at the Michiquillay porphyry Cu-Au-Mo deposit yielded a $^{40}Ar/^{39}Ar$ plateau date at 19.77 ± 0.05 Ma. This is slightly younger than hornblende phenocrysts from a barren intrusion to the north (20.60 ± 0.14 Ma). Two other barren intrusions from the region, Aurora Patricia (21.30 ± 0.80 Ma) and La Carpa (17.85 ± 0.06 Ma) returned similar early Miocene ages. Main stage alteration and mineralisation at the El Galeno Cu-Au-Mo deposit are dated at 17.50 ± 0.30 Ma (hydrothermal biotite), whilst a late- to post-mineralisation intrusion at the same deposit yielded a date of 16.53 ± 0.18 Ma (magmatic biotite).

Results from this and previous studies indicate periods of magmatic and hydrothermal activity in the Cajamarca region were temporally associated with high plate convergence rates. Hydrothermal activity occurred over both prolonged (~7 m.y.) and short periods (~1 m.y.). Whilst mineralisation events did not necessarily coincide with the major orogenic events, intense or peak magmatism may be linked with significant plate tectonic and orogenic episodes.

A.2 Introduction

The Cajamarca mining district lies between 2,300 and 4,400 m elevation in the Western Cordillera of the northern Peruvian Andes, approximately 685 km north of Lima (Fig. 1). The Cajamarca-Hualgayoc region has long been recognised as an important metalliferous area (von Humboldt, 1927; Orton, 1874). Mining in the district extends back to the Spanish colonial times, and possibly even to the Inca period, when Cu and Au were mined from hillsides near Hualgayoc (Macfarlane and Petersen, 1990). Today, the Cajamarca mining district (Fig. 1) is known to host a number of significant mineralised centres that include Yanacocha (Au), Minas Conga (Au-Cu), Minas Carpa (Au-Cu), Michiquillay (Cu-Au-Mo) and El Galeno (Cu-Au-Mo). Other mineralised centres in the region include Sipán (Au), La Zanja (Au) and the polymetallic Hualgayoc region (Fig. 1). These mineralised centres predominantly include high-sulphidation and porphyry Cu deposits, although minor mantos and skarn deposits have been recognised.

Previous geological descriptions and regional mapping of the Cajamarca district includes studies by Benavides (1956), Reyes (1980), Cobbing *et al.* (1981), Wilson (1985a, 1985b) and Noble *et al.* (1990). In addition, numerous deposit-related studies have further contributed to the geological understanding of the district (Hollister and Sirvas, 1974; Macfarlane and Petersen, 1990; Macfarlane *et al.*, 1994; Llosa *et al.*, 1996; Turner, 1997; James, 1998; Cordova and Hoyos, 2000; Sillitoe, 2000a). Based on these studies, the region is largely characterised by deformed Cretaceous sedimentary rocks intruded and overlain by Tertiary calc-alkaline magmatic rocks (Fig. 2). The Cretaceous sedimentary rocks were deformed by several compressional events termed the Incaic (I-IV) and Quechua (I-II) orogenic phases (Benavides, 1999). The Tertiary igneous rocks vary from basic to acidic in composition (Section C) and range in age from late Palaeocene to late Miocene (Llosa *et al.*, 1996; Turner, 1997; this study). Published and unpublished U-Pb, K-Ar, Rb-Sr and ^{40}Ar/^{39}Ar dates (Fig. 3, Table 1) of these igneous units have focussed on rocks from the Yanacocha district (Turner, 1997), Minas Conga (Llosa *et al.*, 1996), Michiquillay (Laughlin *et al.*, 1968) and the Hualgayoc region (Borredon, 1982; Macfarlane *et al.*, 1994; James, 1998). Limited high precision age dates exist for regional barren intrusions and most of the mineralised porphyry centres. Upper and lower age limits for volcanic sequences in the region (Noble *et al.*, 1990; Llosa *et al.*, 1996; Turner, 1997) are also poorly constrained largely.

Fig. 1. Map of Peru displaying the major tectonic units (modified from Benavides, 1999). Also shown are the significant mineralised centres in Cajamarca (defined by the black square, see Fig. 2) and nearby regions.

Fig. 2. Simplified geological map of the Cajamarca area showing the location of the major igneous units and samples used for $^{40}Ar/^{39}Ar$ dates (filled triangles). Map modified from Reyes (1980). Open triangles: previous dates at mineralised centres, 1 = Laughlin *et al.* (1968); 2 = Llosa *et al.*, (1996), 3 = Turner (1997).

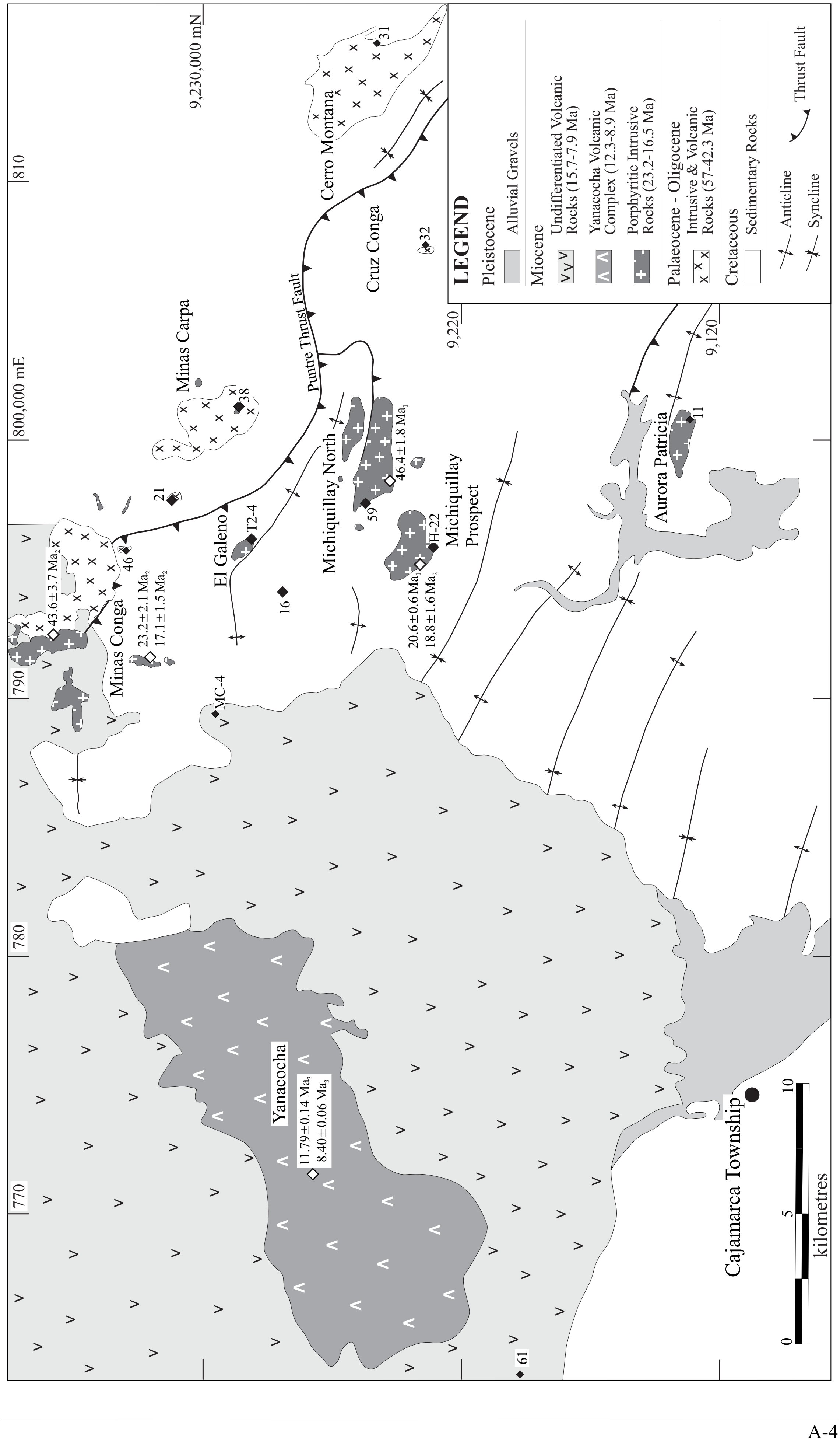

9,230,000 mN
810
800,000 mE
790
780
770
9,220
9,120
Cerro Montana
Cruz Conga
Puntre Thrust Fault
Minas Carpa
31
32
38
21
Michiquillay North
46.4±1.8 Ma$_1$
59
Michiquillay Prospect
H-22
20.6±0.6 Ma$_1$
18.8±1.6 Ma$_2$
El Galeno
T2-4
16
Aurora Patricia
11
Minas Conga
43.6±3.7 Ma$_2$
46
23.2±2.1 Ma$_2$
17.1±1.5 Ma$_2$
MC-4
Yanacocha
11.79±0.14 Ma$_3$
8.40±0.06 Ma$_3$
61
Cajamarca Township
0
5
10
kilometres
LEGEND
Pleistocene
Alluvial Gravels
Miocene
Undifferentiated Volcanic Rocks (15.7-7.9 Ma)
Yanacocha Volcanic Complex (12.3-8.9 Ma)
Porphyritic Intrusive Rocks (23.2-16.5 Ma)
Palaeocene - Oligocene
Intrusive & Volcanic Rocks (57-42.3 Ma)
Cretaceous
Sedimentary Rocks
Anticline
Syncline
Thrust Fault

Fig. 3. Previous radiogenic isotope dates from the Cajamarca and Hualgayoc districts (refer to Table 1). The shaded area defines the magmatic hiatus in the Cajamarca region. B = Borroden (1982); J = James (1998); LD = Laughlin *et al*. (1968); L = Llosa *et al*. (1996); M = Macfarlane *et al*. (1994); N = Noble *et al*. (1990); T = Turner (1997).

