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EARLY MIOCENE BIMODAL VOLCANISM AND SYN-EXTENSIONAL DEPOSITION: THE LARAMPUQUIO FORMATION, AYACUCHO INTERMONTANE BASIN, CENTRAL PERÚ

VOLCANISMO BIMODAL DEL MIOCENO INFERIOR Y SEDIMENTACIÓN EN EXTENSIÓN SINTECTONICA: LA FORMACIÓN LARAMPUQUIO, CUENCA INTRAMONTAÑOSA DE AYACUCHO, PERÚ CENTRAL

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ABSTRACT

The lower Miocene Larampuquio Formation of the Ayacucho intermontane basin, central Perú, consists dominantly of a bimodal volcanic and sedimentary sequence that was deposited during a period of extension that preceded the ca. 17 Ma regional Quechua I compressive event. New geologic mapping and geochronologic data indicate syn-deposition erosion of both the formation and locally exposed bedrock. The formation is composed mostly of flows of lava of andesitic to basaltic composition intercalated with boulder conglomerate and breccia composed mostly of blocks of lithologically similar lava and thin beds of silicic tuff. Conglomerate units additionally include clasts derived from the locally exposed bedrock in the early Miocene. The Larampuquio Formation locally reaches a thickness of 1,200 m; elsewhere only 200 m of section is preserved. The markedly variable observed thickness of the Larampuquio Formation was produced by a combination of pre-depositional, syn-depositional and post-depositional erosion. Four new $^{40}Ar/^{39}Ar$ age determinations on volcanic units within the Larampuquio Formation demonstrate that eruption extended from about 22 to at least 18.7 Ma. Map relations indicate that the formation, where exposed and preserved, was not observably folded during the Quechua I tectonism, in contrast to previous interpretations.

Keywords: *Ayacucho intermontane basin, Larampuquio Formation, extensión and bimodal volcanism, Quechua I compressive deformation.*

RESUMEN

La Formación Larampuquio del Mioceno inferior de la cuenca intermontañosa de Ayacucho, en el centro del Perú, está compuesta de una secuencia dominantemente volcánica bimodal y sedimentaria, las que fueron depositadas durante un periodo de extensión que precede al evento compresivo regional Quechua I, ca. 17 Ma. Los nuevos mapas geológicos y datos geocronológicos indican una erosión y depositación simultánea de ambos que localmente permite exponer el substrato. La formación está principalmente compuesta por flujos de lava de composición andesítica a basáltica, intercalados con conglomerados de canto rodado y brechas mayormente de bloques litológicos similares a la lava, además de capas delgadas de tufos ácidos. Adicionalmente, las unidades conglomerádicas incluyen clastos derivados, en el Mioceno inferior, del substrato localmente expuesto. La Formación Larampuquio localmente alcanza un espesor de 1200 m; en cambio en otros lugares solo 200 m de sección es preservada. El marcado espesor variable de la Formación Larampuquio fue producido por una combinación de erosiones pre-depositación, sin-depositación y post-depositación. Cuatro nuevas determinaciones de edades $^{40}Ar/^{39}Ar$ en unidades volcánicas de la Formación Larampuquio demuestran que estas se emplazaron entre 22 y al menos 18.7 Ma. Las relaciones en el mapa indican que la Formación Larampuquio, donde está expuesta y preservada, no se halla plegada por la tectónica Quechua I, lo que contrasta con las interpretaciones anteriores.

Palabras Claves: *Cuenca Intramontañosa de Ayacucho, Formación Larampuquio, extensión y volcanismo bimodal, Quechua*

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I deformación compresiva.

INTRODUCTION

Of all the Andean intermontane basins, the Ayacucho basin has the best preserved and most accurately dated geologic section, one which documents multiple phases of syn-extensional deposition interspersed with pulses of rapid contraction (Mégard et al., 1984; Wise, 2004). The lower Miocene Larampuquio Formation of the Ayacucho intermontane basin is the oldest dated unit of the composite basin fill sequence and provides evidence for syn-extension eruption based on its bimodal volcanic composition and intercalated clastic units. It represents the beginning of locally voluminous volcanism and active tectonism after a long period of erosion and non-deposition in the Ayacucho region. In addition to being the oldest dated unit in the basin, the formation is the lowest unit within a detailed geochronologically-constrained tectonostragraphic section that extends upward through the upper Pliocene.

The Larampuquio Formation was deposited during a period of intense early Miocene volcanism (Noble et al., 1974) when enormous volumes of silicic and intermediate tuff and lava were erupted from the main magmatic arc to the west. Rocks produced during this episode include the upper part of the Calipuy Group of the Cordillera Negra (Noble et al., 1999a) and innumerable voluminous units of silicic ash-flow tuff and intermediate to silicic lava in central and southern Perú. Most of this section was deformed during the regional Quechua I compressive tectonic pulse.

Mégard et al. (1984) described the contact between the Larampuquio Formation and the overlying upper Miocene Huanta Formation as a major angular unconformity, which is not the case. Although a depositional hiatus or disconformity probably is present, the local effects of the regional early Miocene Quechua I tectonism are significantly different from that previously envisioned. The new geological mapping shows that this part of the Ayacucho basin did not undergo significant folding during the early Miocene, although, the Quechua I event may still have been accompanied by uplift, as suggested by erosion of the Larampuquio Formation. Strong Quechua I angular unconformities are present in many locations in Perú (Benavides-Cáceres, 1999), which taken with the observations from Ayacucho marks the contractional event as having a domainal distribution of strain at the regional scale, at least in the eastern part of the orogen.

This paper gives a detailed description of the Larampuquio Formation, raises it to formal status, refines the geochronology, and discusses stratigraphic and tectonic relations developed from geologic mapping. The character of the formation and comparison to units of similar age to the west are used to interpret early Miocene extensional tectonism in central Peru.

