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EPISODES OF CENOZOIC EXTENSION IN THE ANDEAN OROGEN OF PERU AND THEIR RELATION TO COMPRESSION, MAGMATIC ACTIVITY AND MINERALIZATION

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ABSTRACT

Olivine-bearing basalt, low-silica andesite and low-silica latite of late Eocene, early and middle Miocene, and Pliocene age are present in various places in the Andes of south-central Perú. Neogene units containing basalt, conglomerate and/or freshwater limestone predate pulses of Incaic IV(?), Quechua I and Quechua II compressive deformation in the vicinities of Ayacucho, Lircay, Huancavelica and Huachocolpa by several million years or less. In the Ayacucho basin, conglomerate and alluvial fan deposits are intercalated with mantle-derived olivine basalt, rhyolite and other volcanic rocks that erupted along the high-angle faults, and lacustrine sediments were deposited in closed basins. Near Lircay, extensional basin formation, basaltic volcanism and formation of freshwater limestone was followed by deposition of conglomerate derived from the upthrown block of a high-angle reverse fault. Eruption of latest Miocene-Pliocene low-silica andesite and basalt appears to have been associated with little fault movement or basin formation.

The amount of absolute extension was much less than in regions such as the Great Basin of the western United States, and was localized within basins bounded by high-angle faults, commonly reactivated, parallel to the trend of the Andes. Conglomerate wedges were also sourced from tectonic highs produced by folding and/or reverse faulting and deposited in "piggy-back" basins. Conglomerate cannot be confidently used, without other data, to differentiate episodes of compressive and extensive tectonism.

A possible explanation for the observed geological relations is provided by the model of Mercier et al. (1992), in which a steeping subducting plate first allows spreading of the Andean highlands towards the trench. This is quickly followed by breaking of the sinking slab, more direct interaction between the converging plates, and a resultant pulse of compressional deformation. During the episodes of extension or transtension, faults extending into the lower crust allowed little-modified mafic magma to ascend to the surface.

During late Eocene time, olivine basalt, underlain by a unit containing freshwater limestone, was locally erupted shortly after formation of the regional post-Incaic II erosional surface. In other areas, the Incaic II surface in overlain by coarse conglomerate, in places accompanied by freshwater limestone or dolomite. The age of late Eocene basalt, conglomerate and carbonate is closely constrained by that of overlying volcanic units, and intense Incaic II compression, uplift, formation of the regional erosional surface, as well as subsequent extension of the rising block occurred within no more than two to three million years. The enormous volume of intermediate and silicic volcanic rock subsequently erupted between about 41 and 37 Ma suggests a genetic relation between the relaxation of stress following Incaic II compression and the generation and eruption not only of basalt but also enormous volumes of subduction-related calc-alkalic magma.

The presence of olivine basalt of Neogene and Paleogene age, in conjunction with the common straight traces of faults paralleling the general trend of the Andes, argues that steeply-dipping faults with an important strike-slip component are common, and perhaps typical, of the Western Cordillera of Perú. Faults were typically repeatedly reactivated, with the direction of slip at any given time being a function of the local stress field.

There is some suggestion that mineral deposits were preferentially formed during periods of neutral stress or extension. Possibly stress conditions that allowed the generation and rapid eruption of mafic magma were favorable for the generation of more felsic magmas with mineral potential, and/or the rapidity of eruption to high crustal levels resulted in the preservation of sufficient amounts of the critical chemical components necessary for mineralization.

RESUMEN.- EPISODIOS DE EXTENSIÓN CENOZOICA EN EL ORÓGENO ANDINO DEL PERU Y SU RELACIÓN CON LA COMPRENSIÓN, ACTIVIDAD MAGMATICA Y MINERALIZACIÓN

Basaltos olivínicos, andesitas y latitas subsilíceas del Eoceno tardío, Mioceno temprano y medio y del Plioceno están presentes en varias localidades de los Andes en el sur del Perú. En las vecindades de Ayacucho, Lircay, Huancavelica y Huachocolpa, las unidades del Neógeno que contienen basaltos, conglomerados y/o calizas lacustrinas predatan a los pulsos de compresión Incaico IV (?), Quechua I y Quechua II. En la cuenca de Ayacucho los conglomerados y abanicos aluviales están intercalados con basaltos olivínicos, riolitas y otras rocas volcánicas que erupcionaron a lo largo de fallas de alto ángulo que —a su vez— controlaron la sedimentación lacustrina en cuencas cerradas. Cerca de Lircay, la formación de cuencas extensionales, el volcanismo basáltico y la formación de calizas lacustrinas fueron seguidos por deposición de conglomerados derivados de la erosión de un bloque levantado por fallas inversas. La erupción de andesitas y basaltos del Mioceno-Plioceno parece estar asociada con menor movimiento de fallas y formación de cuencas extensionales.

El grado de extensión absoluta en el Cenozoico del Perú fue mucho menor que aquel descrito para la región del "Great Basin" ubicada al oeste de los Estados Unidos. La tectónica extensional en ambos casos estuvo localizada dentro de cuencas limitadas por fallas de alto ángulo y comúnmente reactivadas paralelamente a las cordilleras. Los lentes de conglomerado tuvieron sus orígenes en altos tectónicos producidos por plegamiento y/o fallas inversas para luego depositarse a horcajadas en cuencas del tipo "piggy-back". La presencia de conglomerados sin otra información adicional no puede ser usada confiablemente para diferenciar episodios de tectonismo compresivo o extensivo.

Una probable explicación para las relaciones geológicas observadas fue propuesta por Mercier et al. (1992), cuyo modelo propone una placa en subducción de alto ángulo que permite la expansión de las planicies altoandinas. A esta etapa le siguen la rotura de la placa en subducción, una interacción directa entre las dos placas convergentes y —como resultante— un episodio de deformación compresional. Durante los episodios de extensión o transtensión, las fallas resultantes atraviesan la corteza inferior y canalizan el ascenso de magmas máficos a la superficie.

Durante el Eoceno tardío los basaltos olivínicos fueron localmente erupcionados después de la formación de la superficie erosional post-Incaica II. En otras áreas sobre esta misma superficie de erosión yacen conglomerados gruesos y calizas a dolomías lacustrinas sin basaltos. La edad de estas secuencias está determinada por las unidades volcánicas superiores, la intensa compresión Incaica II, el levantamiento y la formación regional de la superficie de erosión así como la posterior extensión; todo lo cual sucedió en no más de 2 a 3 Ma. El enorme volumen de rocas volcánicas de composición intermedia a félsica posteriormente erupcionadas entre 41 y 37 Ma sugieren una relación genética entre el relajamiento de los esfuerzos luego de la compresión Incaica II. La generación y erupción de rocas volcánicas incluyó no solamente basaltos sino inmensos volúmenes de magmas calco-alcalinos relacionados a la subducción. La relación entre las fallas de rumbo andino con los basaltos olivínicos del Cenozoico es una característica común y probablemente típica en toda la Cordillera Occidental del Perú. Las fallas y conductos alimentadores fueron repetidamente reactivados con variable dirección de desplazamiento según los esfuerzos locales.

Es aparente que los yacimientos minerales se formaron preferencialmente durante los períodos neutros o extensionales. Asimismo, las condiciones tectónicas que permitieron la generación, el rápido ascenso y la erupción de magmas máficos fueron favorables para la posterior generación de magmas félsicos con potencial polimetálico. Alternativamente, la rapidez eruptiva de estos magmas primitivos hasta alcanzar los niveles corticales superiores habría preservado cantidades suficientes de los componentes químicos críticos para alimentar los procesos hidrotermales mineralizantes.

INTRODUCTION

The Peruvian Andes are a classic area for uplift and compressive tectonism (e.g., Mégard, 1987). It is generally accepted that compressive tectonism was episodic, reflecting a number of pulses of deformation, some of which can be recognized over large areas (e.g., Noble et al., 1974; 1979; 1990, Mégard, 1977; Soulas, 1977; McKee and Noble, 1982; Mégard et al., 1984; Sébrier et al., 1988a; Ellison et al., 1989; Sandeman et al., 1995; Benavides-Cáceres, 1999). These include the Incaic II pulse at 42-43 Ma and the Quechua I, II III, events at about 17, 9, and 5 Ma. In addition, there is evidence for one or more pulses of late Oligocene (~27 Ma) and earliest Miocene (~22 Ma) deformation: the Incaic III and IV pulses of Benavides-Cáceres (1999). There is not, however, unanimity concerning the nature, identity, duration, and degree of synchronicity of individual pulses (e.g., Mégard et al., 1983; Noble et al., 1996).

Strong evidence for transcurrent movement is also present in a number of areas (e.g., Soulas and Mégard, 1980; Mégard, 1984; Mégard et al., 1984; Marocco et al., 1995), which fits well with the partitioning of the known plate vectors (Dewey and Lamb, 1992). Transpressive and transtensive deformation, with common rapid changes in stress direction, was probably a common feature of Andean tectonism (Dorbath et al., 1990; Mercier et al., 1992; Macharé and Ortega, 1997). This is particularly so during the Neogene, when stress patterns reflecting the oblique direction of subduction (Somoza, 1998) would have favored strike-slip movement. In the high Andes, compressive events were separated by longer periods during which tectonic quiescence prevailed. Field relations, controlled by radiometric dating, in a number of localities, mainly in central Perú, provide evidence suggesting that in some cases pulses of extension or, perhaps more commonly, transtension, immediately preceded compression.

Spectacular examples of Plio-Quaternary normal faulting are known in Perú, perhaps the best examples being provided by the normal fault system along the western margin of the Cordillera Blanca in northern Perú (Dalmayrac, 1974; Bonnot et al., 1988; Deverchère et al., 1989) and the Cuzco-Vilcanota fault system in southeastern Perú (Cabrera, 1988; Mercier et al., 1992). Transtensional movement has been postulated for the late Neogene history of the Cordillera Blanca and Callejón the Huaylas (Mercier et al., 1992; Petford and Atherton, 1992). Extension is taking place in the highlands coeval with contraction in the foreland thrust belt. Modern seismicity shows this pattern of coexisting extension/transtension and compression/transpression (Suarez et al., 1983).

Continental-margin rift-extension has also been recognized in the pre-Cenozoic, with examples being provided by the rifting that led to the deposition of clastic and volcanic rocks of the Permian-Triassic Mitu Group (Noble et al., 1978; Kontak et al., 1985). More than nine kilometers of primitive basalt of the early Cretaceous Casma Group are generally believed to have been deposited within the Huarmey-Cañete rift basin or Western Peruvian trough (Wilson, 1963; Atherton and Webb, 1989; Cobbing, 1998), although the possibility exists that the Casma Group may be separated from miogeoclinal rocks to the east by a major trancurrent structure. Both of these examples, however, may reflect a tectonic mode distinct from the Neogene extension-compression events that are the subject of this paper.

In spite of the clear evidence for late Neogene normal faulting and the recognition of episodes of extension in the pre-Cenozoic portion of the Andean cycle (Benavides-Cáceres, 1999), with certain notable exceptions (e.g., Marocco et al., 1995) relatively little attention has been given to the possibility of crustal extension reflected by normal faulting and the formation of grabens and tilted fault blocks prior to latest Miocene time in the High Cordillera. The present paper summarizes the presence of basalt, conglomerate and freshwater limestone in various parts of the Neogene and Paleogene section of central Perú (Figure 1) and interprets this petrotectonic assemblage in terms of extensional/transtensional faulting, basin formation and associated mafic volcanism. Episodes of extension are associated with slightly younger pulses of compressive tectonism, producing extension-compression couples that appear to characterize Neogene deformation in this portion of the Andes (Figure 2).