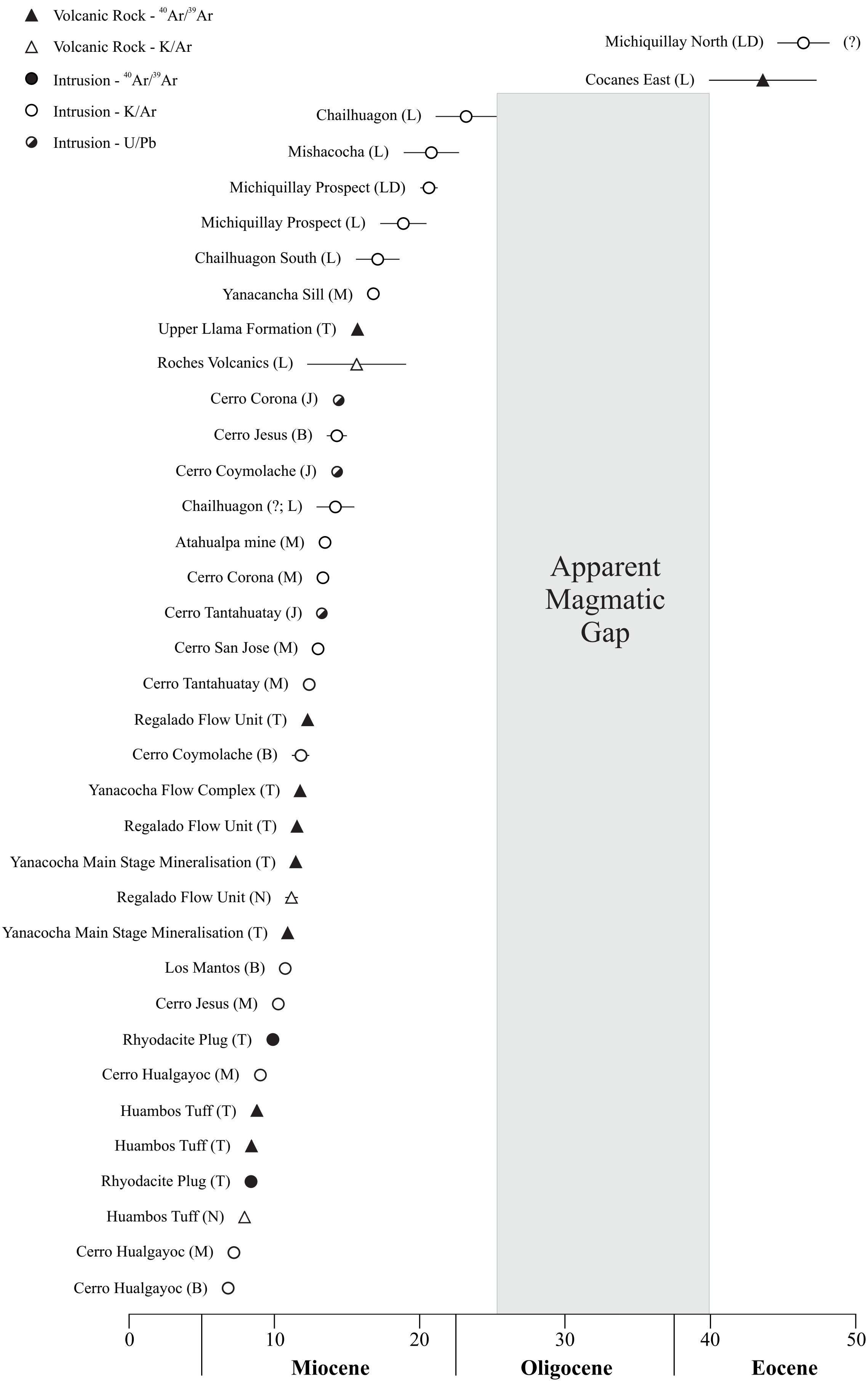

▲ Volcanic Rock - 40Ar/39Ar
△ Volcanic Rock - K/Ar
● Intrusion - 40Ar/39Ar
○ Intrusion - K/Ar
◐ Intrusion - U/Pb
Michiquillay North (LD)
(?)
Cocanes East (L)
Chailhuagon (L)
Mishacocha (L)
Michiquillay Prospect (LD)
Michiquillay Prospect (L)
Chailhuagon South (L)
Yanacancha Sill (M)
Upper Llama Formation (T)
Roches Volcanics (L)
Cerro Corona (J)
Cerro Jesus (B)
Cerro Coymolache (J)
Chailhuagon (?; L)
Atahualpa mine (M)
Cerro Corona (M)
Cerro Tantahuatay (J)
Cerro San Jose (M)
Cerro Tantahuatay (M)
Regalado Flow Unit (T)
Cerro Coymolache (B)
Yanacocha Flow Complex (T)
Regalado Flow Unit (T)
Yanacocha Main Stage Mineralisation (T)
Regalado Flow Unit (N)
Yanacocha Main Stage Mineralisation (T)
Los Mantos (B)
Cerro Jesus (M)
Rhyodacite Plug (T)
Cerro Hualgayoc (M)
Huambos Tuff (T)
Huambos Tuff (T)
Rhyodacite Plug (T)
Huambos Tuff (N)
Cerro Hualgayoc (M)
Cerro Hualgayoc (B)
Apparent Magmatic Gap
0
10
20
30
40
50
Miocene
Oligocene
Eocene

Table 1. Previous radiogenic isotope dates from the Cajamarca and Hualgayoc regions.

Sample	Location / Rock Unit	Sample Type	Mineral Analysed	Date (Ma)	Reference	Method
Cajamarca Region						
YC-1	Upper Llama Formation	Rhyodacite	Biotite	15.78 ± 0.17	Turner (1997)	Ar-Ar
PL-36	Regalado Flow Unit	Andesite flow	Hornblende	12.26 ± 0.12	Turner (1997)	Ar-Ar
MM-165	Regalado Flow Unit	Andesite flow	Hornblende	11.58 ± 0.18	Turner (1997)	Ar-Ar
PL-48	Yanacocha Flow Complex	Andesite	Hornblende	11.79 ± 0.14	Turner (1997)	Ar-Ar
QU-114	Main Alteration (Yanacocha)	Crystalline Alunite	Alunite	11.46 ± 0.15	Turner (1997)	Ar-Ar
CA-SUR	Main Alteration (Yanacocha)	Crystalline Alunite	Alunite	10.92 ± 0.09	Turner (1997)	Ar-Ar
MM-11	Huambos Tuff	Rhyodacite	Biotite	8.42 ± 0.05	Turner (1997)	Ar-Ar
MM-11	Huambos Tuff	Rhyodacite	Hornblende	8.79 ± 0.08	Turner (1997)	Ar-Ar
YA	Rhyodacite Plug	Rhyodacite intrusion	Biotite	9.90 ± 0.05	Turner (1997)	Ar-Ar
YS-2	Rhyodacite Plug	Rhyodacite intrusion	Biotite	8.40 ± 0.06	Turner (1997)	Ar-Ar
Y63	Cocanes East	Diorite	Hornblende	43.6 ± 3.7	Llosa *et al*. (1996)	K-Ar
Y52	Chailhuagon (non-minl zone)	Diorite	Hornblende	23.2 ± 2.1	Llosa *et al*. (1996)	K-Ar
Y41a	Mishacocha (E Maqui-Maqui)	Intrusion	Hornblende	20.8 ± 1.9	Llosa *et al*. (1996)	K-Ar
Y75	Michiquillay Prospect	Diorite	Biotite	18.8 ± 1.6	Llosa *et al*. (1996)	K-Ar
Y501	Chailhuagon South	Diorite	Biotite	17.1 ± 1.5	Llosa *et al*. (1996)	K-Ar
Y4	W Yanacocha (Location?)	Ignimbrites	Biotite	15.7 ± 3.4	Llosa *et al*. (1996)	K-Ar
Y52	Chailhuagon (non-minl zone)	Diorite	Feldspar	14.2 ± 1.3	Llosa *et al*. (1996)	K-Ar
PED-2a-66	Michiquillay North	Hornblende Granodiorite	Hornblende	46.4 ± 1.8	Laughlin *et al*. (1968)	K-Ar
PED-2b-66	Michiquillay Prospect	Altered sulfide-bearing rock	Biotite (hydrothermal)	20.6 ± 0.6	Laughlin *et al*. (1968)	K-Ar
POR-1	Llama (Llama Fm)	Rhyodacite	Plagioclase	54.8 ± 1.8	Noble *et al*. (1990)	K-Ar
YML-4	Huambos (Llama Fm)	Rhyodacitic Ash-Flow Tuff	Sanidine	44.2 ± 1.2	Noble *et al*. (1990)	K-Ar
HMB-1	Huambos (Huambos Fm)	Basal Ash-Flow	Sanidine	39.3 ± 1.0	Noble *et al*. (1990)	Ar-Ar
HMB-4	Huambos (Huambos Fm)	Basal Ash-Flow	Sanidine	36.4 ± 1.0	Noble *et al*. (1990)	K-Ar
UHM-2	Huambos (Huambos Fm)	Overlying Dacite Tuff	Plagioclase	35.4 ± 1.2	Noble *et al*. (1990)	K-Ar
CHB-1	Late Volcanic Rock in Cajamarca	Ash-Flow Tuff	Hornblende	11.4 ± 0.6	Noble *et al*. (1990)	K-Ar
BMC-3	Late Volcanic Rock in Bambamarca	Ash-Flow Tuff	Sanidine	8.2 ± 0.2	Noble *et al*. (1990)	K-Ar

Sample	Location / Rock Unit	Sample Type	Mineral Analysed	Date (Ma)	Reference	Method
Hualgayoc District						
96D-LG	La Granja	Monzonite	Muscovite	13.8 ± 0.4	Noble and McKee (1999)	K-Ar
TANTAD	Tantahuatay	Dacitic Dyke	Biotite	8.5 ± 0.3	Noble and McKee (1999)	K-Ar
TANTAD	Tantahuatay	Dacitic Dyke	Biotite	8.7 ± 0.3	Noble and McKee (1999)	K-Ar
87009	Yanacancha Sill	Propylytized Andesite	K-Feldspar	16.8 ± 0.4	Macfarlane *et al* . (1994)	K-Ar
86027	Cerro Hualgayoc	Rhyodacite	Biotite (magmatic)	9.05 ± 0.21	Macfarlane *et al* . (1994)	K-Ar
	Cerro Corona	Potassic altered felsic pluton	Biotite (hydrothermal)	13.35 ± 0.27	Macfarlane *et al* . (1994)	K-Ar
86039	Cerro San Jose	Seriticized Andesite	Muscovite	13.00 ± 0.4	Macfarlane *et al* . (1994)	K-Ar
85019	Atahualpa mine	Argillically altered sill	Muscovite	13.48 ± 0.19	Macfarlane *et al* . (1994)	K-Ar
86011	Cerro Jesus	Argillically altered andesite	Muscovite	10.29 ± 0.20	Macfarlane *et al* . (1994)	K-Ar
87007	Cerro Tantahuatay	Acid-sulphate alteration	Coarse hypogene alunite	12.4 ± 0.4	Macfarlane *et al* . (1994)	K-Ar
	Cerro Hualgayoc	Rhyodacite	Biotite (magmatic)	7.9 ± 0.3	Macfarlane *et al* . (1994)	K-Ar
9602	Cerro Corona	Quartz Diorite	Zircon	14.4 ± 0.1	James, 1998	U-Pb
9605	Cerro Coymolache	Andesite	Zircon	14.3 ± 0.1	James, 1998	U-Pb
9699	Cerro Tantahuatay	Andesite	Zircon	13.2 ± 0.2	James, 1998	U-Pb
	Cerro Jesus	Argillically altered andesite	Whole-rock	14.3 ± 0.7	Borredon (1982)	K-Ar
	Cerro Coymolache	Propylytized Andesite	Whole-rock	11.8 ± 0.6	Borredon (1982)	K-Ar
	Los Mantos	Argillically altered andesite	Whole-rock	10.5 ± 0.5	Borredon (1982)	K-Ar
	Cerro Hualgayoc	Rhyodacite	Whole-rock	7.2 ± 0.35	Borredon (1982)	K-Ar

Hbl = Hornblende; Bt = Biotite

This section introduces the main magmatic units that crop out in the Cajamarca region and presents new $^{40}Ar/^{39}Ar$ dates for magmatic and hydrothermal minerals. These new dates are used to address to the duration of magmatic-hydrothermal intervals in the region, as well as their association with large-scale tectonic events. The results show short and prolonged magmatic-hydrothermal intervals may be linked to certain tectonic processes.

A.3 Magmatic Centres – Intrusive Rocks

A.3.1 Aurora Patricia

The Aurora Patricia intrusion is located *ca*. 26 km east of Cajamarca (Fig. 2). It is elongate, 2.6 km in length and 0.8 km wide, with the long axis oriented in a near E-W direction. The intrusion is hosted in deformed Upper Cretaceous rocks and located in a hanging wall anticline that plunges gently to the east. The porphyritic intrusion comprises plagioclase and hornblende phenocrysts set in a light grey feldspathic groundmass. The majority of outcropping intrusion has a strong clay alteration, although unaltered rock was observed in the northeastern section. Weak quartz stockwork and pyrite veinlets are evident in outcrop. Previous drilling indicates the Aurora Patricia intrusion is a poorly mineralised hornblende diorite (Jesus Cordova, *pers. commun*., 2000).