REGIONAL SETTING OF THE AYACUCHO INTERMONTANE BASIN

The formation and evolution of the major belt of intermontane basins within the Peruvian Andes is an important aspect of the complicated deformational history of the orogen, being a zone of focused strain accommodation adjacent to the western margin of the strongly and recently uplifted Cordillera Oriental. All but one of the basins lies between the present continental divide and the Cordillera Oriental. Many, and perhaps most, of the basins formed as pull-aparts along steeply-dipping strike-slip faults, and record several periods of fault reactivation (Mégard et al., 1983; Laubacher et al., 1988; Sébrier et al., 1988a; Marocco et al., 1995; Steinmann et al., 1999; Wise and Noble, 2001). The Callejón de Huaylás basin of northern Perú, however, formed in the hanging wall to the Cordillera Blanca normal fault (e.g., Bonnot et al., 1988; Wise and Noble, 2003). At the same time, the Huancayo intermontane basin, located midway between Ayacucho and the Cordillera Blanca, recorded repeated contraction within the NW-elongate depositional trough (Dollfus and Mégard, 1968; Blanc, 1984). In contrast, in Bolivia at least some basins are of a piggyback type (Jordan and Alonso, 1987; Sempere, 1990; Hérail et al., 1996; Rochat et al., 1999; Horton, 1998; Leturmy et al., 2000). Many intermontane basins in Chile are associated with strike-slip and normal faults (Flint et al., 1993; May et al., 1999; Sáez et al., 1999). The Ayacucho basin formed during episodic periods of rapid deposition that were disrupted by very short periods of contraction (Mégard et al., 1984; Wise, 2004). Although the basin was probably bounded by faults throughout much of its history, earlier geometry and sense of slip across these faults remain cryptic, as discussed later in the paper.

GEOLOGICAL BACKGROUND

The Ayacucho intermontane basin preserves the longest, most complicated and best-exposed stratigraphic record of any of the Peruvian intermontane basins. Gerth (1915) first recognized the prominent angular unconformities within the basin. The basin is approximately 150 km long with an average width of about 25 km. It was filled with an aggregate of more than 8,000 m of Tertiary clastic and volcanic strata deposited on a basement of upper Paleozoic and Mesozoic rocks (Fig. 1), although nowhere is the complete section of 8,000 meters preserved intact. As recognized by Mégard et al., (1984), the section consists of abundant volcanic rocks interbedded with conglomerate and other sedimentary and volcaniclastic rocks, yielding isotopically-datable horizons that allow quantification of the timing and duration of not only volcanism but also tectonic extension and contraction.

The basement of the Ayacucho basin is composed of Paleozoic and Mesozoic sedimentary rocks, rift-related volcanic and sedimentary rocks of late Permian to early Triassic age and granitic intrusions probably of similar age. Rocks of the Pennsylvanian Tarma and Early Permian Copacabana Groups, part of a continental-shelf sequence deposited before the Andean cycle, crop out only east of the basin in the Cordillera Oriental (Dunbar and Newell, 1946; Mégard, 1978a). The late Permian to early Triassic Mitu Group, a volcanic- and conglomerate-bearing clastic sequence that fills a continental-margin rift basin extending the length of Perú (Mégard, 1978b; Noble et al., 1978; Kontak et al., 1985), records multiple deformation events and locally low-grade metamorphism. East of Ayacucho, the Mitu Group is