ROCK TYPES INDICATIVE OF EXTENSION

Olivine-bearing basalt and low-silica andesite

Olivine-bearing basalt, low-silica andesite and latite (shoshonite) are found in the Andes of south-central Perú (Noble et al., 1975) More recent work has increased the geographic distribution and range in age of basalt occurrences. Specific occurrences of basalt of Eocene

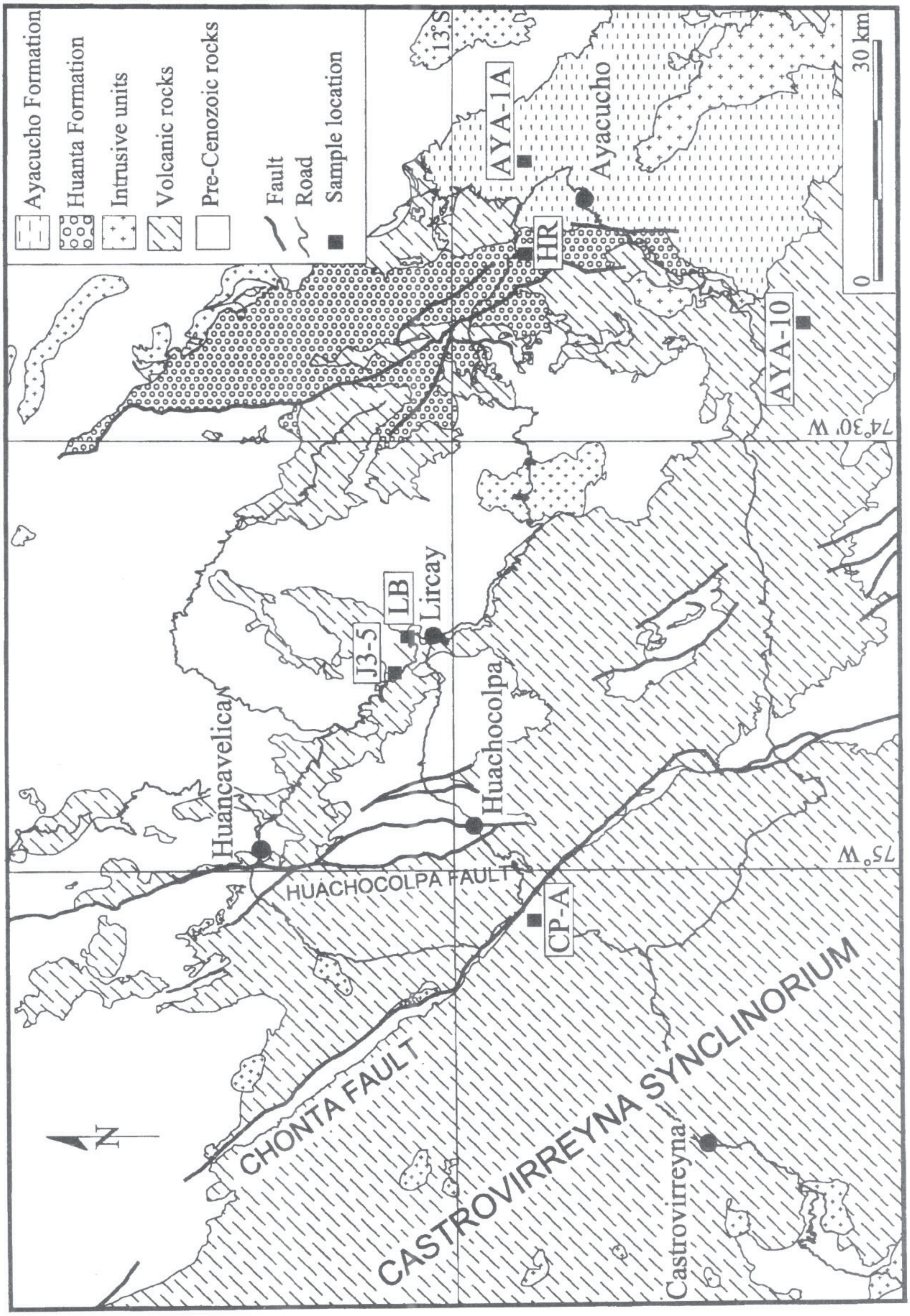

Figure 1. Map of south-central Peru showing localities and sample sites referred to in text.

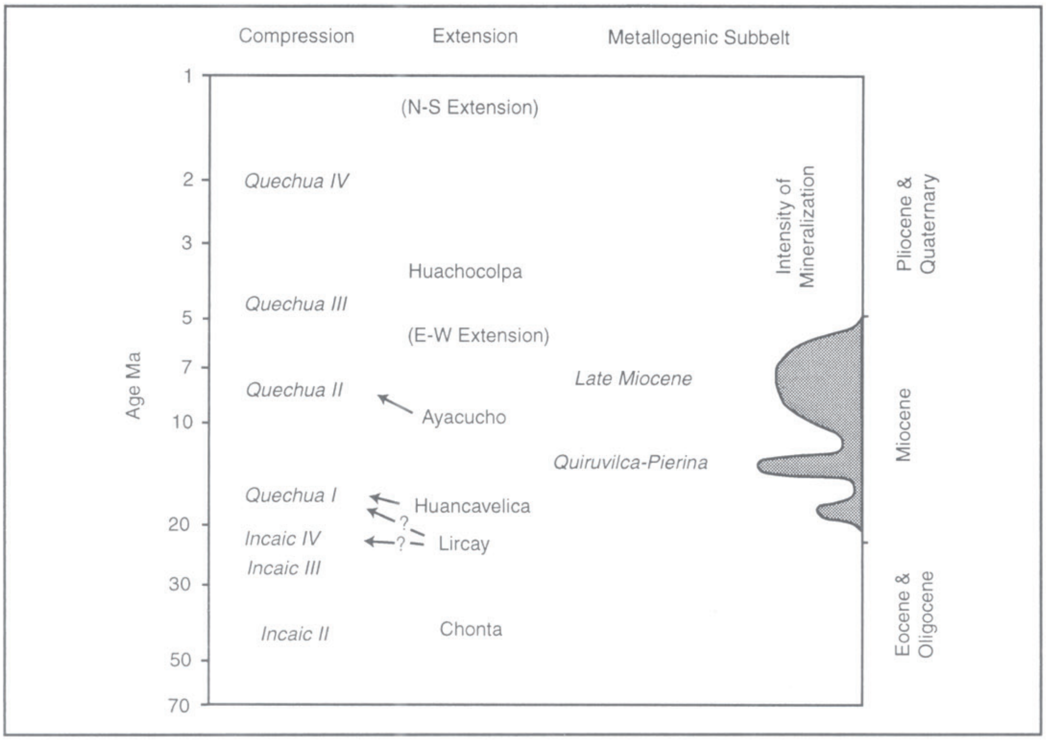

Figure 2. Diagram showing ages of compressive deformational pulses, probable and possible extensional events and metallogenic subbelts, and the relative intensity of mineralization within the Miocene metallogenic belt of central and northern Peru. Compressional pulses are as given by Benavides-Cáceres (1999) and data on metallogenic belts and mineralization are from Noble and McKee (1999). Extensional events are indicated by names of areas where they are best known in south-central Perú.

and early and middle Miocene age in south-central Perú are described in following sections. In addition, basalt of late Miocene and/or Pliocene age is present west of Huancayo, south of Ayacucho and in the Lircay-Huancavelica area in central Perú (Noble et al., 1975).

Basalt is also present locally in northern Perú. Hollister and Sirvas (1978) and Atherton et al. (1985) have reported basalt in the thick sequence of frontal arc volcanic rocks ("Calipuy Group") that that overlies the Incaic II unconformity. (But note that the large areas of "plateau basalt" shown by Petford and Atherton, 1992, Figure 1, are incorrect.) Basalt of late Miocene or younger age is present in the Tamboras district of northern Perú (Heintze, 1985). Basalt and latite (shoshonite) of Neogene age is present in various areas of southeastern Perú (e.g., Cabrera, 1988; Carlier et al., 1993; Sandeman et al., 1997).

Major- and minor-element analyses for eight specimens of olivine-bearing basalt, low-silica andesite and latite from south-central Perú are given in Table 1. All rocks contain abundant olivine and possess moderate to high concentrations of potassium and other large-ion-lithophile elements, and show marked enrichment in the light rare earth elements (Figure 3). The elevated concentrations of many lithophile elements suggest that they were derived from an enriched mantle sources. However, Rb contents and Rb/Sr ratios are unusually low, suggesting one or more prior stages of magma generation that depleted the sources in Rb (cf. Hedge and Noble, 1971).

The rocks can be subdivided into two groups based on the relative amounts of Ta and Th and Ti contents. The four oldest specimens have Ta/(Ta+Th) of between 0.27 and 0.40 and Ti contents between 1.9 and 2.15 wt. percent, whereas the four late Miocene and Pliocene specimens have markedly lower Ta/(Ta+Th) values of between 0.10 and 0.17 and Ti contents of between 1.15 and 1.45 wt. percent. The differences in Ta/(Ta+Th) mostly reflect the markedly lower contents of Ta in the younger rocks. Depletion in Ta, invariably accompanied by lower contents of Nb and Ti, are generally thought to reflect the effects of subduction processes on the source material of the basalt (e.g., Pearce and Peete,

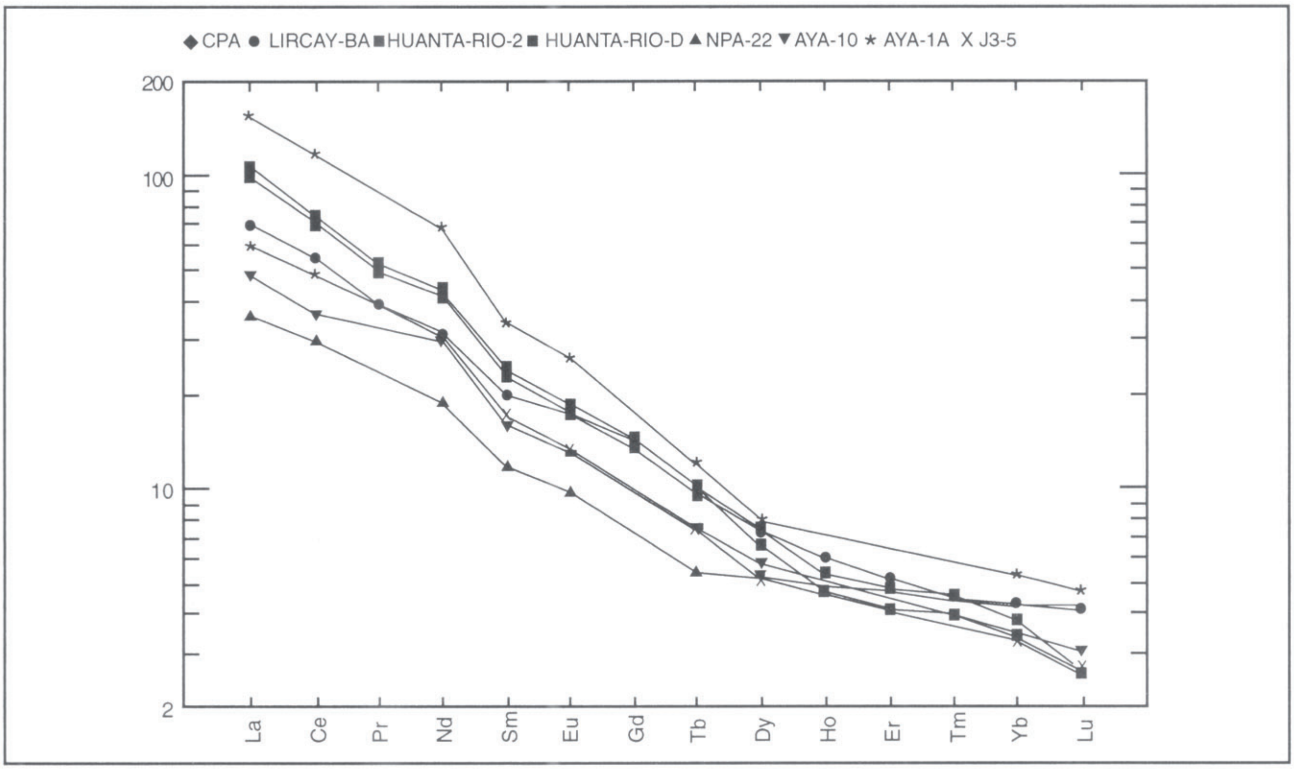

Figure 3. Chrondrite-normalized rare-earth-element diagram for Cenzoic olivine-bearing basalts, low-silica andesites and latite from south-central Perú.