A.3.2 Cerro Montana

Cerro Montana is a strongly altered porphyritic intrusive complex *ca*. 42 km ENE of Cajamarca. The elongate complex (7 km by 3.5 km) has a general NW orientation and is located in the footwall of a regionally-extensive thrust fault, termed the Puntre Thrust Fault (Fig. 2). Its core is characterised by an intense clay alteration that has destroyed most primary igneous textures. Towards the periphery on the northeastern side, the intrusion displays only weak propylitic and argillic alteration. The intrusion contains abundant plagioclase and minor hornblende phenocrysts set in a grey feldspathic groundmass. On the eastern side of the complex, the intrusion has a crowded porphyritic texture with plagioclase, clinopyroxene and hornblende phenocrysts. The groundmass is feldspathic and greenish light grey in colour suggesting weak propylitic alteration.

A.3.3 La Carpa

The La Carpa region, *ca*. 35 km to the NE of Cajamarca (Fig. 2), contains both intrusive and extrusive rocks. Several porphyritic intrusions intrude both the deformed limestone and La Carpa volcanic rocks (see below). Mineralogically, these stocks contain plagioclase, hornblende, biotite and rounded quartz phenocrysts set in a light grey feldspathic groundmass. The intrusive rocks have a lower abundance of hornblende phenocrysts compared to the volcanic rocks. From field and petrographic observations, it is suggested that the intrusions are slightly altered hornblende-biotite quartz diorite stocks. The exact age dates of the intrusions and volcanic rocks are unknown. However, geochemical trends suggest the intrusions are considerably younger (Section C).

A.3.4 Michiquillay North

The Michiquillay North intrusive complex situated ~28 km ENE of Cajamarca consists of numerous medium- to small-sized stocks (Fig. 2). The porphyritic intrusive suite is generally homogeneous and composed of plagioclase, hornblende, biotite and quartz phenocrysts within a feldspathic groundmass. Quartz grains are rounded and may contain minor embayments. Rounded quartzite xenoliths, approximately 10 cm in size, occur within some of the intrusions. The intrusions display a weak to moderate chlorite-carbonate-muscovite-pyrite (propylitic) alteration assemblage. Disseminated fine-grained pyrite occurs in some intrusions, but no veins or stockwork are evident. These propylitically altered stocks are interpreted as hornblende ± biotite diorites. A previous K-Ar date from one of these intrusions by Laughlin *et al*. (1968) yielded a date of 46.4 ± 1.8 Ma from hornblende grains.

A.3.5 Michiquillay Deposit

The Michiquillay Cu-Au-Mo prospect is located *ca*. 4 km SW of the barren stocks (Fig. 2). A comprehensive discussion of the prospect is given in Section D. At the prospect, the most common rock type is a crowded porphyry with plagioclase, hornblende, biotite and rounded quartz phenocrysts. The groundmass is feldspathic. This medium-grained porphyry has previously been referred to as the ‘quartz-biotite monzonite’ (Hollister and Sirvas, 1974). However, petrographic studies (Appendix A1, Section C and D) show this intrusion contains no primary alkali feldspars and igneous hornblende phenocrysts have been replaced by hydrothermal biotite due to hydrothermal alteration. These features indicate this intrusion is a hornblende-biotite diorite. This Michiquillay intrusive phase has similar petrologic textures and mineralogy to the barren intrusions to the north. Previous K-Ar studies yielded dates of 20.6 ± 0.6 Ma (hydrothermal biotite, Laughlin *et al*., 1968) and 18.8 ± 1.8 Ma (magmatic biotite, Llosa *et al*., 1996).

A.3.6 El Galeno Deposit

El Galeno is a Cu-Au-Mo porphyry complex located *ca*. 30 km NE of Cajamarca (see Section D.5). The earliest and main intrusive body (P1) is roughly 1.25 km by 0.6 km, oriented in a NW direction and has been intruded by up to three later intrusive phases. The P1 porphyry and the second oldest intrusion (P2 porphyry) are mineralogically and texturally similar with medium-grained plagioclase, hornblende, biotite and quartz phenocrysts. The synmineralisation P1 and P2 porphyries have a moderate to well-developed quartz stockwork and are inferred to be of similar age (Section D.5.4). P3 porphyries intrude the earlier porphyries and contain coarse-grained plagioclase, hornblende, quartz and biotite phenocrysts. P3 porphyries have both lower metal grades and stockwork density than the P1 and P2 porphyries. This phase is inferred to be a series of late to synmineralisation dykes. The final intrusion (MBx porphyry) is a late- to post-mineralisation stock containing plagioclase, biotite and hornblende phenocrysts. This contains a poorly developed stockwork and is weakly mineralised.

A.3.7 Minas Conga Deposit

The Minas Conga complex is situated *ca*. 25 km NNE of Cajamarca and comprises several intrusive units (Fig. 2). Previous mapping by Llosa *et al*. (1996) and Llosa and Veliz (2000) has defined two mineralised centres, i.e. Chailhuagon and Cerro Perol. These centres are characterised by porphyritic intrusions with plagioclase, hornblende, biotite and rounded quartz phenocrysts. Both mineralised centres are intruded by late barren intrusions. Hornblende from the Chailhuagon intrusion yielded a date of 23.2 ± 2.1 Ma from K-Ar, whilst younger ages from the same intrusive complex were obtained from biotite (17.1 ± 1.5 Ma) and plagioclase (14.2 ± 1.3 Ma; Llosa *et al.*, 1996).

A.3.8 Cerro Perol East

Unmineralised volcanic and intrusive rocks are exposed east of the Minas Conga complex. An altered volcanic to subvolcanic complex east of the Cerro Perol deposit is dominantly located in the footwall of the Puntre Thrust Fault (Fig. 2). Both rock-types contain acicular hornblende (some of them up to 20 mm), as well as plagioclase and pyroxene phenocrysts. The groundmass is feldspathic. In outcrop, these rock types range from intense propylitic to argillic altered. In zones of strong alteration, hornblende grains display intense chloritisation and calcite has partially replaced plagioclase phenocrysts. Chlorite, carbonate and epidote alteration is widespread throughout the volcanic sequence. Llosa *et al*. (1996) dated hornblende from an intrusion in this region which yielded a date of 43.6 ± 1.7 Ma.

Southeast of the Cerro Perol deposit, outcropping intrusive rocks are less altered and several discrete intrusive phases were observed. The least altered rock is holocrystalline and composed of plagioclase and hornblende phenocrysts, plus fine-grained euhedral pyroxene and magnetite. Petrographic and geochemical results (Section C) indicate this rock a hornblende microdiorite (Appendix D1). Randomly-oriented plagioclase- and hornblende-rich dykes crosscut the diorite. The dykes are pink in colour and range in thickness from millimetres to tens of centimetres. Minor epidote alteration and pyrite mineralisation are associated with the pink dykes, although the majority of the host rock is unaltered.

A.4 Mafic Dykes

Outcropping mafic dykes were predominantly observed within the northern part of the field area, particularly within 10 km of El Galeno. They are generally <5 m wide and black to dark greyish green in colour. They generally contain two size populations of plagioclase grains, i.e. phenocryst (1-3 cm) and microphenocryst (<1 cm). Two of the dykes also contain hornblende phenocrysts. The majority have calcite amygdales and strong to moderate chlorite-muscovite alteration. Petrographically, the dykes in the region exhibit consistent features, which include:

- Weakly porphyritic textures with a very low abundance of plagioclase and pyroxene phenocrysts. Plagioclase phenocrysts typically lack zoning textures but may display some twinning.
- A trachytic groundmass consisting of feldspar and quartz grains.
- Abundant very fine-grained opaque minerals, dominantly magnetite.
- Absence of quartz phenocrysts.
- Where less-altered, the dykes contain pyroxene.

These textural and field observations suggest that the emplacement of the dykes occurred at high levels. These dykes range from gabbros to hornblende diorites dykes.

A.5 Volcanic Rocks

Volcanic rocks are mostly exposed north and northwest of Cajamarca (Fig. 2). To date, there has been no comprehensive study of the regional volcanic sequences.

A.5.1 Llama Formation

The Llama Formation belongs to the lower part of the Tertiary Llama-Calipuy Volcanic Sequence (54.8-15.8 Ma) as defined by Noble *et al.* (1990) and Turner (1997). Reyes (1980) mapped equivalent rocks, the Tembladera Formation, in the Cajamarca region and defined the units as avalanche-type breccias and tuffs. Noble *et al.* (1990) described the Llama Formation as rhyolitic ashflow tuffs and dacitic volcanic sequences. Mapping by Turner (1997) of the Yanacocha Volcanic Complex (YVC) and adjacent volcanic rocks identified both the Tembladera and Llama Formation in the Cajamarca region. Turner (1997) dated primary biotite from rhyodacitic tuff using ^{40}Ar/^{39}Ar and yielded a date of 15.78 ± 0.34 Ma. Based on this age, he assigned this unit to the upper part for the Llama Formation.

In the Cajamarca region, some units of the Calipuy-Llama sequence crop out in the northeastern part of the study area, near Cruz Conga and La Carpa (Fig. 2). South of Cruz Conga, porphyritic volcanic rocks unconformably overly deformed Cretaceous rocks. They contain hornblende, clinopyroxene, and plagioclase phenocrysts set in a feldspathic matrix that has a trachytic texture. Based on mineralogy and geochemical evidence (Section C), these volcanic rocks from the Cruz Conga region are inferred to be basaltic andesites.

Volcanic rocks in the La Carpa region unconformably overlie deformed Cretaceous limestone units. They consist of a plagioclase, clinopyroxene and hornblende phenocrysts set in a light grey feldspathic matrix. The abundance of amphibole varies at outcrop scale and grains may exceed 3 cm in length. La Carpa volcanic rocks have a light green colour and display weak chlorite-carbonate (propylitic) alteration. Field and petrographical evidence suggests these rocks are propylitic-altered hornblende andesites.

A.5.2 Regalado Volcanic Rocks

According to Turner (1997), middle to late Miocene (12.3–8.2 Ma) volcanic rocks in the Cajamarca region include the Regalado Volcanic Rocks (RVR) and the Huambos Formation. He distinguished the RVR units from the Huambos rocks based on the absence of quartz phenocrysts. Field mapping and petrographic evidence (Appendix A1) indicates biotite phenocrysts may also be applied in this description. The RVR (~12.3-11.4 Ma) comprises andesitic lavas and tuffs (Noble *et al*., 1990; Turner, 1997). Petrographically, the rocks have a crowded porphyritic texture containing abundant plagioclase, clinopyroxene, acicular hornblende and magnetite phenocrysts. Most hornblende grains are rimmed by hematite. Quartz and biotite are notably absent. These units are greenish brown in colour and thin sections indicate weakly propylitic alteration. The matrix is feldspathic and glassy to trachytic in appearance.

A.5.3 Huambos Formation

Rocks of the Huambos Formation (8.8–8.2 Ma, Noble *et al*., 1990; Turner, 1997) are distinguished from the older RVR by the presence of quartz and biotite phenocrysts. Another distinguishing feature is an increase in hornblende and noticeable decrease in pyroxene compared the older Regalado units (Fig. 3 in Section C). The Huambos rocks are andesitic to dacitic ash flow tuffs with plagioclase, hornblende, quartz, biotite, magnetite and clinopyroxene phenocrysts. Quartz grains have corroded rims and minor embayments. Biotite and hornblende phenocrysts contain small inclusions of plagioclase and magnetite.