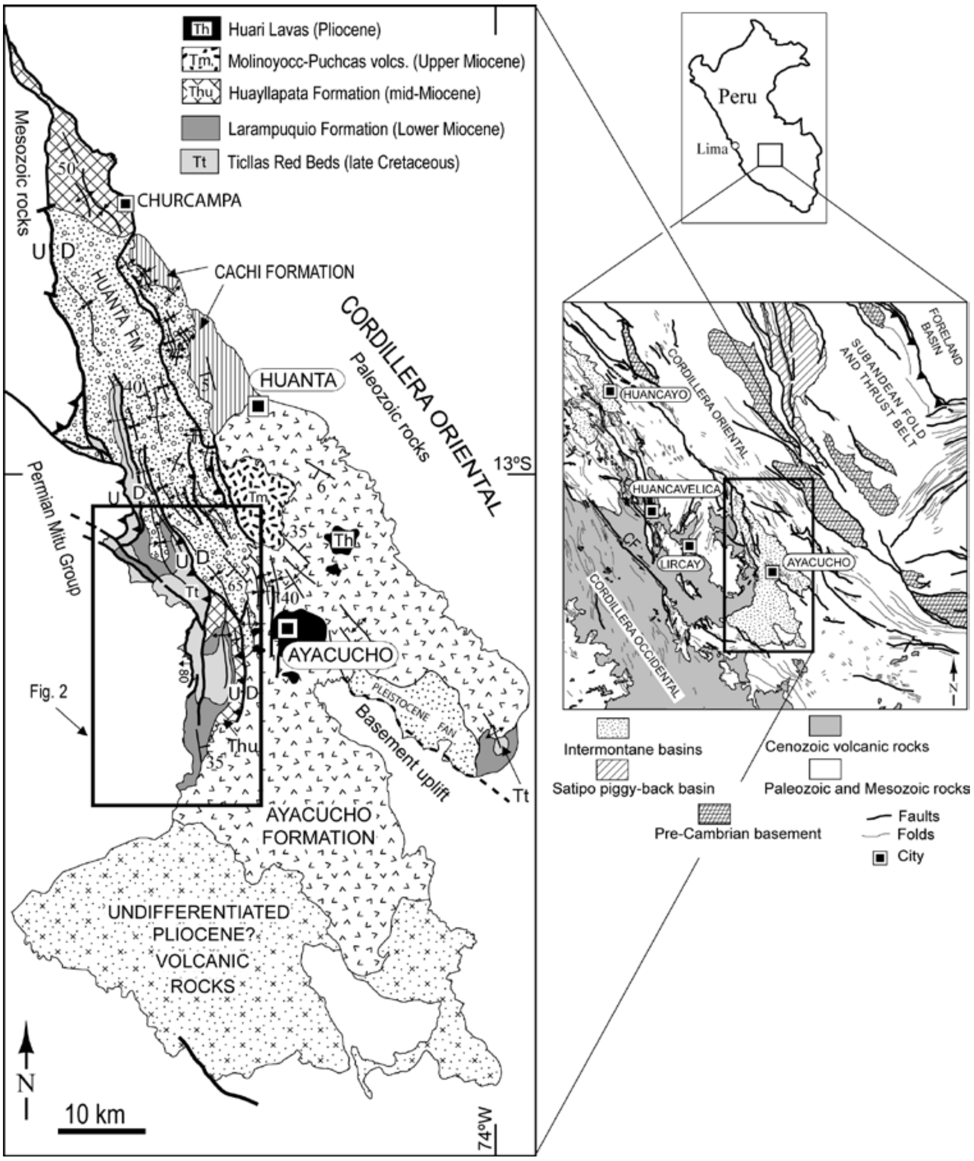

Figure 1.- Location map of the Ayacucho intermontane basin showing general geology surrounding the basin in the first inset to the right, and overview of the Ayacucho intermontane basin geology in the larger map on the left. The area of Figure 3 is marked on the map. SC = pueblo San Pedro de Cachi; S = pueblo Socos.

composed of intermediate to mafic lava accompanied by felsic volcanic rocks and arkosic sandstone. Plutons, mostly of diorite to quartz monzonite composition, cut the Mitu Group and older units along both margins of the basin. Although the plutons have not been dated, they appear to belong to a Permian to Early Triassic magmatic arc suite exposed mainly along the Cordillera Oriental (Lancelot et al., 1978; Mégard, 1978b; Carlier et al., 1984; Laubacher and Naeser, 1994; Noble et al., 1995). Mesozoic rocks are exposed only along the northwestern side of the Ayacucho basin. The two principal units are the Triassic-Jurassic Pucará Group, composed of medium- to thick-bedded limestone, and the Lower Cretaceous Goyllarisquisga Formation, consisting of quartz arenite. All these units were faulted and folded, probably during the latest Cretaceous Mochica orogeny, and the early Paleogene Incaic orogeny, before the development of the Ayacucho basin.

The Cenozoic strata of the Ayacucho intermontane basin record a complex history of repeated deposition, tectonism and erosion. The undated Ticllas Red Beds, of probable latest Cretaceous-Paleogene age although an Eocene age is possible, were deformed during the Incaic I and II orogenies (Noble et al., 1985). The Ticllas Red Beds are unconformably overlain by the Larampuquio Formation, the overlying middle Miocene Huayllapata Formation, and the Huanta Formation of late Miocene age (Fig. 2). The Molinoyocc volcanics, consisting of a complex of dacite domes near the center of the basin (Fig. 1), formed after the Larampuquio and Huayllapata Formations and predates the Huanta Formation. Deposited in strong discordance on top of these units is the uppermost Miocene Ayacucho Formation. Pliocene to Pleistocene volcaniclastic rock, lacustrine

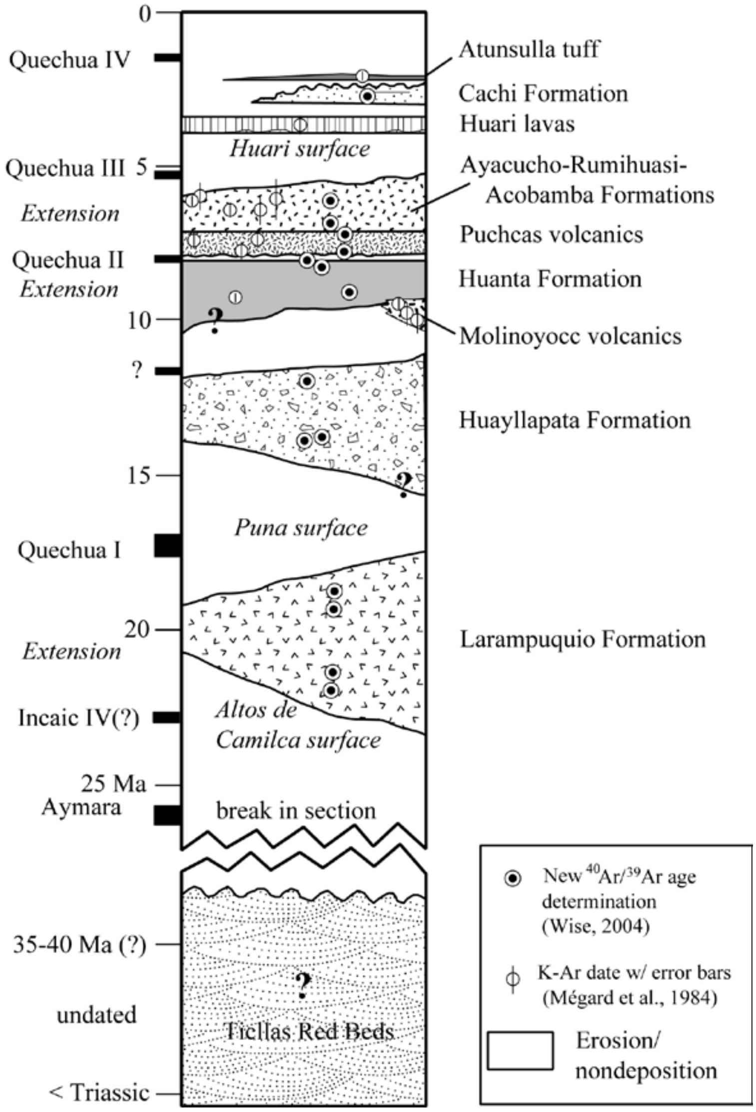

***Figure 2.-** General stratigraphic column showing major units in the Ayacucho intermontane basin and tectonic events of central Perú.*

sedimentary rock, and mafic to intermediate lava, including the Huari lavas and the Cachi Formation (Fig. 1), comprise the last Tertiary units deposited in the basin (Wise, 2004; Wise and Noble, 2007 in press).