1995). These relationships are best shown on a triangular plot of Ta-Th-Hf/3 (Wood, 1980) (Figure 4). The younger specimens fall well within calc-alkaline field of Wood (1980) whereas the rocks of late Eocene to middle Miocene age, irrespective of position relative to the coast, fall within or near the field of continental basalt. The chemistry of these rocks will be discussed in more detail elsewhere.

In south-central Perú, mafic magma was generated in late Eocene and early Miocene time from mantle materials that were largely unaffected by subduction processes. In contrast, the olivine-bearing low-silica andesite and latite erupted during late Miocene and Pliocene time possess a clear subduction signature, as shown by their markedly lower Ta and Ti contents. The data suggest that marked changes in the mantle material beneath central Perú occurred during late Neogene time as the locus of subduction shifted to the east from Eocene through Miocene time. The earlier basalts were erupted from mantle sources lying sufficiently to the east of the subducted slab to have escaped the effect of subduction-related solutions. In early Miocene time (ca. 23 Ma), the zone of subduction lay sufficiently to the west of the Lircay (Figure 2) so that basalt with high Ta and Ti contents could be generated from mantle material unmodified by subduction processes. By 10 Ma, however, magmas of intermediate to silicic composition were generated in the Huachocolpa and Lircay areas (Noble and McKee, 1999). Approximately coeval basalt erupted to the east in the Ayacucho basin lacks evidence of subduction involvement.

Sanidine-bearing rhyolite

Typical volcanic rocks of the late Eocene and Miocene volcanic pulses of central Perú consist of andesite, dacite, rhyodacite and low-silica rhyolite with plagioclase as the only phenocryst typical of a frontal arc environment. Sanidine-bearing rhyolite tuff, however, is locally present. Such rocks appear to have been erupted primarily during periods of general tectonic and volcanic quiescence (for example a sanidine-bearing tuff in the Castrovirreyna synclinorium yielding an age of 25.8±0.3 Ma) and/or in association with conglomerate, freshwater limestone and/or basalt, for example tuffs within the upper part of the Huanta Formation and the early Miocene section of the Huancavelica district (McKee and Noble, 1982; Mégard et al., 1984).

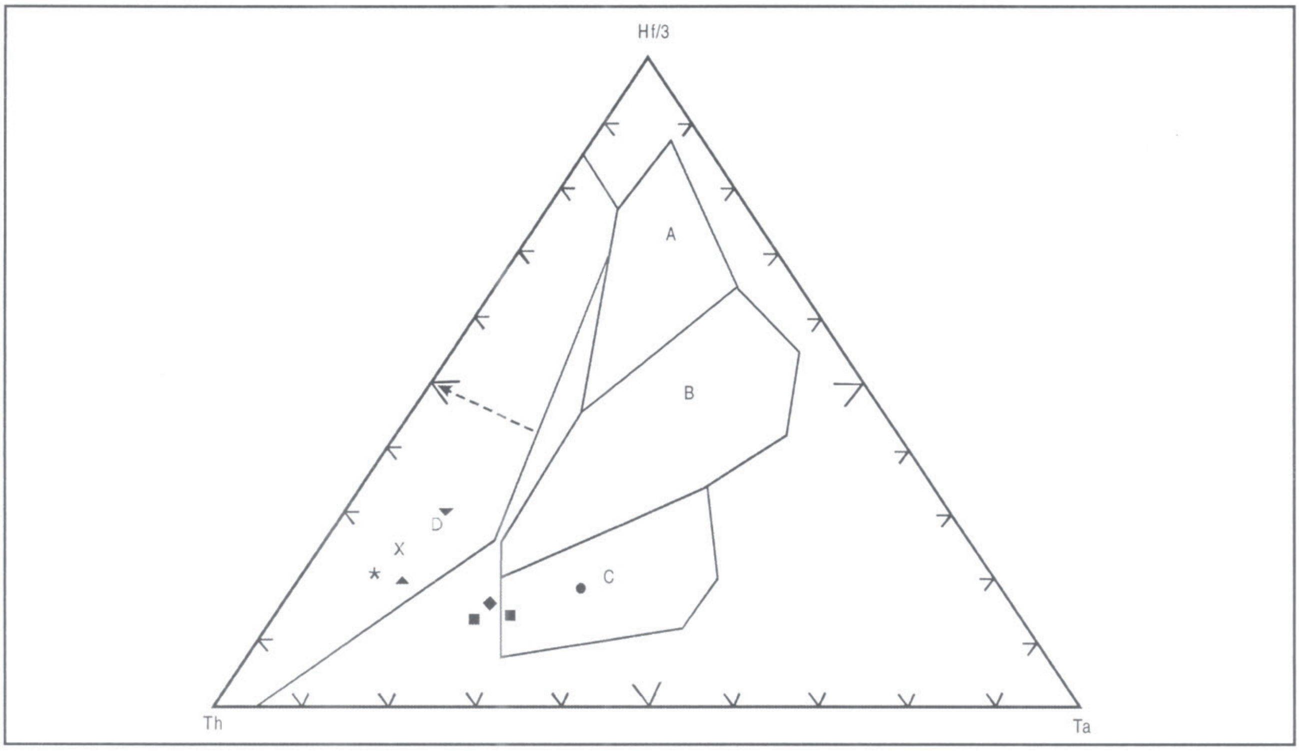

Figure 4. Th-Hf-Ta diagram (after Wood, 1980) for Cenozoic basalts and other rocks from south-central Peru. D is field of subduction-related basalts and intermediate rocks; A, B and C are fields of basalts not affected by subduction. Symbols are the same as in Figure 3.

Conglomerate and fanglomerate

Beds of conglomerate and fanglomerate are present throughout the Paleogene and Neogene section of Perú. Perhaps the most spectacular example is provided by beds of coarse boulder conglomerate of late Eocene age locally more than 100 meters in aggregate thickness that in many places overlie the post-Incaic II (Laderas) erosion surface in northern, central and southeastern Perú (McLaughlin, 1929; Jenks, 1951; Mégard, 1977, Noble et al., 1979b; Benavides-Cáceres, 1999; D.C. Noble, unpublished data). Beds and lenses of conglomerate are also present in many parts of the Neogene section, and selected examples are discussed in following sections.

EXAMPLES OF MIOCENE EXTENSIONAL TECTONISM

While in no way diminishing the importance of compressive and transpressive deformation, extensional tectonism was an integral part of Andean deformation throughout much of Cenozoic time. The following section summarizes the geological relations at certain localities where basalt, conglomerate, freshwater limestone and/or sanidine-bearing tuff suggest crustal extension. Normal faulting produced graben and other extensional/transtensional basins that were filled by conglomerate and lacustrine sediments (e.g., Marocco et al., 1995) that in places are associated with basalt and other volcanic rocks that erupted along extensional structures.

Early Miocene

Rumichaca basin

At Lircay, a sequence of volcanic and sedimentary rocks of early Miocene age, locally referred to as the Rumichaca Group, (Petersen et al., 1977; Mégard et al., 1983; Morche and Larico, 1996) is unconformably overlain by early volcanic rocks of the Julcani volcanic center dated at 10.1 Ma (Noble and Silberman, 1984). The early Miocene sequence consists of several tens of meters or more of olivine basalt overlain in turn by a thin unit of rhyolite tuff dated at about 22.5-23 Ma (McKee and Noble, 1982), and about 100 meters of freshwater limestone with algal laminations and hydrocarbons. These rocks are succeeded by a thick section of conglomerate and boulder conglomerate (Mégard et al., 1983; Marocco et al., 1995). The sequence unconformably overlies Mesozoic limestone in which karst cavities contain a mammalian fauna of early Oligocene age (Hartenberger et al., 1984), suggesting an extended period of Oligocene-earliest Miocene tectonic quiescence.

The association of basalt with the freshwater limestone is strongly suggestive of deposition within an extensional basin. In places, conglomerate is interbedded within the limestone, indicating tectonic instability. The sequence of conglomerates is limited on the west by a west-dipping thrust fault, and fanning dips and internal unconformities near the fault are strongly suggestive of syntectonic compressional deformation (Mégard et al., 1983; Marocco et al., 1995). Compression could belong to the Incaic IV pulse of Benavides Cáceres (1999) or possibly to the Quechua I pulse. Although Mégard et al. (1983) suggested that deposition and syndepositional deformation of the conglomerate sequence took place over a considerable part of middle Miocene time, it is more likely that deposition and deformation took place within a fraction of a million years.

Huancavelica

About 11 kilometers south-southeast of the town of Huancavelica, a section of volcanic sandstone, rhyolite tuff, conglomerate and freshwater limestone is exposed within the core of a syncline, where it unconformally overlies more tightly folded beds of Cretaceous limestone. K-Ar ages of 21.7±0.[illegible] and about 19 Ma have been obtained on units of tuff within the section (McKee and Noble, 1982). The early Miocene rocks therefore appear to have been deposited after the Incaic IV compressive pulse and before the Quechua I event. Folding took place during the Quechua I and/or Quechua II events.

Altos de Camilaca surface

Wedges of conglomerate in several areas, although unaccompanied by basalt, may reflect uplift and extension rather than compression. A candidate is the regional southwest-dipping erosion surface, the Altos de Camilaca surface, in south-central and southern Perú, which is overlain by locally thick beds of boulder conglomerate succeeded by a sequence of ash-flow tuff sheets of early Miocene age (Noble et al., 1979a; Tosdal et al., 1984). A similar surface, overlain by coarse conglomerate and volcanic rocks ranging in age from about 22.2 to 18.6 Ma (D.C. Noble and C.E. Vidal) unpublished data), in the Cordillera Negra northwest of Huaraz in northern Perú is probably of the same age. In both areas, the overlying early Miocene volcanics were strongly folded during the Quechua I event, although in the Nazca-Puquio transect folding took place only east of the rigid Coastal batholith.

Middle and late Miocene

Ayacucho Basin

Mégard et al. (1984) have described a complicated sequence of depositional, magmatic and tectonic events in the Ayacucho basin of south-central Perú, which is located on the northeastern margin of the belt of active Neogene magmatic activity at the boundary of the High Plateau province and the Eastern Cordillera (Figure 1). The Ayacucho basin and areas to the west (McKee and Noble, 1982) together comprise the type region for the Quechua I, II and III tectonic phases in Perú.

The Huanta Formation, which has been divided into several informal members, is perhaps the most important unit exposed in the Ayacucho basin. Mégard et al. (1984) recognized a lower part consisting of beds of arkosic sandstone, siltstone, mudstone, freshwater limestone and, near the base, lenses of breccia and conglomerate. Somewhat different subunits are recognized by Morche et al. (1995) and López et al. (1996). The upper part consists of hundreds of meters of arkose and volcanic sandstone, beds of pebble, cobble and boulder conglomerate and fanglomerate, and volcanic rock. Maximum thickness of the formation approaches, and may exceed, 3,000 m. These units clearly require detailed sedimentological study. They do not, however, appear to contain tilted, fanning angular unconformities, suggesting that they did not form in a contractional piggy-back basin environment.