A.6 Radiometric Dating

Samples selected for $^{40}Ar/^{39}Ar$ studies were chosen based on a variety of factors. Several igneous units in the region had not been dated prior to this study, or had previously been dated using K-Ar and yielded significant errors (Table 2). Field mapping and petrographic studies (Appendix A1; Section C.5) showed mineralogical variations between the different igneous units. Geochemical analyses (major, trace and REE; Appendix C2) further highlighted these variations (Section C.6-C.8). Petrographic evidence combined with electron microprobe analyses (Appendix C1) and electron microscope images were then used on selected samples and minerals to determine the least altered, or otherwise most suitable samples for dating.

A.6.1 Analytical Procedures

Thirteen samples were used for $^{40}Ar/^{39}Ar$ dating, consisting of two samples from the La Carpa region (S-38 and S-21), two from El Galeno (T2 and T4), one from SW of El Galeno, and one each from the Michiquillay deposit (S-H22 176), Michiquillay north (S-59), Cerro Montana (S-31), Cruz Conga (S-32), Aurora Patricia (S-11), Cerro Perol East (S-46), south of Minas Conga (S-MC4) and west of Yanacocha (S-61). Three of these samples (S-21, S-38 and S-59) were analysed at the New Mexico Geochronological Research Laboratory (NMGRL). Inverse isochron ages, $^{40}Ar/^{39}Ar$ intercept and the mean square of weighted deviates (MSWD) were calculated for these samples. The remaining ten samples were analysed at the Argon Geochronology Laboratory at the University of Queensland and only plateau ages are presented. Mineral sample preparation and analytical techniques for both laboratories are provided in Appendix A2.

Table 2. Summary of reason why the various samples were selected for $^{40}Ar/^{39}Ar$ analyses

Sample No.	Location	Lithology	Previous Dates	Reason for Sample Selected
S-21	La Carpa	Hbl Andesite	N/A	Slightly altered volcanic unit unconformably overlying limestone, geochemically significant
S-31	Cerro Montana	Hbl Diorite	N/A	No available radiogenic age, least altered intrusion, geochemically significant
S-16	Sth Galeno	Hbl Gabbro	N/A	No available radiogenic age, least altered dyke observed
S-59	Michiquillay North	Hbl-Bt Diorite	43.6 ± 3.7 Ma_1	Previous age date considered unreliable
S-H22 (176)	Michiquillay Prospect	Hbl-Bt Diorite	20.6 ± 0.6 Ma_1 18.8 ± 1.6 Ma_2	Previous age dates have high uncertainties
S-38	La Carpa	Hbl-Qtz Diorite	N/A	No available radiogenic age
S-T2	El Galeno	Hbl-Bt Diorite	N/A	No available radiogenic age, early mineralised intrusive phase
S-T4	El Galeno	Hbl-Bt Diorite	N/A	No available radiogenic age, final intrusive phase at centre
S-11	Aurora Patricia	Hbl Diorite	N/A	No available radiogenic age
S-61	West Yanacocha	Hbl Bas Andesite	N/A	Fresh volcanic rock, poorly constrained age
S-MC4	Sth Minas Conga	Hbl-Bt Andesite	N/A	Volcanic overlying deformed limestone, poorly constrained age, geochemically significant
S-46	East Minas Conga	Hbl Microdiorite	N/A	No available radiogenic age, geochemically significant
S-32	Cruz Conga	Hbl Basaltic Andesite	N/A	No available radiogenic age, previously unmapped unit, geochemically significant

Hbl = Hornblende; Bt = Biotite; Qtz = Quartz

N/A = not available; 1 = Laughlin *et al*., 1968; 2 = Llosa *et al*., 1996

A.7 ^{40}Ar/^{39}Ar Results

Most of the samples released high amounts of ^{40}Ar during the initial steps suggesting extraneous argon. However, the majority of grains yielded good plateau during later heating steps. Three samples, S-61, S-MC4 and S-32, released insufficient amounts of ^{39}Ar and no meaningful plateaux or spectrums were obtained (Table 3).

Hornblende from a microdiorite (S-46) in the Cerro Perol East region yielded a disturbed spectrum with the majority of ^{39}Ar (~90%) degassed over four heating steps (steps B-E). The final heating steps yielded a complex age spectrum and have a varying K/Ca ratio that suggests alteration (Fig. 4). A plateau age of 57 ± 3 Ma was deduced from steps B-E. This plateau age is considerably younger than the integrated or total gas age of 87 ± 4 Ma. There is low degree of confidence in the total gas age. Phenocrysts of hornblende in S-31, an intrusion from the Cerro Montana region, yielded a disturbed age spectrum during the initial and final heating steps (Fig.4). A plateau age of 47 ± 3 Ma (steps B-F) was obtained from the central portion of the spectrum (~95% of gas released). This plateau age is indistinguishable from the integrated age of 47 ± 2 Ma.

Hornblende from a volcanic rock in the La Carpa region (S-21) yielded a flat spectrum for nearly 85% of the ^{39}Ar released during the step heating (Fig. 5). The calculated weighted mean age for this plateau is 42.55 ± 0.12 Ma (steps B-H), which agrees within error of an inverse isochron age (42.58 ± 0.14 Ma). The last 15% of ^{39}Ar released yielded significant decreases in apparent age. This probably represents degassing of feldspar mineral inclusions observed within the hornblende phenocryst. Slightly altered hornblende grains from a mafic dyke (S-16) in the Galeno region yielded a near plateau age spectrum from ~80% of the gas released (Fig. 5). This sample has low K/Ca ratios for both the initial and final heating steps that correspond to a disturbed age spectrum. These steps suggest the grains have been slightly altered. An age of 29.4 ± 1.4 Ma was obtained from the near plateau (steps C-H). This age is ~5 m.y. older than the integrated age of 24.6 ± 1.2 Ma.

Hornblende from S-11, an intrusion in the Aurora Patricia region, yielded a disturbed age spectrum. High apparent ages were obtained during the initial and final

Table 3. Summary of $^{40}Ar/^{39}Ar$ results

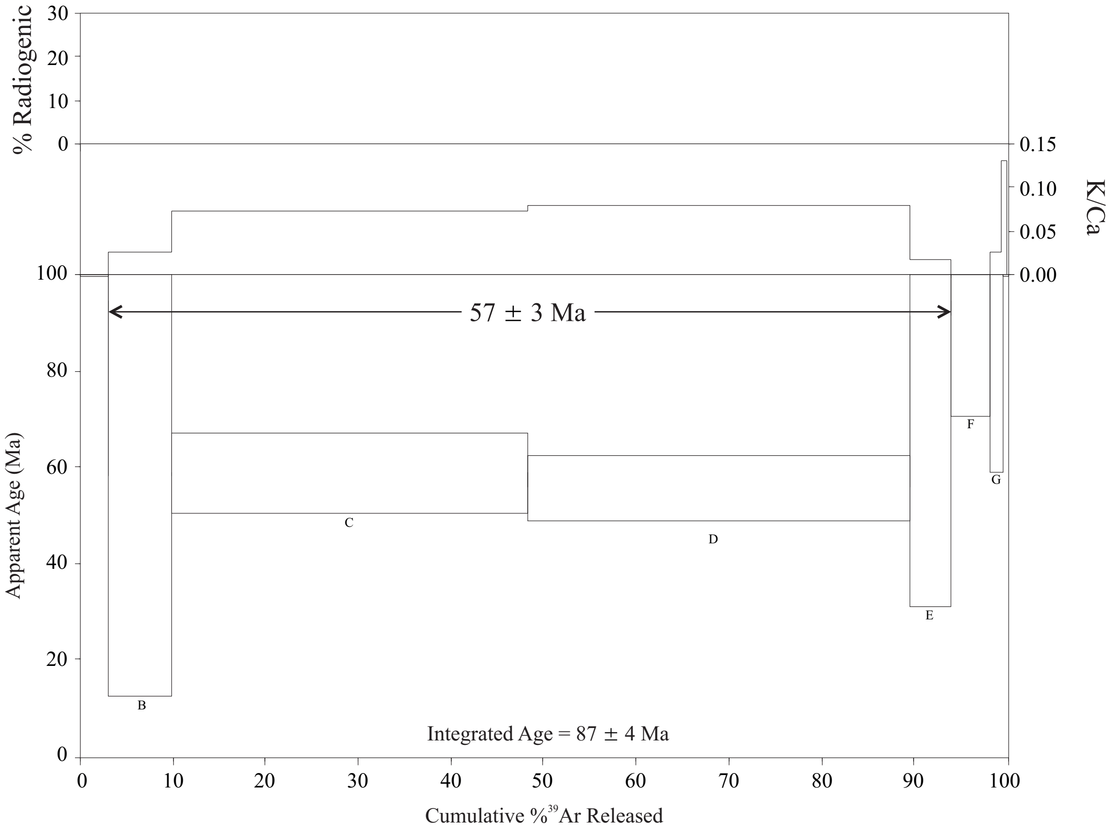
Sample No.	Location	Lithology	Mineral Analysed	Date (Ma)	Error (2σ)	$^{40}Ar/^{36}Ar_i$	MSWD	Quality	Method
S-46	Cerro Perol East	Hbl Microdiorite	Hornblende	57	3			Disturbed	Ar-Ar (UQ)
S-31	Cerro Montana	Hbl Diorite	Hornblende	47	3			Disturbed	Ar-Ar (UQ)
S-21	La Carpa	Hbl Andesite	Hornblende	42.55	0.12	293 ± 7	0.90	Near Plateau	Ar-Ar (NMGRL)
S-16	Sth Galeno	Hbl Gabbro	Hornblende	29.40	1.40			Near Plateau	Ar-Ar (UQ)
S-59	Michiquillay North	Hbl-Bt Diorite	Hornblende	20.60	0.14	294 ± 22	1.70	Plateau	Ar-Ar (NMGRL)
S-11	Aurora Patricia	Hbl Diorite	Hornblende	21.30	0.80			Near Plateau	Ar-Ar (UQ)
S-H22 (176)	Michiquillay Deposit	Hbl-Bt Diorite	Biotite	19.77	0.05			Plateau	Ar-Ar (UQ)
S-38	La Carpa	Hbl-Qtz Diorite	Hornblende	17.85	0.06	296.9 ± 3.4	1.20	Plateau	Ar-Ar (NMGRL)
S-T2	El Galeno Deposit	Hbl-Bt Diorite	Biotite (hydrothermal)	17.50	0.30			Plateau	Ar-Ar (UQ)
S-T4	El Galeno Deposit	Hbl-Bt Diorite	Biotite	16.53	0.18			Plateau	Ar-Ar (UQ)
S-61	West Yanacocha	Hbl Basaltic Andesite	Hornblende	N/A				No Plateau	Ar-Ar (UQ)
S-MC4	Sth Minas Conga	Hbl-Bt Andesite	Hornblende	N/A				No Plateau	Ar-Ar (UQ)
S-32	Cruz Conga	Hbl Basaltic Andesite	Hornblende	N/A				No Plateau	Ar-Ar (UQ)