LARAMPUQUIO FORMATION

The Larampuquio Formation is composed of interfingering flows of andesite and olivine-bearing basalt, thick beds of volcanic conglomerate and sandstone, and silicic ash-flow tuff having both surge beds and cross-stratification representing epiclastic reworking of the tuff. Map relations indicate that most units within the formation are lenticular and laterally variable, with beds of lava, conglomerate, and tuff alternating in a complex pattern without repeating motifs (Fig. 3).

New mapping from this study has more than doubled the known area of the Larampuquio Formation; the unit extends nearly continuously for at least 25 km in a north-south direction (Fig. 3). Even though most of the formation crops out along the southwest margin of the basin (Fig. 1), lithologically

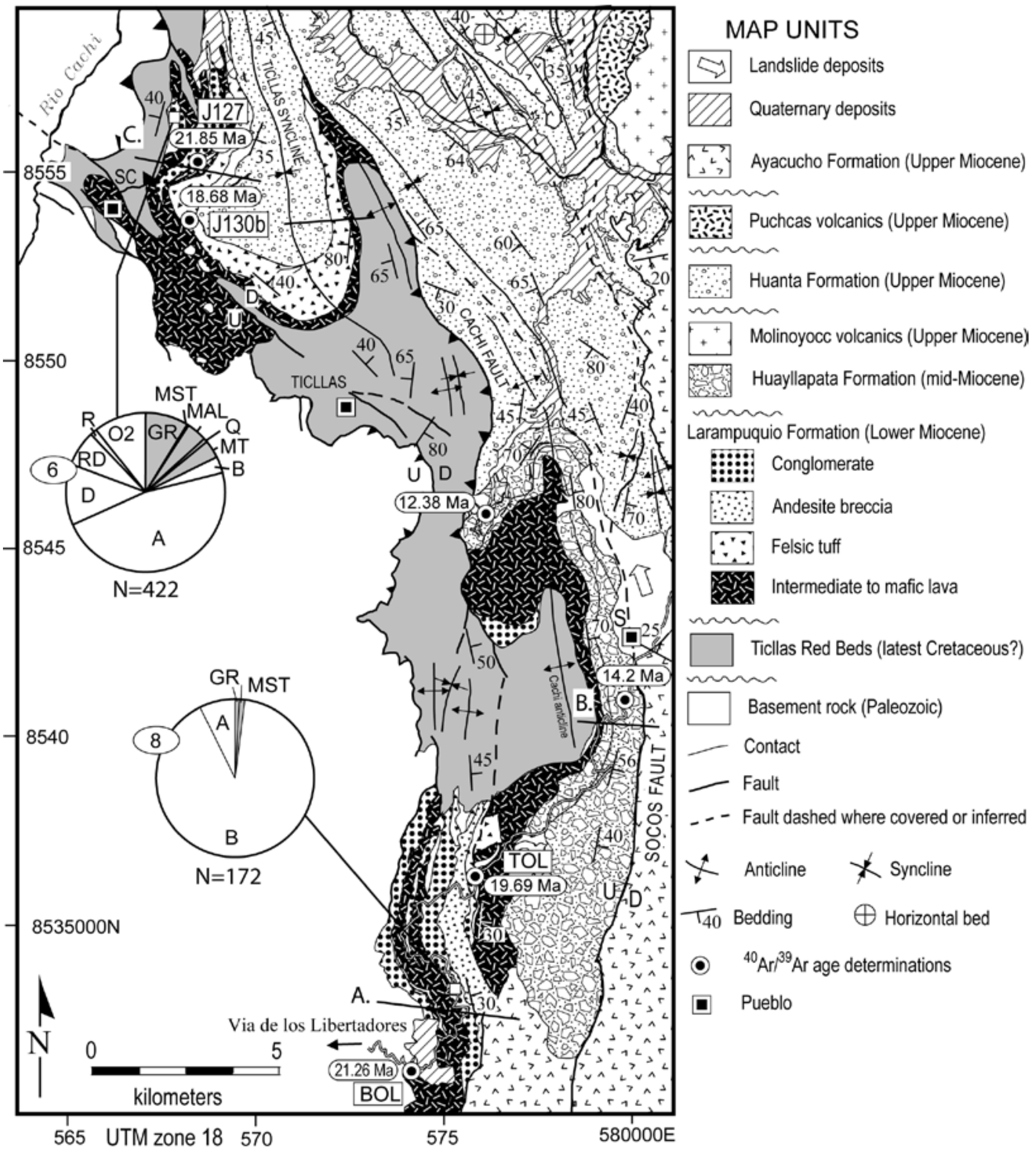

Figure 3.- *Geologic map showing the main exposure area of the Larampuquio Formation along the southwestern margin of the Ayacucho basin. The locations of new age determinations are shown, along with pie diagrams for clast-count sites 6 and 8. Volcanic clast types: A = andesite, B = basalt, D = dacite, RD = rhyodacite, and R = rhyolite. Basement clast types shade gray: Mitu Group; MST = siltstone, MAL = andesite, MT = welded crystal-rich tuff, and GR = Permian(?) quartz monzonite to granite. Q = quartzite, O2= breccia, scoria, glass, and hydrothermally altered volcanic rock where primary composition could not be determined in the field. Stratigraphic sections A, B, and C are shown in Figure 6.*

similar, but undated, strata are exposed southwest of Ayacucho (Fig. 1), suggesting that the Larampuquio Formation may be present beneath younger units throughout much of the Ayacucho basin.

The Larampuquio Formation unconformably overlies the Ticllas Red Beds, the Mitu Group and plutonic rocks of Permian(?) age, and is disconformably overlain by rocks of the Huayllapata and Huanta Formations (Wise, 2004). Because the unit includes a considerable percentage of conglomerate, the term Larampuquio Formation is here applied instead of the informal "Larampuquio volcanics" as named by Mégard et al. (1984). Because of the increased areal distribution and better understanding of the unit, it should be raised to formal rank. The formation is best exposed and most accessible along the Via de los Libertadores road (Fig. 4A), which Mégard et al. (1984) suggested as the type area. The same rocks were later termed the Sallalli Formation by Morche et al. (1995), but this later usage should be discontinued because the unit name assigned by Mégard et al. (1984) was the first to be published and because Morche et al. (1995) did not provide any reason for renaming of the unit.