Volcanic rocks of the Huanta Formation, and other Neogene units of the Ayacucho basin range in composition from basalt, low-silica andesite and latite to rhyolite (Morche et al., 1995). This variability probably owes at least as much to magma mixing as to differentiation, in a manner similar to the inner arc volcanic rocks of southeastern Perú (Carlier et al., 1993; Sandeman et al., 1996). Some of the volcanic rocks in the Huanta Formation are olivine-bearing basalt and/or low-silica andesite (Morche et al., 1995; López et al., 1996; D.C. Noble, unpublished data). Morche et al. (1995) have presented several analyses of rhyolite tuffs with iron contents of less than 0.9 wt. percent. If allowance is made for the addition of Mg and Ca by groundwater, the analyses indicate a high-silica rhyolite composition typical of highly evolved rhyolites of bimodal suites erupted in areas of crustal extension.

The lower part of the Huanta Formation has been dated at about 11.5 Ma (Mégard et al., 1984). Stratigraphic relations and a K-Ar age determination of 9.3±0.3 Ma show that the upper member was deposited before about 9 Ma. Conglomerate and basalt of the upper part of the Huanta Formation were, therefore, deposited within several million years of the subsequent 9 Ma Quechua II compressive tectonic pulse.

Aspects of the depositional environment, such as topographic relief and basins fed by adjacent uplifted blocks, were probably similar to that of the Great Basin of the western United States, and perhaps Death Valley or Owens Valley, California. Coarse clastic units within the Huanta Formation appear to represent high-energy alluvial fans (Marocco et al., 1995) being fed by streams that were continually downcutting because of repeated movement along normal faults bounding the basin (see detailed description of Huanta Formation in López et al., 1996). This analogy, however, does necessarily not imply similar amounts of extension for the two regions.

Faults are present along both flanks of the Ayacucho basin. Mégard et al. (1984) recognized major faults, with in part strike-slip movement, along the southwestern margin of the Ayacucho basin that were interpreted as being a reactivated extension of the braided fault zone of the Ricran synclinorium. A dike of probable low-silica andesite composition about 4.5 km in length and parallel to the structural trend of the basin cuts pre-Cenozoic rock near the northeastern margin of the basin (López et al., 1996). As recognized by López et al. (1996, p. 131) "Las vulcanitas del Miembro Tancas (Formación Huanta) deben de estar relacionados a iniciales y discretos pulsos distensivos de la subfase Quechua 2.". The Molinoyocc and Puchcas volcanics, were erupted between about 10 and 7.5 Ma from vents along the northeastern margin of the basin, providing evidence for an open fault zone during the early part of late Miocene time (Mégard et al., 1984). In conclusion, the Ayacucho basin may have been a rhombochasm, filled with alluvial fan deposits, conglomerate and a bimodal suite of volcanic rocks, including olivine basalt and high-silica rhyolite, generally interpreted as reflecting crustal extension (e.g., Edwards and Russell, 1999), that was reactivated several times during the Neogene and repeatedly overprinted by compressional events.

The late Miocene (ca. 7 Ma) Ayacucho Formation overlies the Huanta Formation with strong unconformity, providing the type example of the Quechua II compressive event (Mégard, 1984). The Ayacucho Formation consists of rhyolitic ash-flow tuff and interbedded lake sediments (Pacaycasa member) that to the southeast interfinger with and are overlain by lava flows of intermediate composition, some of which contain olivine. The Pacaycasa member contains beds of conglomerate, particularly along the northeastern margin of the basin, and intraformational unconformities are locally present. These features have been interpreted by Mégard et al. (1984) to indicate, at least in part, horizontal shortening coeval with deposition. It seems possible, however, that these local unconformities were produced by slumping or even local compression within an actively subsiding extensional or transtensional basin.

Huachocolpa district

In the Arco Iris area directly north on the Tinquicorral zone of the Huachocolpa district, a sequence of boulder conglomerate interbedded with beds of silicic tuff and freshwater limestone is overlain by dacitic tuff and breccia on which K-Ar ages of 10.3±0.3 and 10.6±0.3 Ma have been obtained (McKee et al., 1975). No basalt has been recognized. The overlying volcanic rocks exhibit a progressive shallowing in dip, suggesting tectonic rotation during deposition. Although volcanic rocks interbedded with the conglomerates have not been dated, the transitional relation with overlying rocks dated at about 10.5 Ma suggest deposition between the Quechua I and Quechua II pulses. The conglomerate-bearing sequence was tightly folded by the late Miocene Quechua II event.

Huancavelica mercury district

At the area of the historic Santa Bárbara mercury mine, a sequence of coarse conglomerate composed largely of cobbles and boulders of Mesozoic limestone overlies strata of Mesozoic age with strong unconformity. The conglomerate is overlain by a sanidine-bearing rhyolite tuff intercalated with pebble conglomerate and freshwater limestone that in turn is overlain by lava of intermediate to mafic composition. Although mapped as the Casapalca Formation of latest Cretaceous-early

Paleogene age by Yates et al. (1951), the sequence is appreciably younger. The conglomerate locally contains at its base beds composed almost entirely of blocks of a distinctive phenocryst-rich rhyolite lava lithologically very similar to a unit that crops out less than a kilometer away and has been dated at about 16.6 Ma (McKee et al., 1986). The entire sequence has been tilted about 35 to 40+ degrees to the west. The conglomerate locally hosts ore, which was deposited between about 7 and 4 Ma (McKee et al., 1986), and because the deposit or overlying rocks of late Miocene age have not been tilted, the steep dips must reflect Quechua II deformation. The conglomerate, therefore, is best interpreted as reflecting post-Quechua I extension.

Castrovirreyna district

West of the Huachocolpa and Huancavelica districts and the Chonta fault, a major, very linear structure that was active as late as the Quechua II event, dacite and andesite lavas that host the veins of the Castrovirreyna mineral district grade outward through laharic breccia to volcanic sandstone that locally is intercalated with beds of freshwater limestone and black anoxic shale. Basalt has not been recognized, and in the absence of information from other areas the presence of a closed basin could be ascribed either to extension or to initial phases of Quechua II compression.

Pliocene

In the Huachocolpa district, dikes of rhyodacite or low-silica rhyolite accompanied by domes and small pyroclastic vents of very similar composition that define a north-northwest – south-southeast trending belt at least 25 km in length were emplaced about at about 4 Ma (McKee et al., 1975). The dikes show a consistent north-south trend, suggesting an approximately east-west directed least principal stress direction during the early Pliocene (Mégard et al., 1984). The dikes are identical in age within the limits of analytical uncertainty to the potassic low-silica latite (shoshonite) Huari lavas, dated at 3.8±0.4 Ma (Noble et al., 1975; Mégard et al., 1984; Morche et al., 1995) of the Ayacucho basin, the more mafic of which are clearly of mantle derivation. Beds of conglomerate of Pliocene age in several basins in southeastern Perú (Benavides-Cáceres, 1999) may be interpretable in terms of extension.

Late Pliocene extension is also suggested by small volumes of olivine-bearing low-silica andesite and basalt that locally overlie volcanic rocks of late Miocene age in a belt extending from south of Lircay to several tens of kilometers northeast of Huancavelica. One occurrence in the Julcani district has been dated at 2.24±0.05 Ma (Noble and Silberman, 1984). Southeast of Ayacucho, the morphologically very young lavas of the Lucho Jahuana Pampa volcano, situated along the southeastern extension of the fault system bounding the eastern margin of the Ayacucho basin, include olivine-bearing basalt (Morche et al., 1995).

Latest Miocene-Pliocene extension in south-central Perú with the emplacement of dikes and the eruption of basalt does not appear to have been associated with major fault movement or the formation of extensional basins.

Possible late Eocene extension

The oldest known occurrence of basalt is near the base of the late Eocene (41-37 Ma) section (Sacsaquero Formation), which overlies the ca. 41-42 Ma Incaic II unconformity in south-central Perú. Olivine basalt (Table 1) at the base of the locally recognized Yahuarcocha member overlies a thin discontinuous unit (Chonta member) composed of volcanic sandstone with intercalations of freshwater limestone and pebble conglomerate. Radiometric ages on the Yahuarcocha member and overlying units (Noble et al., 1979b; D.C. Noble, unpublished data) show that basalt was erupted within three million years of the 42-43 Ma Incaic II tectonic pulse. The remainder of the voluminous Sacsaquero Formation consists of andesite, dacite and rhyolite of calc-alkaline aspect. Areal extent and maximum thickness of the basalt flows are unknown.

Perhaps the most spectacular occurrence of late Eocene conglomerate is found in the general region of Colquijirca, Cerro de Pasco, and Gollarisquiza in north-central Perú, where the sequence has been termed the Pocobamba Formation by Jenks (1951). Sequences of coarse conglomerate in places containing blocks in excess of one meter in diameter are interbedded with and overlain by carbonate-bearing beds of lacustrine origin. The sequence of conglomerate, which has been termed the Shuco member, is composed almost entirely of limestone of the Upper Triassic-Lower Jurassic Pucará Group, which is exposed over large areas directly east of the Colquijirca and Cerro de Pasco districts. In the Colquijirca district, the Shuco member is overlain by the Calera member, which includes beds of non-

Table 1. Analyses of Cenozoic Basalt, Low-Silica Andesite and Latite from South-Central Perú

	1	2	3	4	5	6	7	8
SiO_2	47.73	47.17	45.54	48.76	52.6	52.8	53.4	52.8
TiO_2	1.88	2.14	2.14	1.92	1.16	1.35	1.45	1.39
Al_2O_3	15.30	15.44	14.42	15.07	16.6	16.4	15.5	16.8
Fe as Fe_2O_3	10.59	10.00	10.63	9.72	7.59	8.40	7.40	7.80
MgO	6.10	7.36	7.87	7.44	8.16	7.03	5.91	6.62
CaO	9.79	8.14	10.90	8.41	7.66	8.03	8.02	7.56
Na_2O	3.25	3.66	3.22	3.74	3.3	3.8	3.8	4.0
K_2O	1.58	1.72	0.95	2.22	1.72	1.40	2.86	1.80
MnO	0.17	0.14	0.16	0.13	0.12	0.12	0.16	0.12
P_2O_5	0.96	0.91	1.33	1.07				
LOI	2.49	3.23	3.42	1.47				
Total	99.84	99.94	99.77	99.97	99.0	99.4	98.5	98.9
Ni (ppm)	109	39	88	77	139	134	74	79
Co	35	32	34	34	35.8	35.1	31.0	33.6
Cr	210	203	186	194	395	328	172	210
Rb	28	24	18	37	54	32	52	46
Sr	870	898	2,022	1,236	624	695	2,200	1,030
Ba	576	741	1,064	1,004	482	488	3,050	768
Zr	201	204	190	190				
Hf					3.8	4.6	6.3	5.0
Nb	45	54	51	49				
Ta	2.37	3.2	2.8	2.7	0.79	0.60	0.84	0.64
Th	6.0	4.7	6.1	7.4	4.5	3.0	7.4	4.6
La	46	44	62	67	22.3	30.3	95	37.7
Yb	1.9	1.9	1.7	1.5	1.83	1.55	2.36	1.45

1. Olivine-bearing basalt (CP-A) Base of Sacsaquero Formation, late Eocene.
2. Olivine-bearing basalt (LIRCAY-BA), Rumicancha Formation, early Miocene.
3. Olivine-bearing basalt (HUANTA-RIO-2), Huanta Formation, late middle Miocene.
4. Olivine-bearing basalt (HUANTA-RIO-D), Huanta Formation, late middle Miocene.
5. Olivine-bearing low-silica andesite (NPA-22), late Miocene or Pliocene. Data from Noble et al. (1975).
6. Olivine-bearing low-silica andesite (AYA-10), late Miocene or early Pliocene. Data from Noble et al. (1975)
7. Olivine-bearing low-silica latite (AYA-1A), Huari lavas, early Pliocene. Data from Noble et al. (1975)-
8. Olivine-bearing low-silica andesite (J3-5), late Pliocene. Data from Noble et al. (1975).

marine dolomite containing organic material (Angeles, 1993). A K-Ar age on biotite from a thin unit of tuff within the Calera member has been dated at about 36-37 Ma (D.C. Noble and E.H. McKee, unpublished data).