N/A = No meaningful plateau obtained

Hbl = Hornblende; Bt = Biotite; Qtz = Quartz

NMGRL = New Mexico Geochronology Research Lab, UQ = University of Queensland

Sample 46 - Hornblende



Sample 31 - Hornblende

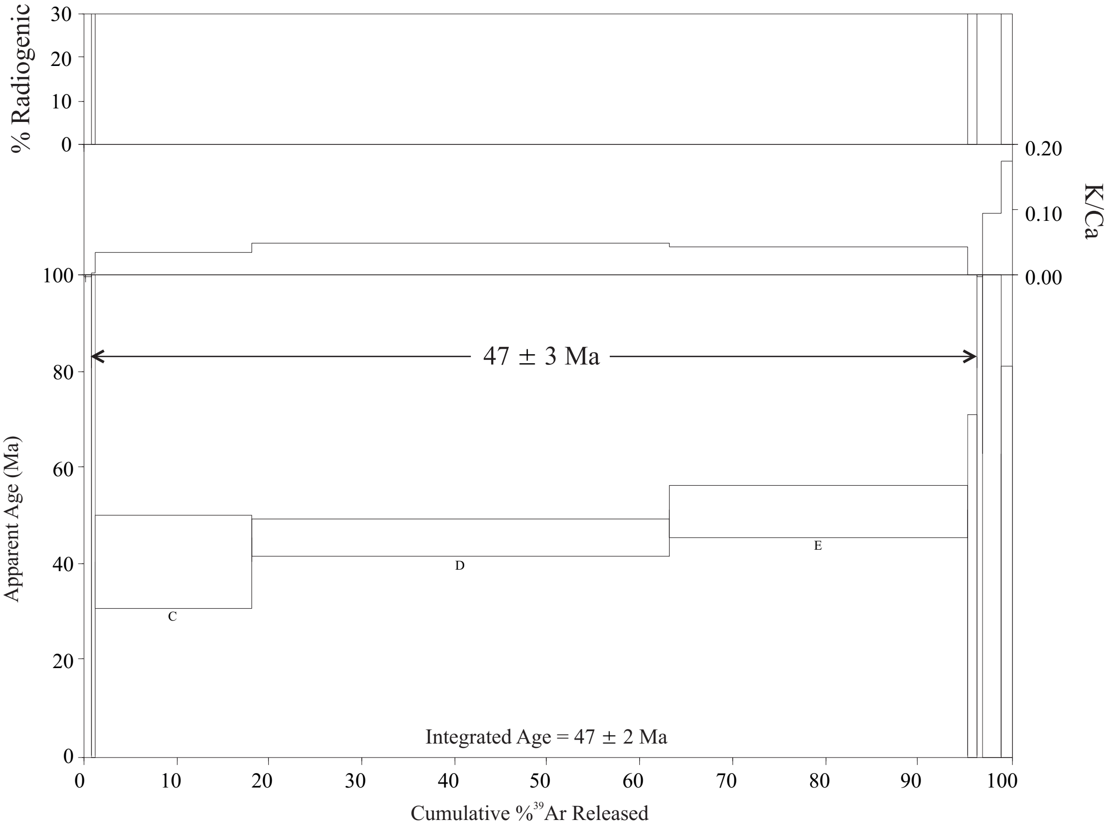
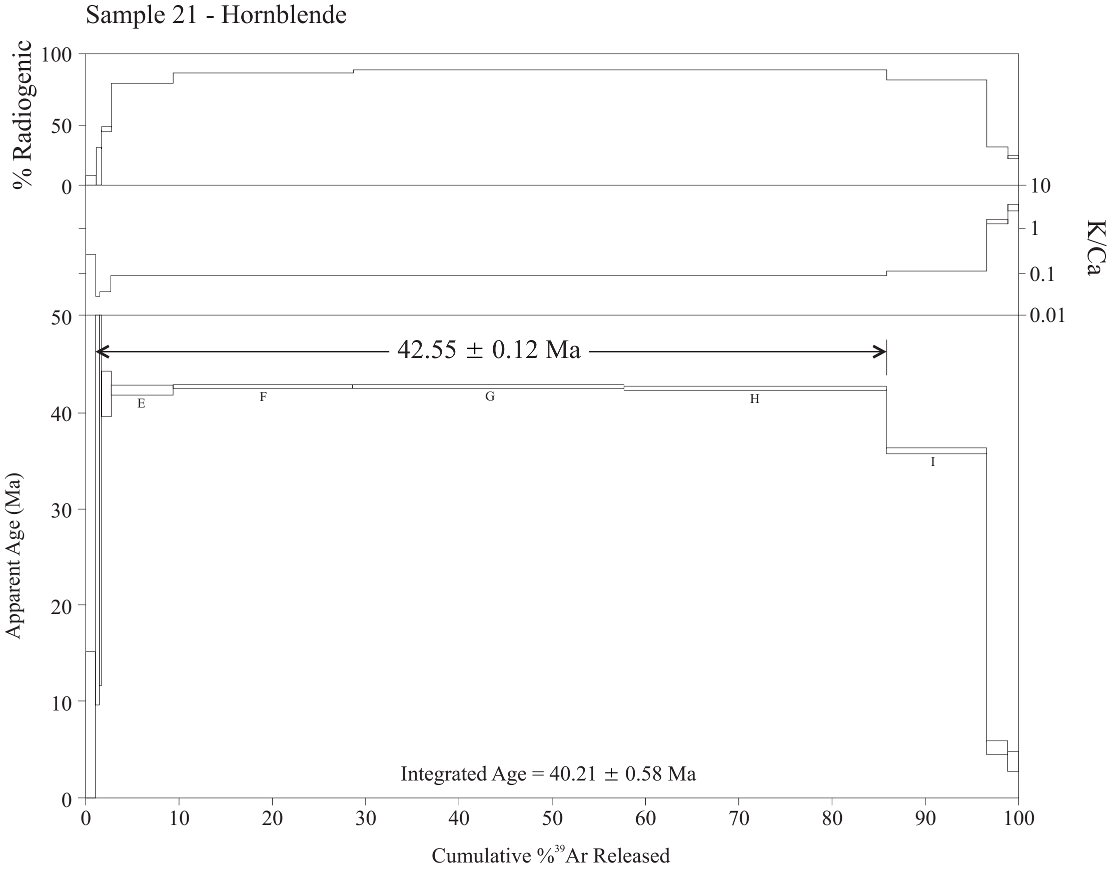


Fig. 4. ^{40}Ar/^{39}Ar apparent age spectra of intrusive rocks from the east Cerro Perol region and the Cerro Montana region analysed by incremental step heating.



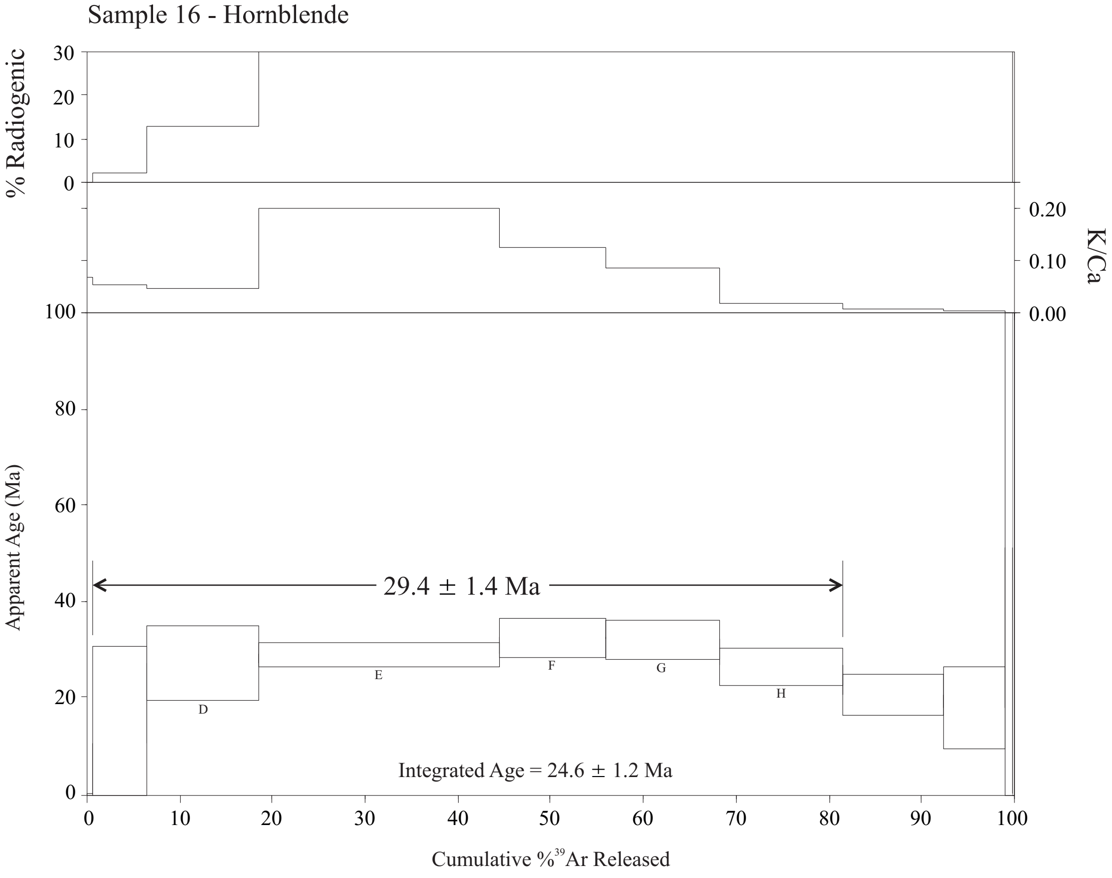


Fig. 5. ^{40}Ar/^{39}Ar apparent age spectra for a volcanic rock from the La Carpa region and mafic dyke near El Galeno region analysed by incremental step heating.

heating steps. This suggests either the presence of excess argon or minor alteration. A plateau age of 21.3 ± 0.8 Ma was calculated from ~99% of the gas released (Fig. 6, steps A-F). Hornblende from an intrusive rock (S-38) in the La Carpa region yielded an undisturbed age spectrum with a weighted mean age of 17.85 ± 0.06 Ma (steps A-H, Fig. 6) from ~99% of the ^{39}Ar released. This date is concordant with an inverse isochron age (17.83 ± 0.06 Ma) that produced a ^{40}Ar/^{39}Ar intercept (296.9 ± 3.4) within error of the atmospheric ratio.

Hornblende from a barren intrusive rock from Michiquillay North (S-59) yielded young apparent ages for the first 5% of ^{39}Ar released that possibly suggests minor alteration. The remaining portion (~95%) of the spectrum yields a weighted mean age of 20.61 ± 0.14 Ma (steps C-J, Fig. 7), that is concordant with an inverse isochron analysis (20.66 ± 0.64 Ma). Magmatic biotite from a synmineralisation stock at the Michiquillay prospect (S-H22) yielded old apparent dates for the initial nine heating steps suggesting extraneous ^{40}Ar (Fig. 7). The remaining spectrum (~80%) yielded a nearly undisturbed plateau giving a date of 19.77 ± 0.05 Ma.

Hydrothermal biotite from an early intrusive phase (S-T2) at El Galeno yielded a nearly undisturbed age spectrum with the initial two steps producing firstly younger then older apparent ages (Fig. 8). The remaining 96% of ^{39}Ar released yields a plateau age of 17.5 ± 0.3 Ma (steps C-I). This date is indistinguishable from the integrated age of the spectra (17.5 ± 0.3 Ma). A post-mineralisation intrusion (S-T4) from the same deposit produced a slight saddle-shaped age spectrum with the initial steps having an apparent date of *ca*. 25 Ma. The remaining 86% of the spectrum for the magmatic biotite yields a plateau age of 16.53 ± 0.18 Ma (steps D-K; Fig. 8).