Volcanic Units

The Larampuquio Formation contains two thick units of mafic to intermediate composition lavas overlain by felsic tuff and breccias in the northern part of the section along the Ticllas syncline (Fig. 4B) and more variable units of similar lithology to the south (Fig. 3). These thick lava flows have well-developed columnar cooling joints (Fig. 4E), and fractures approximately parallel to flow banding have produced platy slabs of rock. One flow from the type area contains phenocrysts of clinopyroxene, altered olivine, hornblende, and abundant plagioclase accompanied by large crystals of embayed quartz (Fig 4F). The mafic minerals are almost completely replaced by iron oxides. The quartz grains have melt inclusions and are clearly phenocrysts rather than xenocrysts derived from the Permian(?) granitic rocks. The close association of quartz and magnesian olivine indicates mixing of mafic and silicic magmas, with a resulting intermediate composition. Two whole-rock analyses reported by Morche et al. (1995) plot within the trachy-andesite field of a TAS diagram.

Very thick bodies of breccia of andesitic to basaltic composition, possibly of collapse origin, are locally present in the section. The breccias are framework-supported and contain angular clasts as much as 40 cm in diameter. Other thin units of andesitic to basaltic clastic rocks are well bedded and probably represent lahars (Fig. 4C). Units of silicic tuff occur mainly in the lowermost and upper part of the formation. These tuffs are of rhyolitic to rhyodacitic composition, and at least one unit in the upper part of the formation contains abundant phenocrysts of sanidine. Surge beds in the upper part of the formation are locally overlain by high-silica vitric rhyolite breccia that probably developed at or near the source vent, as based on the size, angularity, monolithic character, and composition of the blocks (Fig. 4D). In contrast, the thick, structureless unit of dacitic or low-silica rhyolitic tuff exposed at the base of the unit along the Via de los Libertadores road is probably the distal part of a major ash-flow sheet erupted somewhere along the early Miocene volcanic arc to the west.

Sedimentary Units

Conglomerate makes up about 35% of the section exposed along the Via de los Libertadores road, and is more common lower in the section along the Ticllas syncline (Fig. 3). The beds of conglomerate are typically very thick, poorly-sorted and framework-supported, and generally lack both cross stratification and clast imbrication. The clasts are mainly subrounded cobbles and boulders of lava lithologically identical to the interbedded basaltic andesite to basalt lava flows found throughout the formation. Clast count site 6 (Fig. 3) shows more variety and greater contribution of basement-derived clasts than site 8. Both sites contain material locally derived from the Permian(?) granite and the Permian-Triassic Mitu Group.

Age Determinations

Four new $^{40}Ar/^{39}Ar$ age determinations were obtained on the Larampuquio Formation (Table 1, Appendix I, and Fig. 5 for samples BOL, TOL, J127, and J130b). Plagioclase from a unit of ash-flow tuff deposited upon Permian(?) quartz monzonite in the type area (sample BOL) yields a preferred isochron age of 20.42±0.12 Ma. The $^{40}Ar/^{36}Ar$ ratio of 306.6±2.3 and the shape of the incremental-heating plot indicate that the plateau age of 21.26±0.16 Ma (Fig. 5) reflects the presence of excess argon (e.g., Kelley, 2002). Sanidine from a tuff bed at the top of the same section (sample TOL) gave a reliable isochron age of 19.69±0.10 Ma with concordant plateau and total-gas ages (Fig. 5). McKee and Noble (1982) reported K-Ar ages of 18.3±0.6 and 17.3±0.2 Ma on plagioclase and sanidine, respectively, from