The coarse conglomerates of the Pocobamba Formation, which in places reach thicknesses of hundreds of meters, have conventionally been interpreted as having been produced by erosion from the toe of a major east-dipping thrust fault (Jenks, 1951). An alternative interpretation is that the Pocobamba group reflects extension, resulting in down-to-the west movement along the longitudinal, Sacrafamilia and other faults of the region. In the vicinity of Colquijirca an olivine-bearing basaltic dike has been deveded in the San Gregorio prospect (Pinto, 1997). About 30 km north-northwest of Cerro de Pasco, near the Pacos Hill prospect, conglomerate of the Pocobamba Formation is underlain by a sequence of about 50 meters of olivine basalt that in turn is overlain by a thick flow or flows of hornblende-biotite dacite. These lavas are probably of late Eocene age, although no radiometric age determinations are available. Mineralization at Cerro de Pasco and Colquijirca did not take place, however, until middle Miocene time (Silberman and Noble, 1977; Vidal et al., 1984), when relaxation of stress allowed renewed fault movement and the upward movement of magmas and hydrothermal solutions.

DISCUSSION

Compression and extension

Compressional pulses, episodes of inferred extension/transtension, and metallogenic events are summarized on Figure 2. Extension/transtension appears to precede the Miocene Incaic IV, Quechua I, Quechua II and Quechua III compressive pulses by, at most, several million years. In contrast, extension appears to follow the major late Eocene Incaic II pulse by a very short period of time. Zones of extension appear to be preferentially situated to the northeast of zones of most intense contemporaneous arc magmatism. The existence of episodes of pronounced extension of Tertiary age is not surprising when considered in light of the commonly spectacular active extensional faulting observed in many parts of Perú. What is notable is the apparently short duration of periods of marked extension/transtension and the fact that these episodes appear to immediately precede compressive pulses. The shortness of periods of marked extension is consistent with a growing body of geologic and radiometric data that demonstrate very rapid movement along major extensional faults (e.g., Hodges et al., 1998).

Neogene extension in the high cordillera appears to have been restricted to relatively narrow belts, commonly bounded by faults reactivated from earlier episodes of Cenozoic and pre-Cenozoic tectonism. Total extension across the Andes probably totaled less than perhaps five percent. The situation is much different, for example, than the pervasive and profound regional extension of the Great Basin area of the western United States during the Neogene.

Relation of large-scale magmatism to episodes of extension

The temporal relation of large-volume arc magmatism to episodes of extension suggest a genetic relationship. The conglomerate, basalt and freshwater limestone that overlie the Incaic-II unconformity in the Western Cordillera are followed by several kilometers of lava and tuff of intermediate to silicic composition. Volcanism began at 41 to 42 Ma and was essentially finished by about 37 Ma. The major period of early Miocene volcanism (e.g., Noble et al., 1974; Swanson et al., 1993) generally coincides with episodes of extension associated with the Incaic IV and Quechua I pulses. In contrast, metallogenic belts, as discussed by Noble and McKee (1999), appear to fall within periods of relative tectonic quiescence (Figure 2), although the tectonic changes during middle and particularly late Miocene time were so rapid that the timing and nature of tectonic events is not fully resolved.

Tectonic implications of basaltic magmatism

Perú is characterized by unusually thick crust and lithosphere. The presence of basalt at high crustal levels requires that faults penetrated deeply to tap little-modified basalt derived from below the aesthenosphere-lithosphere contact and that stresses across these faults were sufficiently low to allow ready upward movement of magma. Moreover, the basalt magma that reached the surface must have moved upward so rapidly that interaction with the thick lithosphere was minimized. Basaltic magma clearly passed in some manner through rock situated below the brittle-ductile transition zone. Faults that channeled basalt magma clearly were not listric structures. Field geologists who have worked in the Peruvian Andes commonly portray many faults as high-angle, at least in the upper portions (e.g., Mégard, 1987), and the fact that basalt has arisen along certain of these structures supports this inference. The steepness of certain, and perhaps many of the faults may, at least in part, be attributed to the common occurrence of transcurrent movement along Andean structures (e.g., J.-P. Soulas and F. Mégard, 1980; Mégard, 1984). Deep-seated, subvertical faults in the highlands along the central Peruvian Andes do not fit the balanced models of thrust duplexing on a crustal scale as shown by such authors as Schmitz (1994) and Baby et al. (1997). At least in Perú, the Andean highlands form a definite structural domain distinct from the foreland thrust belt that has the classical fold and thrust fault structural pattern.

Central and northern Perú is presently an amagmatic region. This is generally interpreted as reflecting a flat subduction mode, which occludes aesthenospheric material. The distribution of basalt and other igneous rocks generally follows this model. For example, volcanic rocks of various types were erupted along the Cuzco fault zone in southern Perú, but not along the presently active normal fault system of the Cordillera Blanca in northern Perú. The 4 Ma dikes in the Huachocolpa district along with other early Pliocene volcanic rocks and high-level intrusive rocks in the western Cordillera of central and northern Perú (Noble and McKee, 1999; Benavides-Cáceres, 1999), and the early Pliocene Huari lavas in the Ayacucho basin have been considered to reflect the last igneous activity before the magmatic shutdown. The Pliocene basalt occurrences in the Lircay-Huancavelica region are anomalous. Although only one radiometric age of 2.24±0.05 Ma is available (Noble and Silberman, 1984), the age was carefully determined on a specimen of fine-grained holocrystalline basalt very suitable for K-Ar dating in laboratories of the U.S. Geological Survey. The age must be taken as reflecting an episode of late Pliocene extension and mafic volcanism in the zone of Lircay and Huancavelica.

RELATION OF TECTONISM TO SUBDUCTION

Neogene tectonism

As summarized by Mercier et al. (1992), a variety of neotectonic data from Perú and Bolivia indicate a period of Pliocene extension in the high cordillera followed closely by a pulse of east-west directed compression (The Quechua IV pulse of Benavides-Cáceres, 1999). Mercier et al. (1992) have also suggested that a similar sequence of events may have occurred several times previously during the Neogene. Marocco et al. (1995) have discussed a similar, albeit more temporally extended, pattern of extension followed by compression. The data presented in this paper are consistent with, and perhaps support this suggestion, and lead to a possibly generally applicable model of episodic subduction-related tectonism for the central Andes.

The typical state of stress at higher elevations in the central Andes during the Neogene appears to have been neutral or weakly extensional. Body forces tending to produce extension (Dalraymac and Molnar, 1981; Sébrier et al., 1988b; Deverchère et al., 1989) are approximately balanced by compressive forces produced by subduction. This quasi steady state was punctuated by relatively short-lived periods not only of compression but also of marked extension. More than simple gravitational extension was in all probability involved at various times, because both in Perú and elsewhere (e.g., Marrett et al., 1994), extensional faults have formed over a wide range of elevation.

Mercier et al. (1992) have explained the sequence of extension followed closely by compression using a more sophisticated version of the model presented by Sébrier and Soler (1991). In this model, as subduction progresses, the subducting slab begins to steepen, reducing the stress applied to the overriding plate. This, in turn, results in absolute extension in the cordillera and locally at lower elevations. The subducting slab continues to steepen, and eventually breaks, allowing the oceanic plate to more directly interact with the continental plate and producing a pulse of compressive deformation best recognized as a discrete event at high elevations.

Extension and subsequent compressive deformation, therefore, comprise two portions of a coupled deformational cycle that may be explainable in terms of a repetitive pattern of subduction episodes. If the hypothetical model of Mercier et al. (1992) is correct, then the geological record may provide information useful in understanding details of the subduction process. Although in some cases volcanism or plutonism may be more-or-less contemporaneous with tectonism (e.g., McKee and Noble, 1989), magmatic activity cannot, in itself, be used as evidence for tectonism.

Paleogene tectonism

Although the mechanism of Mercier et al. (1992) may explain the Neogene tectonic history of Perú, it probably is not the only process that has produced compressive deformation. Various workers (e.g., Suarez et al., 1983) have attempted to explain certain of the empirically observed tectonic pulses as a result of a change in subduction rate or direction of plate movement. Possibly the best correlation is between the major Incaic II pulse and the age of the bend in the Hawaii-Emperor chain (Clague and Jarrard, 1973; Dalrymple and Clague, 1976). The Incaic II phase was a major tectonic event that has been recognized throughout Perú as well as in northern Chile and Argentina (e.g., Noble et al., 1990; Sandeman et al., 1995). Profound uplift occurred after compressive deformation, as shown by the deep erosion that to the west exposed the Coastal Batholith (Noble et al., 1978). Incaic II compression is not known to have been preceded by extension. The post-Incaic II erosion surface, however, is in places overlain by conglomerate, basalt, freshwater limestone and/or other rocks suggestive of extension. A possible explanation is that the Incaic II pulse was the result of the major Eocene plate reorganization mentioned above (Noble et al., 1974; 1979b), and that the extensional lithofacies reflect gravitational extension on continued uplift of a regional paleohighland that had already been uplifted and eroded, producing the Incaic II surface, very shortly after the cessation of an unusually strong pulse of compressive deformation.

Evolution of mantle chemistry with time

The trace-element composition of the basalts and low-silica andesites indicate that the nature of the source for mafic magma beneath south-central Perú changed progressively through time. Mafic magma was generated in late Eocene and early Miocene time from mantle materials that were largely unaffected by subduction processes. In contrast, the olivine-bearing low-silica andesites and latites erupted during late Miocene and Pliocene time possess a clear subduction signature, as shown by their markedly lower Ta and Ti contents.

At the end of the Incaic II compressional pulse, mantle material unmodified by subduction was present beneath the general area of the present continental divide. Within several million years, the horizon from which specimen CP-A was collected was overlain by thousands of meters of intermediate to silicic rock of clearly calc-alkalic character of late Eocene age.

The locus of volcanism remained sufficiently to the west so that mantle unaffected by subduction was present beneath Lircay during earliest Miocene time (≈23 Ma). By 10 Ma, strongly calcalkalic dacite of the Julcani district, with Ta/(Ta+Th) between 0.06 and 0.11 and other chemical characteristics indicative of strongly calc-alkalic character, were being erupted at the same locality as well as in the Huachocolpa district to the west (Noble and McKee, 1999; D.C. Noble, unpublished data), whereas to the east in the Ayacucho basin coeval mafic magmas with much higher Ta/(Ta+Th) were reaching the surface. The four specimens of low-silica andesite and latite of late Miocene and Pliocene age, two of which are from the region of Ayacucho, all possess clear subduction signatures, indicating that mantle material with a subduction signature was present, at least locally beneath the Andes as far east as the Eastern Cordillera.