A.8 Interpretation of ^{40}Ar/^{39}Ar Dates

level of analytical precision (within 2σ values) and are consistent with standard criterion for classification of plateaux as defined by Dalrymple and Lanphere (1974). Therefore, these results are considered reliable. S-46 yielded a disturbed spectrum and a ‘plateau’

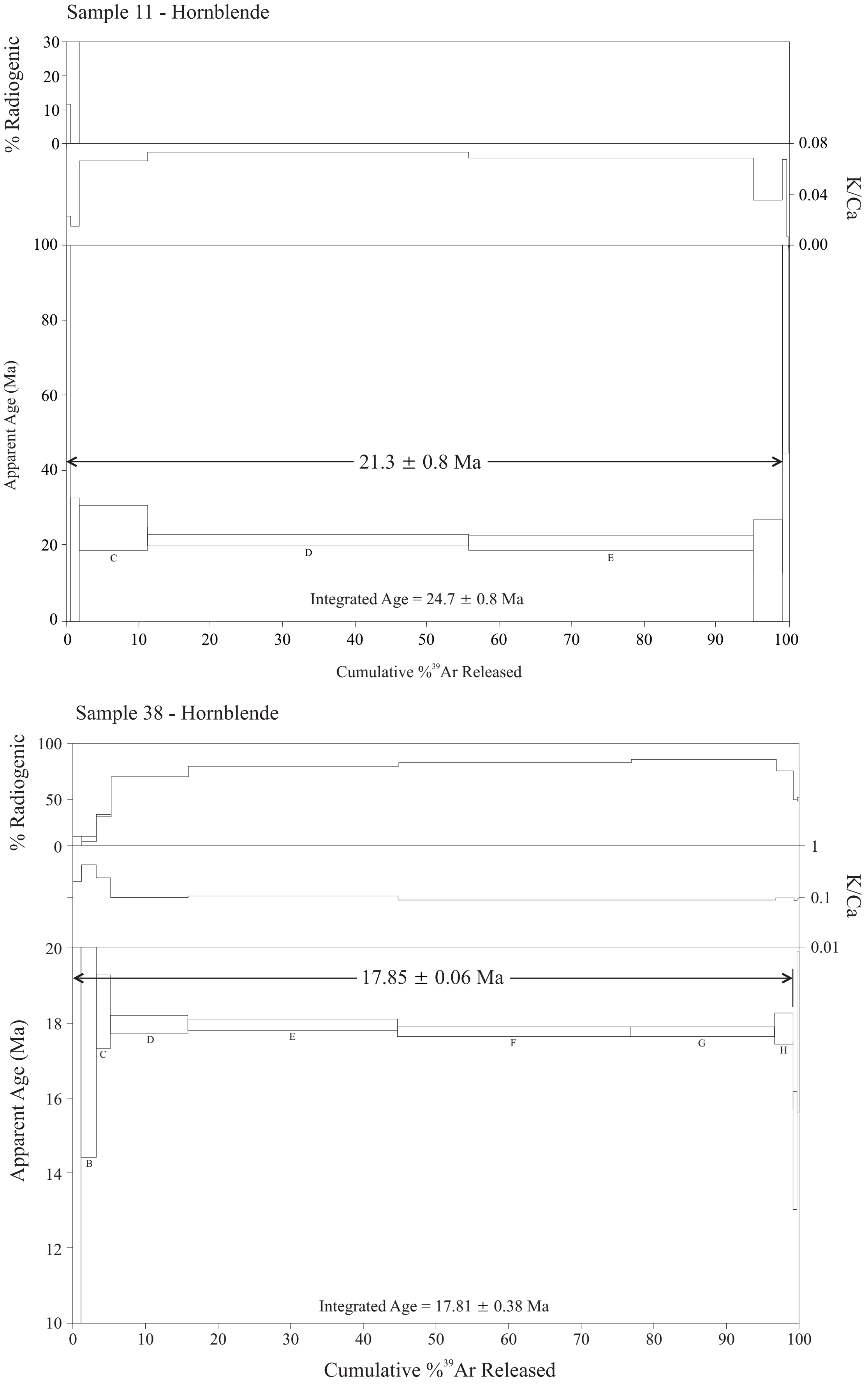
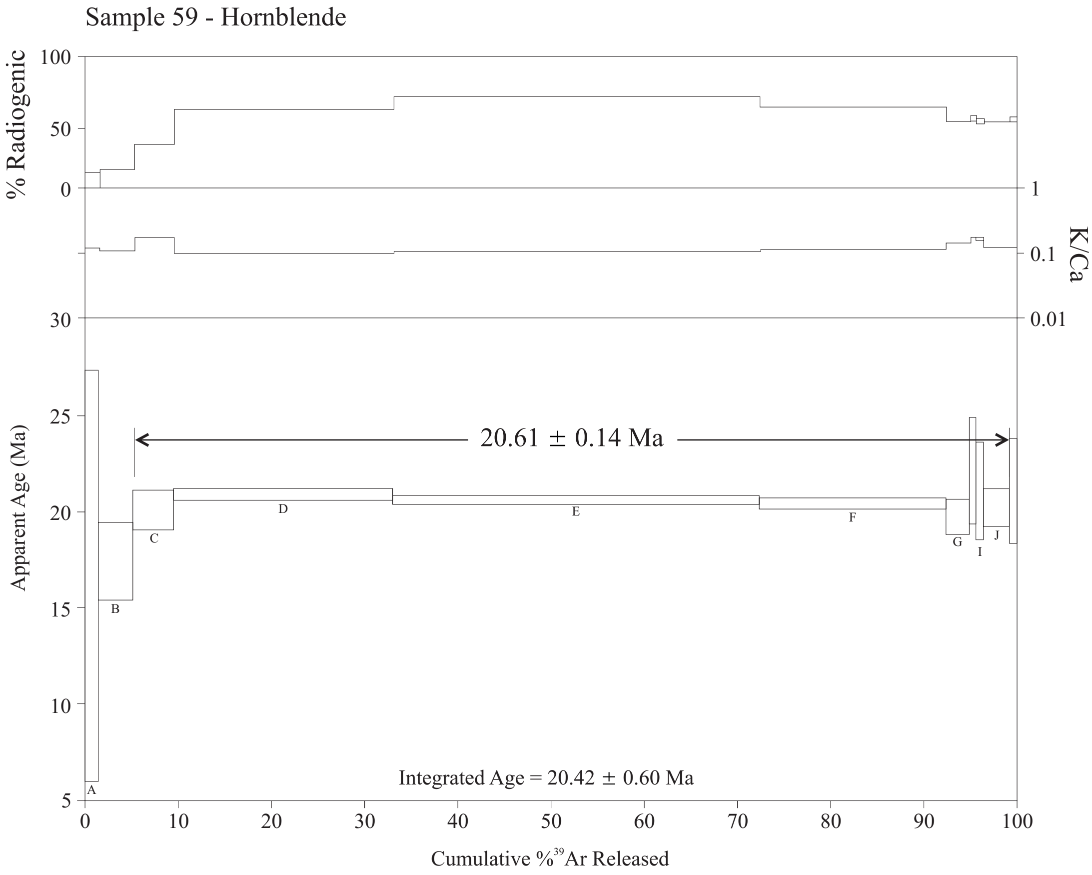


Fig. 6. ^{40}Ar/^{39}Ar apparent age spectra of intrusive samples from the Aurora Patricia and La Carpa regions analysed by incremental step heating.


Sample 59 - Hornblende

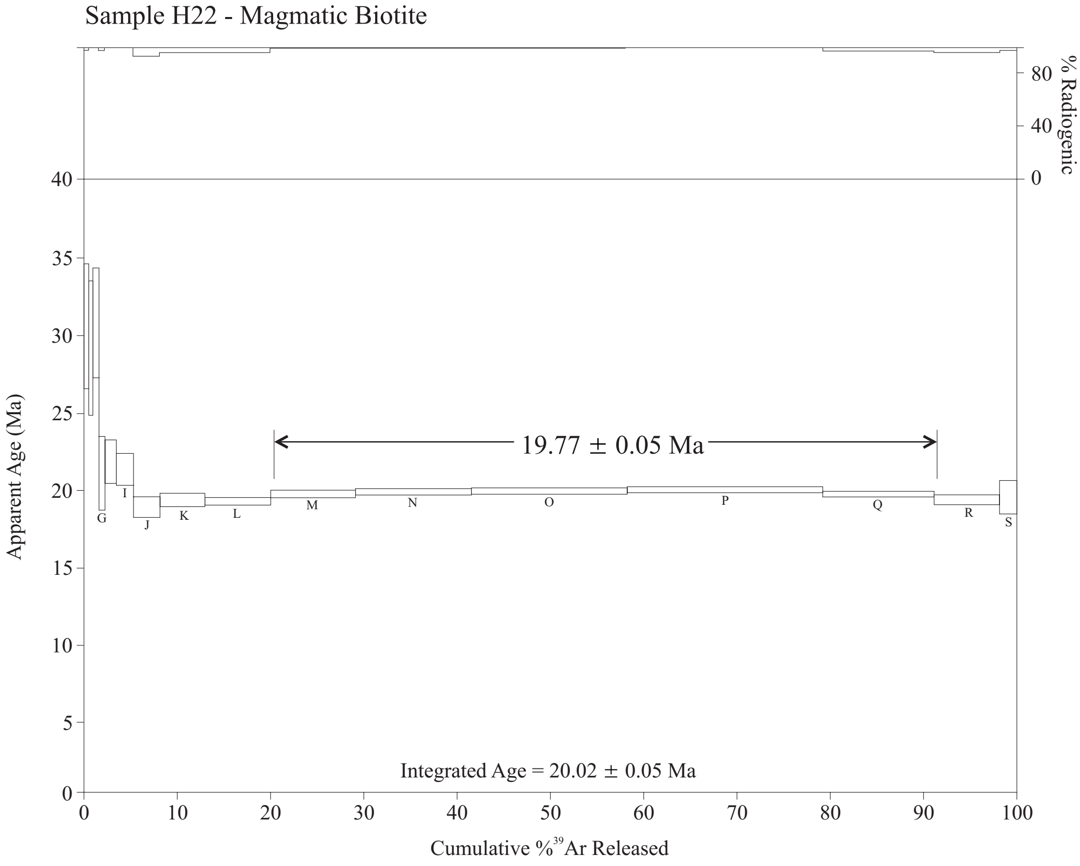
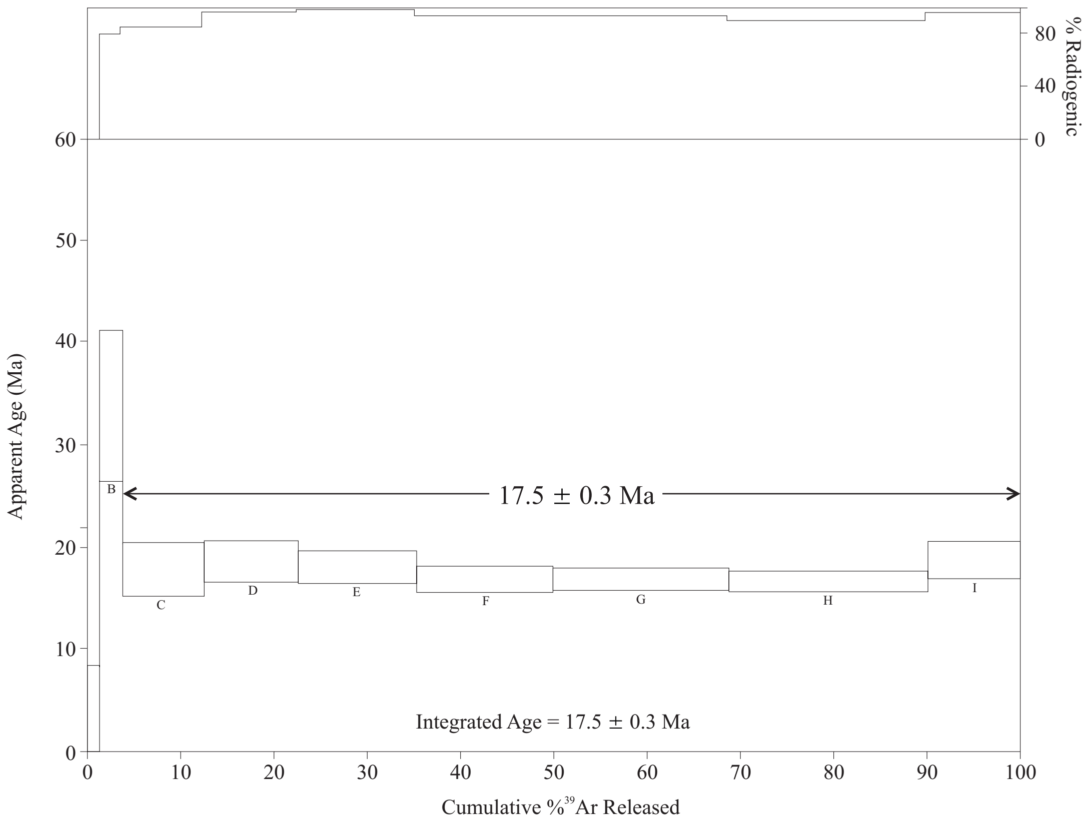
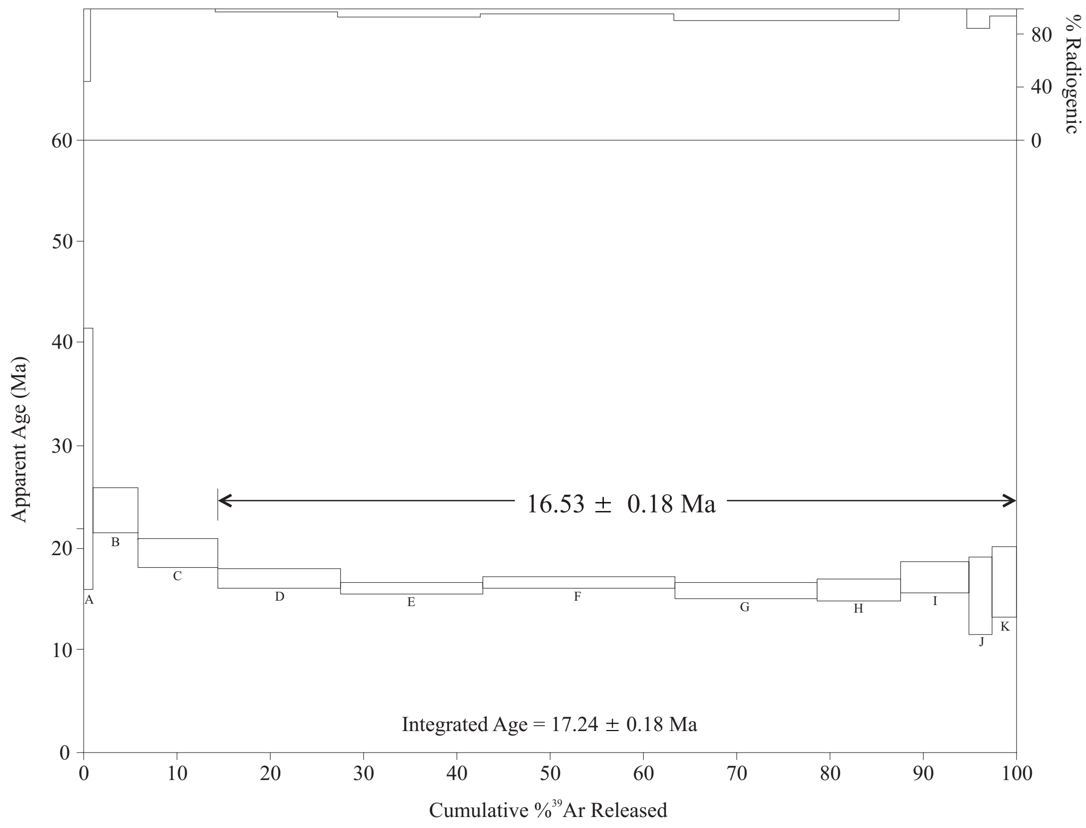