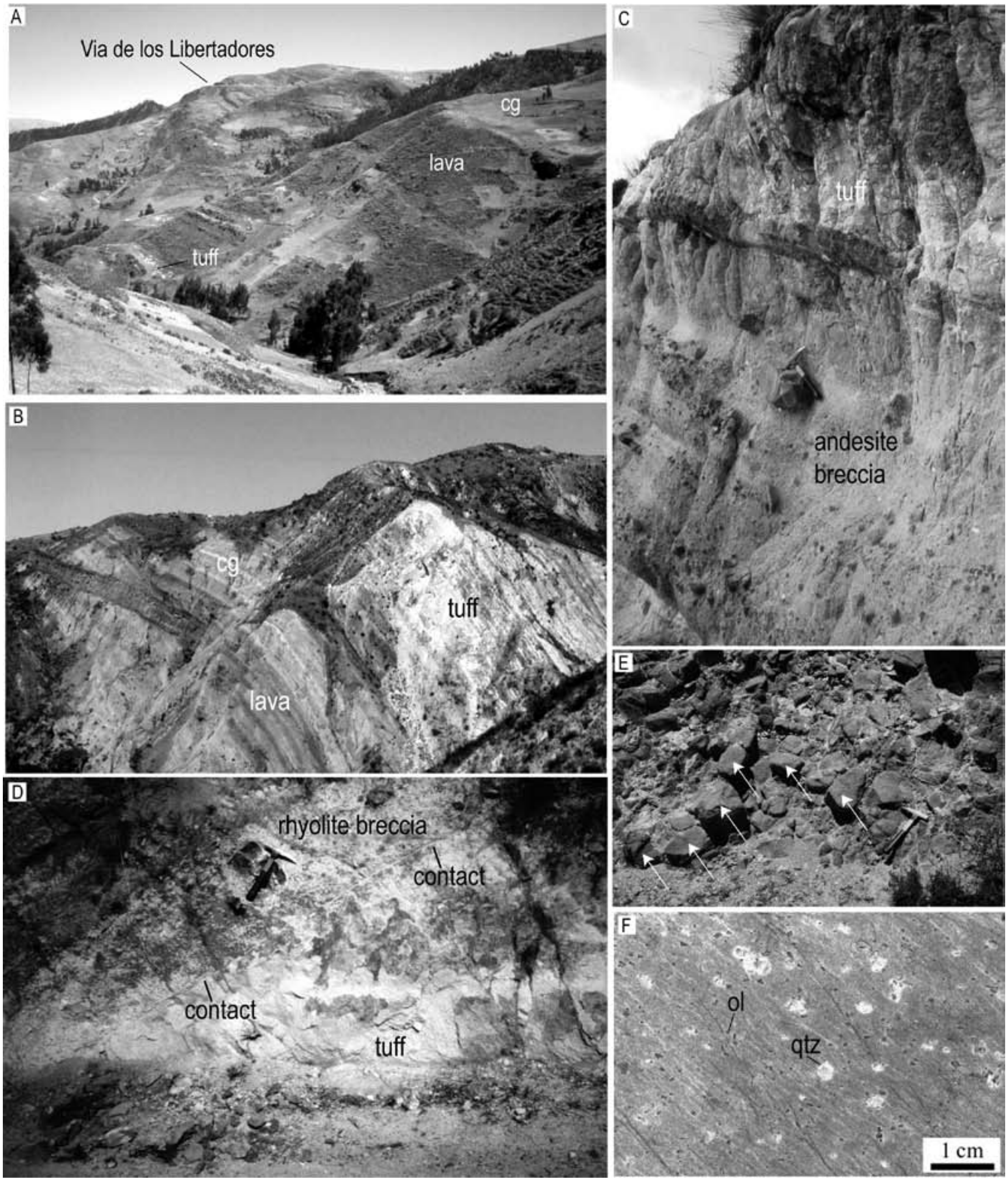

Figure 4.- *A. Photograph looking northward from the BOL sample site at the type area of the Larampuquio Formation. B. View southwest showing the Larampuquio Formation in the eastern limb of the Ticllas syncline. C. Felsic tuff sampled in location TOL overlying bedded pyroclastic rocks composed of andesite breccia. D. Photograph of contact between unwelded pumice-rich tuff near sample site J130b and overlying high-silica rhyolite breccia; note the angular clast beneath the rock hammer is made of glassy lava. E. View looking down at the top of a basalt flow, showing columnar jointing (tops marked with arrows) in unit along the southwest side of the Ticllas syncline. F. Slab rock specimen of quartz-bearing basalt flow exposed along the Via de los Libertadores road about 1 km west of sample site TOL.*

locations in the same section but between samples BOL and TOL. The new $^{40}Ar/^{39}Ar$ ages best constrain the time of formation; there is no ready explanation for the large discrepancies between these and the previously-reported younger K-Ar ages.

Two samples from the section east of San Pedro de Cachi, about 20 km north of the type area, were also dated (Fig. 3). Sample J127 is from lithic-rich tuff of intermediate composition from the middle of the San Pedro de Cachi section on the west limb of the Ticllas syncline. A separate of phenocrystic biotite produced a plateau age of 21.85±0.17 Ma and isochron age of 22.0±0.5 Ma, both using heating steps 5 through 11 (Fig. 5). The spectrum shows a slight U-shaped curve, presumably from the inclusion of excess argon, suggesting that the plateau age is a maximum value. Sample J130b is from a thick unit of rhyolite tuff (Fig. 4D) deposited