Whereas in south-central Perú mafic magma was generated in late Eocene and early Miocene time from mantle materials that were largely unaffected by subduction processes, the olivine-bearing low-silica andesites and latites erupted during late Miocene and Pliocene time possess a clear subduction signature, as shown by their markedly lower Ta and Ti contents. The very sparce, but consistent, data suggest that marked changes in the mantle material beneath central Perú occurred during late Neogene time as the locus of subduction shifted to the east from Eocene through Neogene time. The earlier basalts were erupted from mantle sources lying sufficiently to the east of the subducted slab to have escaped the effect of subduction-related solutions (e.g., Pearce and Peete, 1995). In early Miocene time, the zone of subduction lay sufficiently to the west of the Lircay so that basalt with high Ta and Ti contents could be generated from mantle material unmodified by subduction processes. By 10 Ma, however, magmas of intermediate to silicic composition were generated in the Huachocolpa and Lircay areas (Noble and McKee, 1999), whereas approximately coeval basalts erupted to the east in the Ayacucho basin lack evidence of subduction involvement.

The change from an enriched mantle source region to one modified by the subduction process must reflect, in a qualitative manner, the interaction between the position, orientation and evolution of the subduction zone and the preservation and/or westward movement of aesthenospheric material in front of the subducting plate. More detailed and regionally systematic analysis of mafic and low-silica intermediate rocks has the potential of providing information on the evolution of the uppermost mantle beneath the Andes.

RELATION OF MINERALIZATION TO EXTENSION AND COMPRESSION

A large number of mineral deposits were formed in central and northern Perú during Neogene time (Noble and McKee, 1999). The more important deposits for which radiometric ages are available are shown in figure 5.

Castrovirreyna-Huachocolpa-Lircay transect

Within the belt trending east-west from Castrovirreyna district through Huachcolpa to the region

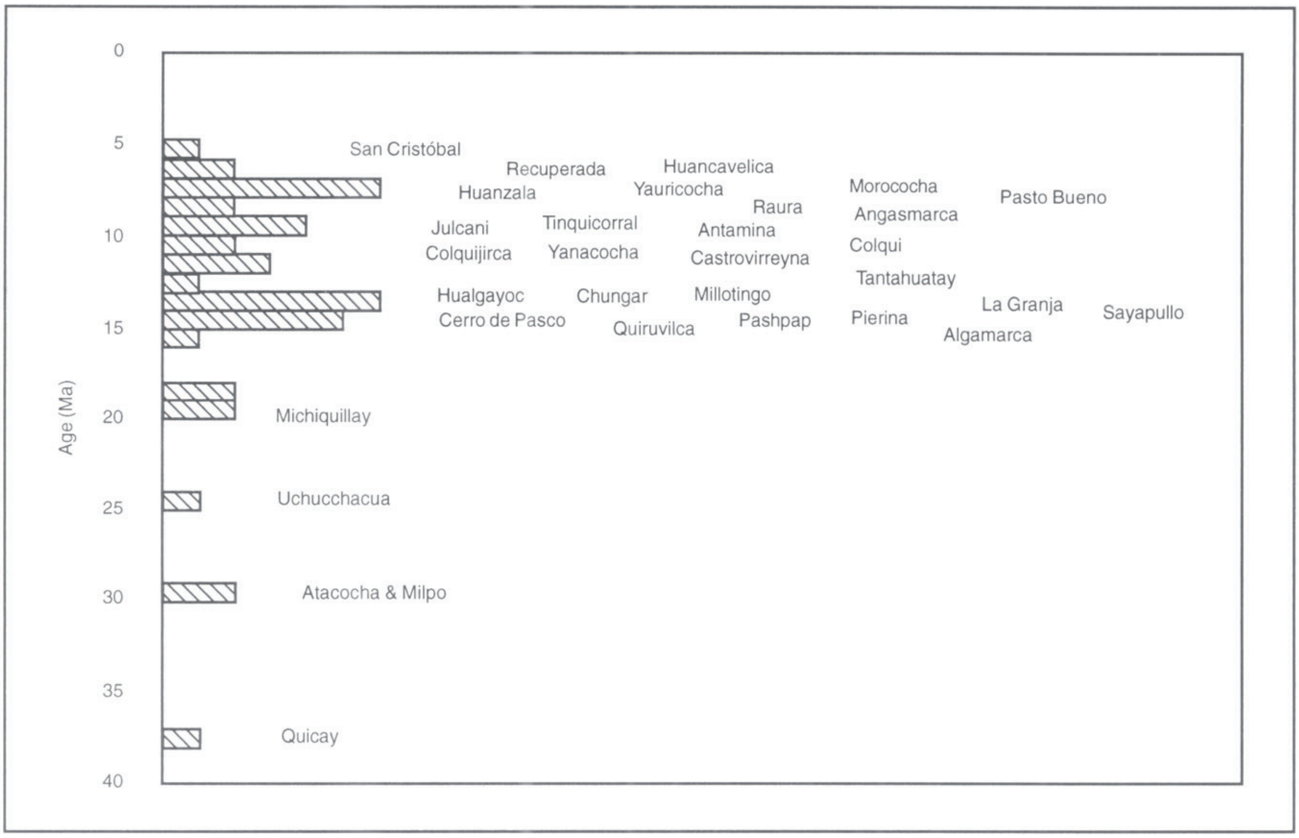

Figure 5. Diagram showing the ages of more important mineral deposits in central and northern Perú for which radiometric ages are available from Noble and McKee (1999).

of Lircay and Julcani, mineralization and magmatic activity took place before, during and after the Quechua II and probably the Quechua III compressive events (Noble and McKee, 1999). In the Castrovirreyna district, a large field of andesite and dacite lava and tuff were erupted between about 12 and 11 Ma immediately prior to mineralization. Volcanic rocks of the Julcani center were formed between about 10.1 and 9.7 Ma. In both districts, magmatic activity and mineralization took place during the period of tectonic quiescence and subsequent extension that immediately preceded Quechua II compression. In the Huachocolpa district, magmatic activity commenced about 10.5 to 11 Ma coeval with, or very shortly after, the onset of extension. Volcanism was concentrated within a northwest-southeast trending graben bounded on the west and east, respectively, by the Chonta and Huachocolpa faults (Figure 1). These are linear, steeply dipping, probably reactivated structures that at various times must have experienced various combinations of dip-slip and strike-slip movement. Magmatic activity was focused within the graben, forming a thick, interfingering pile of lava, volcanic breccia and related rock related to central volcano – volcanic dome complexes. Conglomerate, freshwater limestone and associated volcanic rock exposed in the Arco Iris area were folded early in the history of volcanic activity. This is shown by the fact that isoclinally folded beds are overlain by near ninety-degree unconformity by hydrothermally altered and mineralized volcanic breccia and lava of the Huachocolpa volcanic field. At this time, renewed movement may have taken place along the Huachcolpa and Chonta faults. After deposition of most of the volcanic rocks of the Huachocolpa district, and emplacement of stocks at 9.3±0.3, 8.4±0.3 and 7.9±0.3 Ma, a new tectonic pulse produced steeply dipping fractures, including several sets that host the polymetallic vein mineralization of the Recuperada subdistrict. The stress history is not clear, but SW-NE and/or E-W compression may have been followed by relaxation and extension in a N-S to NW-SE direction. The latest stages of vein mineralization in the Teresita vein is dated at 6.4±0.2 Ma. A small amount of late Miocene magmatic activity appears to have postdated mineralization in certain areas. Hydrothermal activity had completely terminated by 4 Ma, when east-west extension is demonstrated by the completely unaltered north-south trending dikes of the Huachocolpa district.

Uncertainties exist concerning the exact timing and assignment of regional compressive events. Sébrier et al. (1988a) and Sébrier and Soler (1991) recognize Quechua II and Quechua III events at about 10 and 7 Ma, respectively, whereas Benavides-Cáceres (1999) places these pulses at about 8-7 and 5-4 Ma, respectively. Mégard et al. (1984) assigned an age of about 9 Ma for Quechua II compression in the Ayacucho basin. There appear to be two compressive events in the Huachcolpa district. If an age of about 6.5 Ma is accepted for Quechua III, the vein-hosting fractures may be provisionally assigned to Quechua III, and the effects of Quechua II may be restricted to the early folding in the Arco Iris area. Alternatively, both early folding and late fracturing must be assigned to a prolonged episode of Quechua II deformation.

Several acid-sulfate – high-sulfidation type magmatic-hydrothermal systems are present in the Huachocolpa district. Of these, the most important is Arco Punco, which is spatially associated with the Tinquicorral system of gold- and copper-bearing polymetallic veins. A K-Ar age determination of 9.5±0.3 Ma has been on hypogene alunite from Arco Punco (Noble and McKee, 1999). Other high-sulfidation systems in the area may have formed at various times both after, and possibly prior to, the Arco Punco system. It has been suggested that Arco Punco and the Tinquicorral veins are part of a large, complex magmatic-hydrothermal system formed several types of potentially economic mineral deposits (Noble, 1997). A not unreasonable alternate view is that the veins formed several million years later, and were mineralized at about the same time as Teresita and other veins of the Recuperada subdistrict. A new K-Ar age determination of 9.4±0.3 Ma on hydrothermal sericite from one of the veins of the Tinquicorral system would appear to support the first interpretation. (Analytical data for this age, from Geochron Laboratories, Inc., Cambridge, Massachusetts, USA, are as follows: K_2O = 7.13 and 7.17 wt. percent; radiogenic ^{40}Ar = 0.9915 x 10^{-10} moles ^{40}Ar/gram, with $^{40*}Ar$/Total ^{40}Ar = 10.4 and 13.0 percent, respectively.) The Tinquicorral vein structures, therefore, would appear be too old to have been formed by the Quechua II event, and perhaps reflect local stresses related to a subjacent stock.

The recognition of episodes of extension as well as compression lends insight into the kinematics of certain faults, for example the regional Chonta and Huachocolpa faults. For example, in the Huachocolpa district, the north-south striking Huachocolpa fault, which passes a short distance to the west of the pueblo of Huachocolpa, marks the contact between steeply dipping Mesozoic strata on the east and gently east-dipping andesitic breccia and lava of late Miocene age on the west. This contact has been interpreted by various workers as being either a normal fault, a reverse fault, or representing a depositional contact. A reasonable scenario is that extensional movement along a reactivated older structure produced a fault scarp that was partly buried by middle to late Miocene sedimentary rocks and volcanic rocks. Later compression may have resulted in compressive or, more likely, transpressive deformation. Likewise, the Chonta fault, a major linear structure that extends in a northwest-southeast direction for at least 100 kilometers, probably experienced various combinations of normal, reverse, dextral and sinistral movement before it was intruded by intermediate and silicic magmas in late Miocene time. In a general sense, the deposition of relatively incompetent material within graben or other basins bounded by extensional faults may provide a partial explanation for the relative intensity of folding of the fault-basin sediments compared to degree of folding produced in rocks in adjacent areas.

Regional metallogenesis

Noble and McKee (1999) have recognized a locus of late Miocene hydrothermal activity and mineralization extending from the Huachocolpa district to Pasto Bueno in northern Perú. On a regional scale, more intense mineralization appears to fall between compressive pulses (Figure 2). This is well shown by mineralization of the middle Miocene Quiruvilca-Pierina subbelt, defined by a number of deposits formed mainly between about 13 and 15.5 Ma. Although at least one hydrothermal system in the Cordillera Negra, that of the Chururopampa district, was formed during the later stages of eruption of the youngest part of the early Miocene sequence of tuff and lava that comprise the upper part of the "Calipuy Group", the major districts in the Cordillera Negra and areas to the north and south, for example Pierina, Pashpap and Quiruvilca all postdate both early Miocene volcanism and the Quechua II tectonic pulse. Similar relations appear to hold for the late Miocene subbelt, although there are uncertainties in the ages of the Quechua II and III pulses.