Sample H22 - Magmatic Biotite

Fig. 7. $^{40}Ar/^{39}Ar$ apparent age spectra for samples from intrusions in the Michiquillay region analysed by incremental step heating.



S-T2 (Hydrothermal Biotite)



S-T4 (Magmatic Biotite)

Fig. 8. ^{40}Ar/^{39}Ar incremental heating age spectra for a hydrothermal biotite from a synmineralisation intrusion and a magmatic biotite from a late-mineralisation stock at El Galeno.

age of 57 ± 3 Ma from step four heating steps. A second hornblende grain analysed from this sample yielded an apparent date of 59 ± 4 Ma from a disturbed plateau. Therefore, the age of this intrusion is cautiously interpreted at *ca*. 57 Ma. The following paragraphs will compare the reliable dates from this study with previous geochronology dates from the region.

Few dates exist for Palaeocene igneous rocks in the Cajamarca-Hualgayoc region (Laughlin *et al*., 1968; Macfarlane *et al*., 1994; Llosa *et al*., 1996) and prior to this study dates had only been obtained on intrusive rocks using the K-Ar or Rb-Sr systems. Llosa *et al*. (1996) dated an intrusion from Cocanes East at Minas Conga at 43.6 ± 3.7 Ma, whilst the Coymolache intrusion from Hualgayoc has been dated at 45 ± 3.4 Ma (Rb-Sr mineral isochron, Macfarlane *et al*., 1994). Recently however, James (1998) dated zircons from the Coymolache intrusion at 14.3 ± 0.1 Ma (U-Pb) indicating the Rb-Sr date is unreliable (Macfarlane, *pers commun*., 2002). New ^{40}Ar/^{39}Ar dates for S-46 (57 ± 3 Ma) and S-31 (47 ± 3 Ma) are the oldest igneous rocks dated in the region. These dates indicate that magmatic and intrusive activity in the Cajamarca commenced some 13 m.y. earlier than previous analyses suggested. Noble *et al*. (1990) dated several volcanic rocks of Palaeogene age (54.8–35.4 Ma) in the Llama and Huambos region, some 100 km NW of Cajamarca. S-21, an andesitic rock from La Carpa (42.55 ± 0.12 Ma), is also the first Palaeogene volcanic rock dated in the Cajamarca district. It is assigned to the Lower Llama Formation based on this date.

Intrusions from both Michiquillay north (46.4 ± 1.8 Ma) and the Michiquillay deposit (20.6 ± 0.6 Ma) were previously dated by Laughlin *et al*. (1968). These authors concluded that the apparent Eocene age of the Michiquillay north intrusion was unreliable and resulted from excess ^{40}Ar. They suggest this intrusion was more likely to have been emplaced around the same time as the intrusion from the Michiquillay deposit, i.e. ~20 Ma. A weighted mean age of 20.61 ± 0.14 Ma calculated for hornblende phenocrysts from S-59 confirms this suggestion and indicates these barren propylitically altered intrusions are early Miocene. Hornblende from a barren unaltered intrusion at Aurora Patricia, S-11, yielded a slightly older ^{40}Ar/^{39}Ar date at 21.3 ± 0.8 Ma. Previous K-Ar dates from the Michiquillay deposit include 20.6 ± 0.6 Ma (hydrothermal biotite, Laughlin *et al*., 1968) and 18.8 ± 1.6 Ma (magmatic biotite, Llosa *et al.*, 1996). These dates have high uncertainties. A $^{40}Ar/^{39}Ar$ weighted mean age for magmatic biotite (S-H22 176) from a synmineralisation intrusion constrains the age of crystallisation at the Michiquillay deposit to 19.77 ± 0.05 Ma. These results also suggest mineralisation at the Michiquillay deposit occurred slightly later than the emplacement of barren Michiquillay north intrusions.

Hornblende phenocrysts from a barren La Carpa intrusion yield a weighted mean age of 17.85 ± 0.06 Ma. This result is similar to a K-Ar date (17.1 ± 1.5 Ma; Llosa *et al.*, 1996) from a Chailhuagon South intrusion at Minas Conga and a $^{40}Ar/^{39}Ar$ date of hydrothermal biotite (17.50 ± 0.30 Ma) from the second intrusive phase (P2 porphyry) at El Galeno. These results suggest a temporal link between these three intrusions and the main P1 porphyry at El Galeno. This is supported by similar geochemical trends in the La Carpa and El Galeno intrusions (Section C).

Magmatic biotite in a late- to post-mineralisation intrusion (16.53 ± 0.18 Ma) at El Galeno crystallised about one million years after main stage alteration at the deposit and *ca*. 800,000 years before deposition of the Upper Llama Formation (15.78 ± 0.17 Ma; Turner, 1997). The next youngest intrusion dated in the district is from the Yanacocha deposit and has a $^{40}Ar/^{39}Ar$ date of 9.90 ± 0.05 Ma (Turner, 1997). Despite intense magmatic and hydrothermal activity in the Hualgayoc region throughout middle Miocene times (16.8–7.2 Ma), this stock at El Galeno is inferred to represent the last intrusive rock emplaced during early to middle Miocene times in the Cajamarca region. If this is assumed, emplacement and formation of most recognised porphyry-related deposits in the Cajamarca region occurred over an approximately 7 m.y. period, spanning from 23.2 to 16.5 Ma.