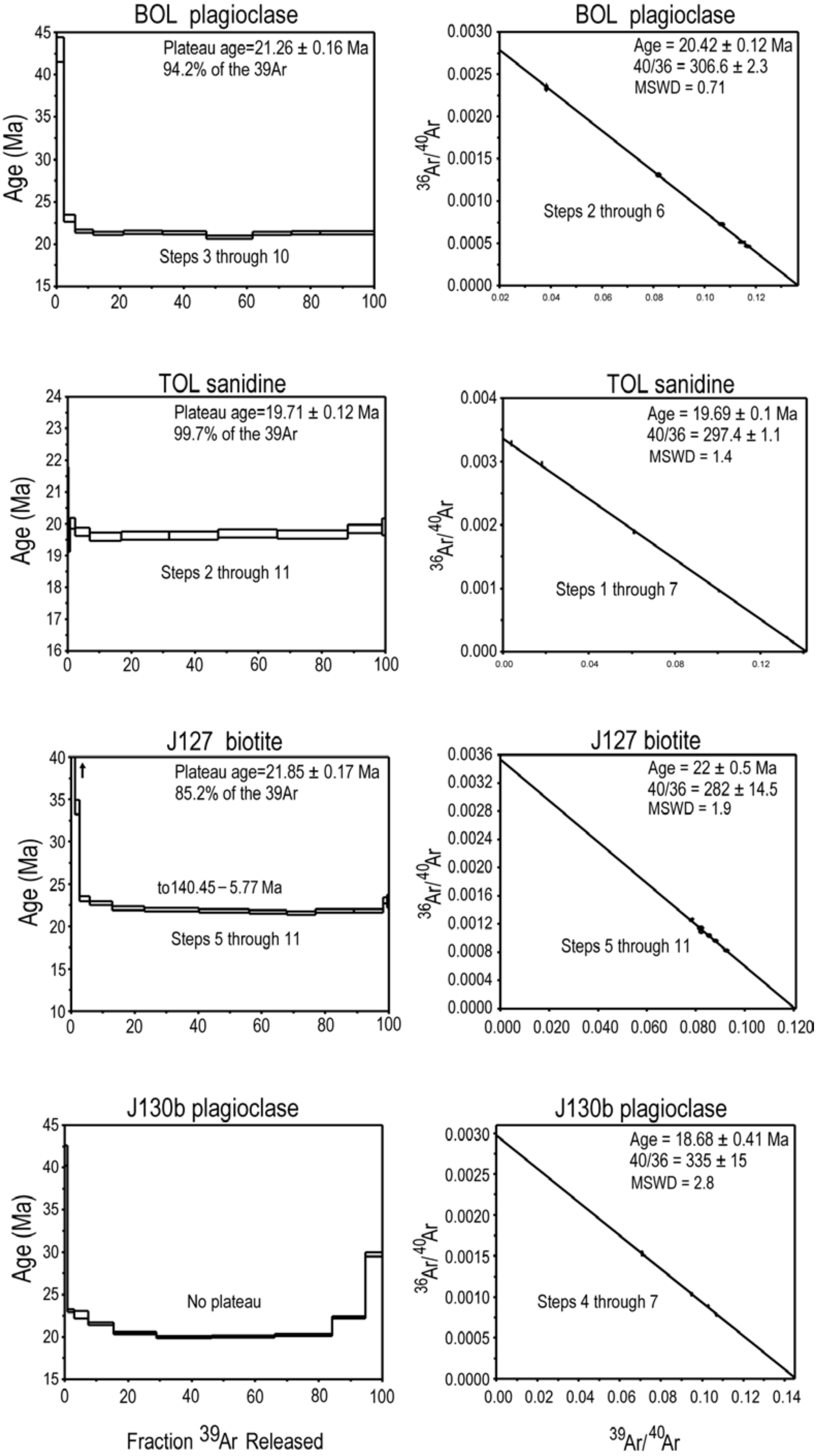

Figure 5.- *Incremental-heating and isochron plots for dated samples discussed in text.*

on top of conglomerate and lava beds above the tuff sampled at site J127. The plagioclase separate dated was prepared from a single large pumice clast in the tuff, minimizing the possibility of contamination by older grains. The separate gave a reliable, although imprecise, isochron age of 18.68±0.41 Ma; no plateau age was defined (Fig. 5). Both the U-shape of the incremental-heating spectrum and the $^{40}Ar/^{36}Ar$ value of 335±15 indicate the presence of excess argon and show that the total-gas age of 21.38±0.13 Ma is too old.

Interpretation of age variations. Ages for samples J127 and J130b indicate a period of deposition for the Larampuquio Formation greater than that implied by the ages obtained on samples BOL and TOL. Because several thick units of lava and conglomerate underlie the unit from which sample J127 was collected, a ca. 22 Ma age should, on geological grounds, be considered a minimum age for the base of the unit. The fact that the formation was deposited on both basement and older Cenozoic rocks suggests erosion before 22 Ma, possibly following the ca. 28 Ma Aymara and/or the ca. 23 Ma event (Incaic IV) regional contractional events (Benavides-Cáceres, 1999). In this context, we interpret the bimodal volcanism of the Larampuquio Formation as probably related to crustal-scale extension leading up to the major Quechua I contractional pulse (e.g., Noble et al., 1999b).

Deposition apparently continued until about 19 Ma or less, although there is a problem in that the unit from which sample J130b was collected is only about 200 m stratigraphically above the position of J127, which is apparently about three million years older. A possible explanation is that pronounced erosion and/or nondeposition took place between the deposition of the two dated units (see below). The thick conglomerate beds containing clasts derived from the lava beds are consistent with extensive erosion and reworking during deposition of the formation, although constructional volcanic edifices can be eroded extremely quickly, especially in the case of contemporary faulting. The uppermost preserved units are rhyolitic pyroclastic rocks that perhaps blanketed the entire region, capping the various sections in the study area, suggesting that some time-equivalent units are present within the formation.

Thickness

There is considerable variation in the thickness of the Larampuquio Formation from south to north. About 2,200 m of apparent section, dipping about 35 degrees to the east, are exposed in the type area (Fig. 6A). Northeast of pueblo Socos, however, only about 200 m of intermediate to mafic lava are sandwiched between the Ticllas Red Beds and the overlying Huayllapata Formation (Fig. 6B). Farther north, east of pueblo San Pedro de Cachi, a section exposed in the west limb of the Ticllas syncline, spanning the same general age as the type area, is about 700 m thick (Fig. 6C). Along the east limb of the Ticllas syncline, in the hanging wall to the Cachi thrust, the formation is consists of several flows of andesite and/or basalt overlain by beds of felsic tuff and coarse breccia of rhyolitic composition with a combined thickness of about 500 m (Fig. 4B).

Interpretation of thickness variations. Rocks of the Larampuquio Formation overlying the basal unconformity vary along strike. To the south, a relatively thick unit of rhyolitic ash-flow tuff probably is a distal part of a major ash-flow sheet produced during the period of intense early Miocene caldera-related silicic volcanism that had it locus along the eastern margin of the Cretaceous and Paleocene Coastal Batholith (Noble et al., 1979; 2007 in press). Farther north, thick flows of mafic to intermediate composition with interbedded conglomerate-bearing cobbles of similar lithology were deposited on the Ticllas Red Beds. This contrast in underlying rock units suggests either that the Larampuquio Formation spread beyond the limits of the basin in which the Ticllas Red Beds were deposited or that it overlapped paleobasement highs that exposed crystalline rock. If the former is true, it may suggest widening of the Ayacucho basin through relocation of the bounding faults with the present western basin-bounding faults having formed after the Larampuquio Formation, obscuring the earlier basin geometry. The faults bounding the western margin of the basin clearly place basement rock over the upper Miocene Huanta Formation.

The thicker portion of the Larampuquio Formation in the type area may represent filling of a paleotopographic low. In contrast, the thickness of only 200 m of the section northeast of Socos seems to require erosion of the Larampuquio Formation before the deposition of the overlying units. Finally, the formation may have been structurally thickened by unrecognized bed-parallel thrust repetition of the section. In fact, the southward projection of the Cachi thrust intersects the upper part of the section south of the Via de los Libertadores road.