A number of mineral deposits of Paleogene age were formed during periods of neutral stress or extension at high elevations, and relative magmatic quiescence. These include the early Oligocene skarn and related deposits of the Andahuaylas-Yauri mineral belt (Santa Cruz et al., 1979; Noble et al., 1984) and late Oligocene-earliest Miocene W-Cu vein systems of southeastern Perú (Clark et al., 1983). In central Perú, the Quicay acid-sulfate gold system was active at about 37 Ma (Noble and McKee, 1999), the major Pb-Zn-Ag replacement deposits of the Atacocha and Milpo districts formed at about 29-30 Ma (Soler, 1988), and the Uchucchaqua Ag-Zn-Pb deposit was formed about 24.5-25 Ma (Noble and McKee, 1999).

It is not clear whether or not the high-level intrusive and volcanic rocks typically spatially and temporally associated with mineralization (Petersen, 1965; Noble and McKee, 1999) are in some manner different from the common calc-alkalic arc rocks of the central Andes. The sparce minor-element and isotopic data available indicates a "subduction signature" (e.g., low Ta/(Ta+Th). Glassy volcanic rocks from the Julcani district, where fresh dacite and rhyodacite are fortuitously locally preserved, have retained portions of what must have been unsually high contents of magmatic arsenic and other elements (Noble et al., 1998). Whether such elevated initial contents are unique to magmas associated with mineralization is unclear. One can speculate on the possibility that the stress conditions that permitted little-modified basaltic magma to reach the surface may also have permitted more silicic magmas with high "mineral potential" to be generated and/or reach high crustal levels, in the process perhaps loosing relatively small amounts of the various components necessary for the formation of hydrothermal mineral deposits.

Explanation of the location of mineral districts is complicated. Not only is there control by regional magmatic belts presumably localized by subduction processes, but also control by fractures generally paralleling the trend of the Andes that may extend to mantle depths. In addition, major northeast-trending transandean structures that apparently date from pre-Cenozoic time may exert some control over district location (Vidal and Noble, 1994).

CONCLUSIONS

Tertiary deposits consisting conglomerate and/or alluvial fan deposits, basalt and/or freshwater limestone and other lacustrine deposits in the high Andes are best interpreted as the result of brief episodes of crustal extension. During Neogene time, episodes of marked extension/transtension occurred shortly before pulses of compressive deformation, suggesting the existence of coupled extension-compression pairs. Basalt was derived from enriched mantle sources that in part had been affected by subduction processes. The presence of basalt strongly suggests the existence of steeply dipping faults along which basaltic magma was erupted to the surface during periods when conditions of extension or transtension prevailed. Mineral deposits of magmatic hydrothermal affinities appear to have preferentially formed during periods of tectonic quiescence or extension.

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REFERENCES

ANGELES Z. C. (1993).- Geología de Colquijirca y alrededores. Unpublished report, Lima, Sociedad Minera El Brocal S.A., 76 p.

ATHERTON M.P., SANDERSON L.M., WARDEN V. & McCOURT W.J. (1985).- The volcanic cover: Chemical composition and the origin of the magmas of the Calipuy Group. *In*: Pitcher, W.S., Atherton, M.P., Cobbing, E.J., and Beckinsale, R.D. (eds), Magmatism at a plate edge. The Perúvian Andes: Blackie and Son, Glasgow, 273-310.

ATHERTON M.P. & WEBB S. (1989).- Volcanic facies, structure, and geochemistry of the marginal basin rocks of central Perú. *Journal of South American Earth Sciences* 2, 241-261.

BABY P., ROCHAT P., MASCLE G. & HERAIL G. (1997).- Neogene shortening contribution to crustal thickening in the back arc of the Central Andes, *Geology* 25, 883-886.

BENAVIDES-CACERES V. (1999).- Orogenic evolution of the Peruvian Andes: The Andean cycle. *In:* Skinner B.J. (ed), Geology and mineral deposits of the central Andes. *Society of Economic Geologists Special Publication* No 7, *in press.*

BONNOT D., SEBRIER M. & MERCIER J. (1988).- Evolution geodynamique Plio-Quaternaire du bassin intracordillerain du Callejón de Huaylás et de la Cordillere Blanche, Pérou. *Géodynamique*, 3, 57-83.

CABRERA N. J. (1988).- Neotectonique et sismotectonique dans la Cordillere Andine au niveau du changement de géometrie de la subduction: la region de Cuzco (Pérou). Thése Docteur en Sciences, Université de Paris-Sud, Centre d'Orsay, Paris, 275 p.

CARLIER G., LORAND J., KIENAST J. & AUDEBAUD E. (1993).- Ultrapotassic and perealuminous magma mixing and origin of the high-K latites from the Eastern Cordillera of southern Peru. Deuxième Symposium International Géodynamique Andine, Colloques et Séminaries, Oxford, Editions de l'ORSTOM, Paris, 339-342.

CLAGUE D.A. & JARRARD R.D. (1973).- Tertiary Pacific plate motion deduced from the hawaiian-Emperor chain. *Geological Society of America Bulletin*, 84, 1135-1701.

CLARK A.H., PALMA V.V., ARCHIBALD D.A., FARRAR E. & ARENAS M.J. (1983).- Occurrence and age o f tin mineralization in the Cordillera Oriental, southern Peru. *Economic Geology*, 70, 514-520.

COBBING E.J. (1998).- The Coastal Batholith and other aspects of Andean magmatism in Peru. *Boletín de la Sociedad Geológica del Perú*, 88, 5-20.

DALMAYRAC B. (1974).- Un exemple de tectonique vivante: les failles subactuelles du pied de la Cordillére Blanche (Pérou). *Cahiers ORSTOM, Série Géologie*, 6, 1, 19-27.

DALMAYRAC B. & MOLNAR P. (1981).- Parallel thrust and normal faulting in Peru and constraints on the state of stress. *Earth and Planetary Science Letters*, 55, 473 481.

DALRYMPLE G.B. & CLAGUE D.A. (1976).- Age of the Hawaiian-Emperor bend. *Earth and Planetary Science Letters*, 31, 313-329.

DEVERCHERE J., DORBATH C. & DORBATH L. (1989).- Extension related to a high topography: Results from a microseismic survey in the Andes of Peru and tectonic implications. *Geophysics Journal International*, 98, 281-292.

DEWEY J.F. & LAMB S.H. (1992).- Active tectonics of the Andes. *Tectonophysics*, 205, 79-95.

DORBATH C., DORBATH L., CISTERNAS A., DEVERCHERE J. & SEBRIER M. (1990).- Seismicity of the Huancayo Basin (central Peru) and the Huaytapallana fault. *Journal of South American Earth Sciences*, 3, 21-30.

EDWARDS B.R. & RUSSELL J.K. (1999).- Northern Cordilleran volcanic province: A northern Basin and Range?. *Geology*, 27, 247-250.

ELLISON R.A., KLINCK B.A. & HAWKINS M.P. (1989).- Deformation events in the Andean orogenic cycle in the Altiplano and Western Cordillera, southern Peru. *Journal of South American Earth Science*, 2, 263-276.

HARTENBERGER J.-L., MEGARD F. & SIGE B. (1984).- Faunules à rongeurs de l'Oligocéne inférieur á Lircay, Andes du Pérou central: Datation d'un épisode karstique: Intérêt paléobiogéographique des remplissages tertiaires en Amérique du Sud. *Comptes Rendus Académie des Sciences Paris*, 299, Série II, 565-568.

HEDGE C.E. & NOBLE D.C. (1971).- Upper Cenozoic basalts with high Sr^{87}/Sr^{86} and Sr/Rb ratios, southern Great Basin, western United States. *Geological Society of America Bulletin*, 82, 3503-3510.

HEINTZE L. (1985).- Geologie und geochemie der porphyrischen stockwerk-molybdän-Lagerstätte Tamboras, Zone La Negra (Perú). Hannover, Bundesanstalt für Geowissenschaften und Rohstoffe und der Landesämter der Bundesrepublik Deutschland, *Geologisches Jahrbuch, R.D.*, No 72, 3-94.

HODGES K., BOWRING S., DAVIDEK K., HAWKINS D. & KROL M. (1998).- Evidence for rapid displacement on Himalayan normal faults and the importance of tectonic denudation in the evolution of mountain ranges. *Geology*, 26, 483-486.

HOLLISTER V.F. & SIRVAS B. E. (1978).- The Calipuy Formation of northern Peru and its relation to volcanism in the northern Andes. *Journal of Volcanology and Geothermal Research*, 4, 89-98.

JENKS W.F. (1951).- Triassic to Tertiary stratigraphy near Cerro de Pasco, Perú. *Geological Society of America Bulletin*, 62, 203-220.

KONTAK D.J., CLARK A.H., FARRAR E. & STRONG D.F. (1985).- The rift associated Permo-Triassic magmatism of the eastern Cordillera: A precursor of the Andean orogeny. *In:* Pitcher W.S., Atherton M.P., Cobbing E.J. & Beckinsale R.D. (eds), Magmatism at a plate Edge: The Peruvian Andes. Blackie and Son, Glasgow, 37-44.

LÓPEZ A.J.C., CERRON Z.F., CARPIO R.M. & MORALES R.M. (1996).- Geología del cuadrángulo de Huanta. *Instituto Geológico Minero y Metalúrigico del Perú Boletín*, No. 72, 192 p.

McKEE E.H. & NOBLE D.C. (1982).- Miocene volcanism and deformation in the western Cordillera and high plateaus of south-central Peru. *Geological Society of America Bulletin*, 93, 657-662.

McKEE E.H. & NOBLE D.C. (1989): Tectonic events, magmatic pulses, and base- and precious-metal mineralization in the central Andes. *In:* Ericksen G.E., Cañas-Pinochet M.T. & Reinemund J.A. (eds), Geology of the Andes and its relation to hydrocarbon and mineral resources. *Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series*, 11, 189-194.

McKEE E.H., NOBLE D.C. & VIDAL C. (1986).- Timing of volcanic and hydrothermal activity, Huancavelica mercury district, Peru. *Economic Geology*, 80, 489-492.

McKEE E.H., NOBLE D.C., PETERSEN U., ARENAS F.M. & BENAVIDES Q.A. (1975).- Chronology of late Tertiary volcanism and mineralization, Huachocolpa district, central Peru. *Economic Geology*, 70, 388-390.

McLAUGHLIN D.H. (1924).- Geology and physiography of the Peruvian Cordillera, Departments of Junin and Lima. *Geological Society of America Bulletin*, 35, 591-632.

McLAUGHLIN D.H. (1929).- Review of Steinmann, G., Geologie von Peru (Heidelberg, Carl Winters Universitäts Buchandlung, 448 p.). *Economic Geology*, 24, 664-669.

MACHARE O. J. & ORTEGA T. H. (1997).- Estudio estructural del sector este de la veta Calera, mina Orcopampa-Perú. Sociedad Geológica del Perú, Volumen Especial No. 1, 95-99.

MAROCCO R. (1984).- Dynamique du remplissage d'un bassin intramontagneux cénozoïque andin: le Bassin Moquegua (Sud du Pérou). *Cahiers ORSTOM, Série Géologie*, 14, No 2, 117-140.

MAROCCO R., LAVENU A. & BAUDINO R. (1995).- Intermontane late Paleogene-Neogene basins of the Andes of Ecuador and Peru: Sedimentologic and tectonic characteristics. *In:* Tankard A.J., Suárez S., R. & Welsink H.J. (eds), Petroleum basins of South America. *American Association of Petroleum Geologists Memoir*, 62, 597-613.