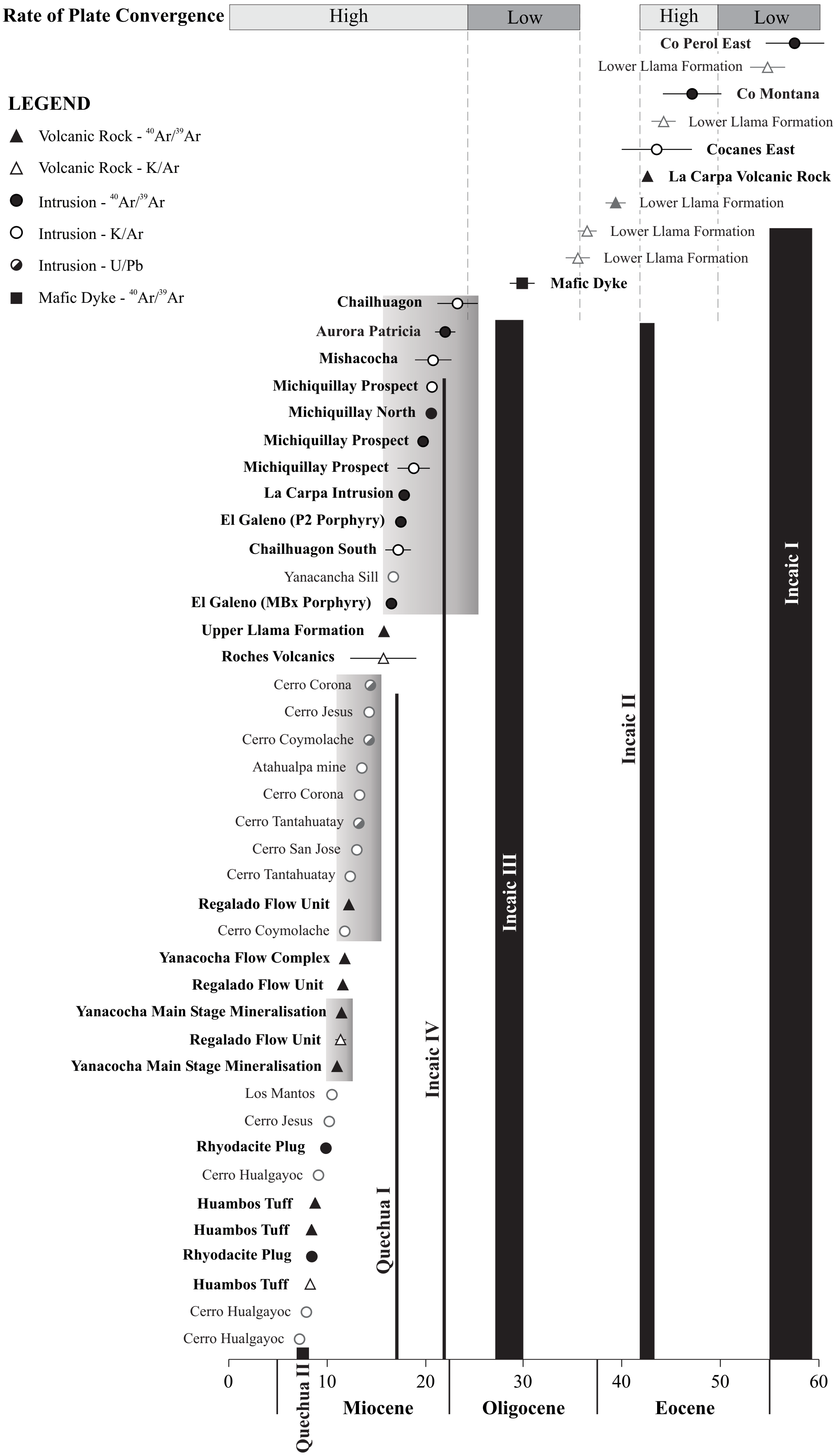
A.9 Discussion

Noble *et al.* (1990) recognised a close association between Tertiary tectonism and magmatism in the Central Andes. They inferred this association was directly linked to large-scale tectonic events, such as relative motion of major lithospheric plates and rate of plate convergence. This assumption appears to be partially true based on results from this and other age dating studies (Fig. 9). Between 50 and 42 Ma the western margin of the South American plate was characterised by high convergence rates (~150 mm/year, Pardo-Casas and Molnar, 1987). This interval roughly corresponds with widespread deposition of Llama-Calipuy Volcanic rocks (~54-43 Ma) in the northern Peruvian Andes (Benavides, 1999). The dates of four igneous rocks from the Cajamarca-Llama region fit within this interval of high convergence. Three of these four dates are toward the end of the interval and coincide with the Incaic II (43-42 Ma) tectonic event. Two igneous rocks predate this interval, with a crystallisation age of the oldest igneous rock (S-46 at 57 Ma) corresponding with the Incaic I orogenic event (59-55 Ma, Benavides, 1999).

This period of high convergence rates was followed by low convergence rates, from 36 to 24 Ma (Pardo-Casas and Molnar, 1987), during which some volcanic rocks were erupted (39.3-35.4 Ma, Noble *et al*., 1990) and high-level mafic dykes were emplaced (*ca*. 29.5 Ma). This age coincides with the onset of the Quechua III tectonic event (30-27 Ma, Benavides, 1999). A strong link between low convergence and magmatism quiescence is evident in northern Peru where few Oligocene igneous rocks have been documented or dated (Noble and McKee, 1999).

Magmatic activity recommenced around the early Miocene (*ca*. 23 Ma) and was temporally linked with the Incaic IV orogenic pulse (22 Ma, Benavides, 1999), clockwise rotation of the Nazca Plate and an increase in plate convergence rate (Fig. 9, Pardo-Casas and Molnar, 1987). Early Miocene magmatism near Cajamarca resulted in formation of numerous porphyry-related Cu ± Au deposits including Minas Conga (23.2-17.1 Ma), Michiquillay (19.8 Ma), El Galeno (17.5-16.5 Ma) and possibly Minas Carpa (~17.5 Ma?). Several similar-aged barren intrusions also crop out in the region, such as intrusions at Aurora Patricia (21.3 Ma), Michiquillay north (20.6 Ma) and La Carpa (17.9 Ma). Results from this study indicated early Miocene porphyry-related deposits formed over a 7 m.y. period. Noble and McKee (1999) and Petersen (1999) both suggested magmatic and metallogenic provinces in central and northern Peru formed over short time intervals. Noble and McKee (1999) further concluded prolonged magmatic-hydrothermal intervals (5–10 m.y.), such as documented in the Potrerillos district of Chile (Marsh *et al*., 1997), are favourable for formation of giant porphyry deposits. Therefore, the absence of giant deposits in central and northern Peru is

Fig. 9. Diagram illustrating the timing of magmatic-hydrothermal events in the Cajamarca (bold), Hualgayoc and Llama-Huambos regions (refer to Tables 1 and 3) with recognised orogenic pulses (Benavides, 1999) and changes in the rate of convergence between the South America and Nazca plates (Pardo-Casas and Molnar, 1987). Shaded regions define periods of mineralisation in the Cajamarca and Hualgayoc regions. Dates considered or shown to be unreliable, such as Michiquillay North by Laughlin *et al*. (1968), have been omitted from this diagram.


Rate of Plate Convergence
High
Low
High
Low
LEGEND
▲ Volcanic Rock - 40Ar/39Ar
△ Volcanic Rock - K/Ar
● Intrusion - 40Ar/39Ar
○ Intrusion - K/Ar
◐ Intrusion - U/Pb
■ Mafic Dyke - 40Ar/39Ar
Co Perol East
Lower Llama Formation
Co Montana
Lower Llama Formation
Cocanes East
La Carpa Volcanic Rock
Lower Llama Formation
Lower Llama Formation
Lower Llama Formation
Mafic Dyke
Chailhuagon
Aurora Patricia
Mishacocha
Michiquillay Prospect
Michiquillay North
Michiquillay Prospect
Michiquillay Prospect
La Carpa Intrusion
El Galeno (P2 Porphyry)
Chailhuagon South
Yanacancha Sill
El Galeno (MBx Porphyry)
Upper Llama Formation
Roches Volcanics
Cerro Corona
Cerro Jesus
Cerro Coymolache
Atahualpa mine
Cerro Corona
Cerro Tantahuatay
Cerro San Jose
Cerro Tantahuatay
Regalado Flow Unit
Cerro Coymolache
Yanacocha Flow Complex
Regalado Flow Unit
Yanacocha Main Stage Mineralisation
Regalado Flow Unit
Yanacocha Main Stage Mineralisation
Los Mantos
Cerro Jesus
Rhyodacite Plug
Cerro Hualgayoc
Huambos Tuff
Huambos Tuff
Rhyodacite Plug
Huambos Tuff
Cerro Hualgayoc
Cerro Hualgayoc
Incaic I
Incaic II
Incaic III
Incaic IV
Quechua I
Quechua II
0
10
20
30
40
50
60
Miocene
Oligocene
Eocene

possibly explained by the lack of prolonged magmatic intervals. However, results from this study indicate prolonged magmatic-hydrothermal activity has occurred in the Cajamarca region. Whilst no giant porphyry deposits developed during this interval, a number of significant Au-rich (Minas Conga and Minas Carpa) and Cu-Au-Mo (Michiquillay and El Galeno) porphyry deposits did form. A cluster of dates between 17.85 and 16.53 Ma (Fig. 9) suggests early Miocene magmatism peaked and terminated contemporaneously with Quechua I tectonic event (17 Ma; Benavides, 1999). This magmatic interval appears to have been followed by an approximately three million year magmatic hiatus.

The timing of magmatic and hydrothermal activity in the polymetallic Hualgayoc region has been well documented (Fig. 9, Borredon, 1982; Macfarlane *et al.*, 1994; James, 1998). The oldest igneous rock dated in this region, the Yanacancha Sill, was emplaced at *ca*. 16.8 Ma (Macfarlane *et al.*, 1994) and followed by the Cerro Corona and Cerro Coymolache intrusions at ~14.4 Ma (James, 1998). A Tantahuatay intrusion yielded a slightly younger date of 13.2 ± 0.2 Ma (James, 1998) that concurs with hydrothermal activity at Cerro Corona, Cerro San Jose and the Atahualpa mine (Macfarlane *et al.*, 1994). Despite later sporadic hydrothermal activity and emplacement of rhyodacitic stocks in the region (Fig. 9; Borredon, 1982; Macfarlane *et al.*, 1994), intense magmatism largely ceased after *ca*. 12.5 Ma. The cause of this apparent change in focus of Miocene magmatic-hydrothermal activity between the Cajamarca and Hualgayoc districts is unclear. This possibly reflects a bias in sampling and the number of igneous rocks dated. High precision ^{40}Ar/^{39}Ar dates from Turner (1997) indicate eruption of andesitic to rhyodacitic rocks (12.3-8.4 Ma) and formation of the Yanacocha high-sulphidation deposit (11.46-10.92 Ma) characterises middle to late Miocene magmatic activity in the Cajamarca region. Termination of magmatism in both Cajamarca and Hualgayoc occurred during the Quechua II orogenic event (7-8 Ma, Benavides, 1999).

In summary, the ages of Tertiary igneous rocks in the Cajamarca and Hualgayoc regions further support the association between periods of magmatic activity, tectonism and high convergence rates proposed by Noble *et al.* (1990). Palaeocene-Eocene magmatism appears to have peaked during the Incaic II orogenic event and towards the end of a period of high convergence rate. Oligocene times were characterised by a lack of magmatic activity and low plate convergence rates. Intense Miocene magmatism commenced shortly after the Incaic IV compressional event, which was associated with a change to high convergence and rotation in plate motion (Pardo-Casas and Molnar, 1987). Significantly, periods of Miocene mineralisation in the Cajamarca-Hualgayoc region did not necessarily coincide with orogenic intervals or changes in plate subduction angle.

A.10 Conclusion

New $^{40}Ar/^{39}Ar$ dates further constrain the timing of magmatic and hydrothermal events in the Cajamarca region. These high precision results combined with previous age dating studies suggest the following magmatic-hydrothermal history:

1. Palaeogene magmatism (57-35 Ma) was characterised by both deposition of the Upper Llama Volcanic Formation and emplacement of felsic intrusions.
2. Several mafic dykes were possibly emplaced around middle Oligocene times. However, the Oligocene appears to have been characterised by a lack of volcanic and intrusive activity.
3. Formation of porphyry-related deposits occurred over a 7 m.y. interval during the early to middle Miocene (23.2 – 16.5 Ma) and coincided with emplacement of coeval barren intrusions. Thus far, no volcanic rocks have been dated during this 7 m.y. interval.
4. Deposition of the Lower Llama Volcanic Formation *ca*. 15.8 occurred following formation of the porphyry deposits.
5. Deposition of middle to Lower Miocene volcanic rocks (~12.3 Ma) occurred after an apparent 3.5 m.y. magmatic hiatus.
6. Formation of the Yanacocha district and main stage Au mineralisation between 11.5 and 10.9 Ma.
7. Cessation of magmatic activity in the Cajamarca region during late Miocene times (8.4 Ma).

The new $^{40}Ar/^{39}Ar$ dates suggest magmatic events in the Cajamarca region may have occurred over longer intervals than previously suggested. At present, a high concentration of age dates for magmatic-hydrothermal events in the Cajamarca-Hualgayoc region are from known mineralised centres, such as Yanacocha, Minas Conga, Michiquillay and El Galeno. This has created a bias towards understanding the age of mineralised centres. Further dates of barren igneous rocks are required to fully constrain the duration of regional magmatism so we understand to the timing of mineralisation events relative to magmatic intervals. Furthermore, a number of previous age dates were determined using the K-Ar system. Compared to the high precision $^{40}Ar/^{39}Ar$ results, previous K-Ar dates of igneous rocks in the region have high uncertainties or represent unreliable dates.