MARRETT R.A., ALLMENDINGER R.W., ALONSO R.N. & DRAKE R.E. (1994).- Late Cenozoic tectonic evolution of the Puna Plateau and adjacent foreland, northwestern Argentine Andes. *Journal of South American Earth Sciences*, 7, 179-207.

MEGARD F. (1977).- Etude géologique des Andes du Pérou Central. *Mémoir ORSTOM*, No 86, 310 p.

MEGARD F. (1984).- The Andean orogenic period and its major structures in central and northern Peru. *Journal of the Geological Society of London*, 141, 893-900.

MEGARD F. (1987).- Structure and evolution of the Peruvian Andes, *in* Schaer, J.P., and Rodgers, J. (eds), The anatomy of mountain ranges. Princeton University Press, Princeton, 179-210.

MEGARD F., NOBLE D.C., McKEE E.H. & BELLON H. (1984).- Multiple pulses of Neogene compressive deformation in the Ayacucho intermontane basin, Andes of Central Peru. *Geological Society of America Bulletin*, 95, 1108-1117.

MEGARD F., MAROCCO R., VICENTE J., MUÑOZ C., PASTOR R. & MEGARD-GALLI J. (1983).- Apuntes sobre la geología de Lircay (Huancavelica, Perú central), el plegamiento tardihercínico y las modalidades del plegamiento andino (fase quechua). *Boletín de la Sociedad Geológica del Perú*, 71, 255-262.

MERCIER J.L., SEBRIER M., LAVENU A., CABRERA J., BELLIER O., DUMONT J.-F. & MACHARE J. (1992).- Changes in the tectonic regime above a subduction zone of Andean type: the Andes of Perú and Bolivia during the Pliocene-Pleistocene. *Journal of Geophysical Research*, 97, No B8, 11945-11982.

MORCHE W., ALBAN C., DE LA CRUZ J. & CERRÓN F. (1995).- Geología del cuadrángulo de Ayacuco. *Institudo Geológico Minero y Metalúrigico del Perú Boletín*, No. 61, 120 p.

MORCHE W. & LARICO C.W. (1996).- Geología del cuadrángulo de Huancavelica. *Instituto Geológico Minero y Metalúrgico del Perú Boletín*, No 73, 172 p.

MORCHE W., LA TORRE O., DE LA CRUZ N. & CERRÓN F. (1996).- Geología del cuadrángulo de Huachocolpa. *Instituto Geológico Minero y Metalúrgico del Perú Boletín*, No 63, 132 p.

NOBLE D.C. (1997).- Geologic model for exploration at Arcopunco and Tinquicorral, Huachocolpa. Unpublished report for Compañia de Minas Buenaventura S.A., Lima, 8 p.

NOBLE D.C. & McKEE E.H. (1999).- The Miocene metallogenic belt of central and northern Perú. *In:* Skinner B.J. (ed), Geology and mineral deposits of the central Andes. *Society of Economic Geologists Special Publication No. 7, in press.*

NOBLE D.C. & SILBERMAN M.L. (1984).- Evolución volcánica y hidrotermal y cronología de K/Ar del distrito minero de Julcani. Sociedad Geológica del Perú, Volumen Jubilar, LX Aniversario, Homenaje al Dr. Georg Petersen, Fasc. 5, 35 p.

NOBLE D.C., FARRAR E. & COBBING E.J. (1979a).- The Nazca Group of south-central Peru: Age, source, and regional volcanic and tectonic significance. *Earth and Planetary Science Letters*, 45, 80-86.

NOBLE D.C., McKEE E.H. & MEGARD F. (1979b).- Early Tertiary "Incaic" tectonism, uplift, and volcanic activity, Andes of central Peru. *Geological Society of America Bulletin*, 90, 903-907.

NOBLE D.C., RESSEL M.W. & CONNORS K.A. (1998).- Magmatic As, Sb, Cs and other volatile elements in glassy silicic rocks. *Geological Society of America Abstracts with Programs*, 30, A377.

NOBLE D.C., McKEE E.H., EYZAGUIRRE V.R. & MAROCCO R. (1984).- Age and regional tectonic and metallogenetic implications of igneous activity and mineralization in the Andahuaylas-Yauri belt of southern Peru. *Economic Geology*, 79, 172-176.

NOBLE D.C., McKEE E.H., FARRAR E. & PETERSEN U. (1974).- Episodic Cenozoic volcanism and tectonism in the Andes of Peru. *Earth and Planetary Science Letters*, 21, 213-221.

NOBLE D.C., McKEE E.H., MOURIER T. & MEGARD F. (1990).- Cenozoic stratigraphy, magmatic activity, compressive deformation, and uplift in northern Perú. *Geological Society of America Bulletin*, 102, 1105-1113.

NOBLE D.C., SILBERMAN M.L., MEGARD F. & BOWMAN H.R. (1978).- Comendite (peralkaline rhyolite) and basalt in the Mitu Group, Peru: Evidence for Permian-Triassic lithospheric extension in the central Andes. *U.S. Geological Survey Journal of Research*, 6, 453-457.

NOBLE D.C., BOWMAN H.R., HEBERT A.J., SILBERMAN M.L., HEROPOULOS C.E., FABBI B.P. & HEDGE C.E. (1975).- Chemical and isotopic constraints on the origin of low-silica latite and andesite from the Andes of central Peru. *Geology*, 3, 501-504.

NOBLE J.A. (1931).- Colquijirca examination 1930-1931. Unnpublished report, Lima, Geological Department, Cerro de Pasco Copper Corporation, Exploration Division, Lima, 34 p.

NOBLET C., LAVENU A. & MAROCCO R. (1996).- Concept of continuum as opposed to periodic tectonism in the Andes. *Tectonophysics*, 255, 65-78.

PEARCE J.A. & PEATE D.W. (1995).- Tectonic implications of the composition of volcanic arc magmas. *Annual Review of Earth and Planetary Sciences*, No 23, 251-285.

PETERSEN U. (1965).- Regional geology and major ore deposits of central Peru. *Economic Geology*, 30, 407–476.

PETERSEN U., NOBLE D.C., ARENAS F.M. & GOODELL P.C. (1977).- Geology of the Julcani mining district, Peru. *Economic Geology*, 72, 931-949.

PETFORD N. & ATHERTON M.P. (1992).- Granitoid emplacement and deformation along a major crustal lineament: the Cordillera Blanca, Peru. *Tectonophysics*, 205, 171-185.

PINTO, V. (1997).- Petrografía del prospecto San Gregorio, Colquijirca. Unpublished Batchelors Thesis, Universidad Nacionoal San Agustín, Arequipa.

SANDEMAN H.A., CLARK A.H. & FARRAR E. (1995).- An integrated tectono-magmatic model for the evolution of the southern Peruvian Andes (13-20°S) since 55 Ma. *International Geology Review*, 37, 1039-1073.

SANDEMAN H.A., CLARK A.H., FARRAR E. & ARROYO P.G. (1997).- Lithostratigraphy, petrology, and ^{40}Ar/^{39}Ar geochronology of the Crucero Supergroup, Puno Department, SE Peru. *Journal of South American Earth Sciences*, 10, 223-245.

SANTA CRUZ S., GUERRERO T., CASTILLA F., CARO E. & CANDIOTTI, H. (1979).- Geológia de yacimientos de cobre en "skarn" en la region Sur-Oriental del Perú. *Boletín de la Sociedad Geológica del Perú*, 60, 153-174.

SCHMITZ M. (1994).- A balanced model of the southern central Andes. *Tectonics* 13, 484-492.

SEBRIER M., LAVENU A., FORNARI M. & SOULAS J.-P. (1988a).- Tectonics and uplift in central Andes, Perú, Bolivia, northern Chile, from Eocene to present. *Géodynamique*, 3, 85-106.

SEBRIER M., MERCIER J.L., MACHARE J., BONNOT D., CABRERA J. & BLANC J.L. (1988b).- The state of stress in an overriding plate situated above a flat slab: the Andes of central Peru. *Tectonics*, 7, 895-928.

SEBRIER M. & SOLER P. (1991).- Tectonics and magmatism from late Oligocene time to the present. *In:* Harman R.S. & Rapela C.W. (eds), Andean magmatism and its tectonic setting. *Geological Society of America Special Paper*, 265, 259-278.

SILBERMAN M.L. & NOBLE D.C. (1977).- Age of igneous activity and mineralization, Cerro de Pasco, central Peru. *Economic Geology*, 72, 925-930.

SIRVAS B.E. & HOLLISTER V.R. (1979).- La formación Calipuy del norte del Perú. *Boletín de la Sociedad Geológica del Perú*, 64, 1-15.

SOLER P. (1988).- Oligocene magmatic activity and associated mineralization in the polymetallic belt of central Peru. *Economic Geology*, 83, 657-663.

SOMOZA R. (1998).- Updated Nazca (Farallon)-South America relative motions during the last 40 My: Implications for mountain building in the central Andean region. *Journal of South American Earth Sciences*, 11, 211-215.

SOULAS J.P. (1977).- Les phases tectoniques andines du Tertiaire supérieur: Résultats d'un transversale Pisco-Ayacucho, Pèrou Central. *Comptes Rendus Académie des Sciences Paris*, 284, Série D, 2207-2210.

SOULAS J.P. & MEGARD F. (1980).- Kinematics and tectonic significance of sigmoidal fault and fold systems in central Peru. Unpublished manuscript, 21 p. plus 7 Figures.

SUAREZ G., MOLNAR P. & BURCHFIEL B.C. (1983).- Seismicity, fault plane solutions, depth of faulting, and active tectonics of the Andes of Peru, Ecuador, and southern Colombia. *Journal of Geophysical Research*, 88, 10403-10428.

SWANSON K.E., NOBLE D.C., McKEE E.H. & GIBSON P.C. (1993).- Collapse calderas and other Neogene volcanic and hydrothermal features of the Chila Cordillera and adjacent areas, southern Peru. *Geological Society of America Abstracts with Programs*, 25, No 5, 153.

TOSDAL R.M., CLARK A.H. & FARRAR E. (1984).- Cenozoic polyphase landscape and tectonic evolution of the Cordillera Occidental, southernmost

Peru. *Geological Society of America Bulletin*, 95, 1318-1332.

VIDAL C.E. & NOBLE D.C. (1994).- Yacimientos hidrotermales controlados por estructura y magmatismo en la región central del Perú. *Sociedad Geológica del Perú, Volumen de Resúmenes Extendidos, VIII Congreso de Geología*, 48-52.

VIDAL C.E., PROAÑO J.A. & NOBLE D.C. (1997).- Geología y distribución hidrotermal de menas con Au, Cu, Zn, Pb, y Ag el distrito minero Colquijirca, Pasco. *Sociedad Geológica del Perú, Volumen de Resúmenes Extendidos, IX Congreso de Geología*, 217-219.

VIDAL C.E., MAYTA O., NOBLE D.C. & McKEE E.H. (1984).- Sobre la evolución de soluciones hidrotermales desde el centro volcánico Marcapunta en Colquijirca, Pasco. *Sociedad Geológica del Perú, Volumen Jubilar, LX Aniversario, Homenaje al Dr. Georg Petersen*, Fasc. 10, 14 p.

WILSON J.J. (1963).- Cretaceous stratigraphy of the central Andes of Peru. *Bulletin of the American Association of Petroleum Geologists*, 47, 1-34.

WOOD D.A. (1980).- The application of a Th-Hf-Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province. *Earth and Planetary Science Letters*, 50, 11-30.

YATES R.G., KENT D.F. & FERNANDEZ CONCHA J. (1951).- Geology of the Huancavelica quicksilver district, Peru. *U.S. Geological Survey Bulletin 975-A*, 59 p.