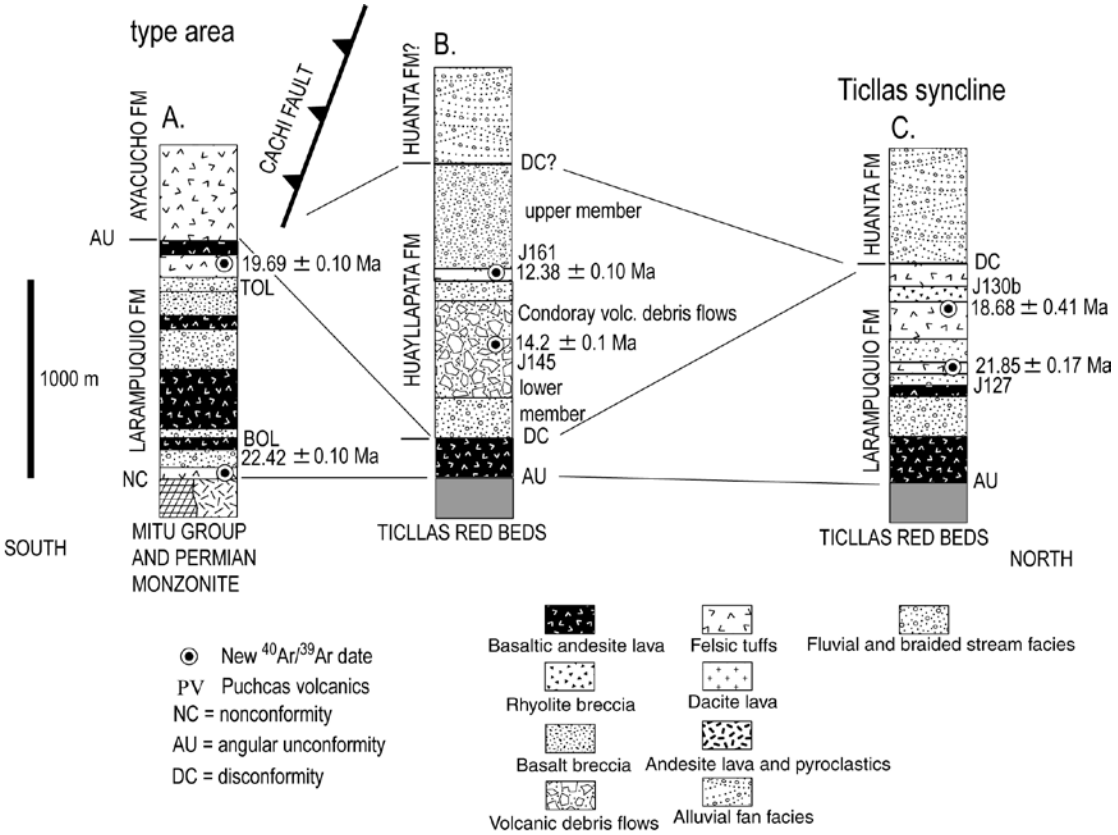

Figure 6.- *Diagram comparing three sections through the Larampuquio Formation (locations shown in Figure 3). A Section from the type area, B section from the east limb of the Cachi anticline, and C section is along the west limb of the Ticllas syncline. The thinner section in B may be from channel erosion that was subsequently filled by the Huayllapata Formation fluvial gravels and volcanic debris flows. Data for age determinations in section B are reported in Wise and Noble (2005). Upper contacts between the Larampuquio Formation and the overlying units shown in sections B and C are conformable.*

DISCUSSION

Crustal extension and bimodal volcanism dominated the early development of the Ayacucho basin, which began after folding the Ticllas Red Beds and probably after a subsequent prolonged period of erosion and/or nondeposition. As discussed above, the ash-flow sheet in the Larampuquio Formation dated at about 20.4 Ma probably belongs to the earlier tectono-stratigraphic sequence characterized by large-volume silicic ash-flow sheets erupted along the main magmatic arc to the west. This period of explosive volcanism and the subsequent extension-related volcanism, to which the bimodal volcanic rocks of the Larampuquio Formation belong, followed what appears to have been a regional decrease in the intensity of magmatic activity across Perú (Noble et al., 1974; McKee and Noble, 1989). We provisionally consider that the subducting slab changed from subhorizontal or gently dipping to steeply dipping after the ca. 28 Ma Aymara (or the later Incaic IV) compressive event.

In the southernmost exposures of the formation, a unit of low-silica rhyolitic ash-flow tuff overlies the Permian(?) granitic basement, whereas to the north intermediate to mafic lava flows and beds of breccia and conglomerate composed mainly of blocks of the same composition were deposited unconformably upon the Ticllas Red Beds. This relation may be explained in several ways, mostly involving assumptions concerning the original basin size or the presence of uplifted basement horsts within the basin, because the nature of the faults that controlled the basin and the initial basin geometry are unclear. Volcanism continued for a period of at least about 3 to 4 million years, mainly from vents marginal to and probably also within the basin.

The dominantly intermediate to mafic and silicic bimodal rocks of the Larampuquio Formation are coeval with the voluminous strongly calc-alkaline intermediate to silicic pyroclastic rocks, plutons, and lavas of the same age erupted along the main magmatic arc to the west as well as in other parts of Perú (Noble et al., 2007 in press). They appear to be age correlatives of the widespread mafic volcanic rocks in central Bolivia (Lamb and Hoke, 1997). Volcanic rocks in the near backarc setting – between the main magmatic arc and the zone of major extensional basins – typically are not bimodal across much of Perú. The presence of bimodal rocks in the Larampuquio Formation at the Ayacucho intermontane basin points to extensional conditions. In North America, similar strongly bimodal extensional settings are present in the backarc of the Cascades in northwestern Nevada and southeastern Oregon: for example, the northwestern Nevada volcanic field and the Kings River and Northern Nevada rifts of north-central Nevada all have bimodal volcanic suites (Noble et al., 1970; McKee and Noble, 1986; Zoback et al., 1994).

The Larampuquio Formation was eroded, locally deeply, during its deposition. Additional erosion before deposition of the middle Miocene Huayllapata Formation is shown by the marked changes in thickness of the formation, by the different rock types preserved in various localities at the top of the unit and by the conglomeratic nature of the lower part of the Huayllapata Formation (Wise and Noble, 2005; Fig. 6). The high percentage of plutonic rock in the lower conglomerate member of the Huayllapata Formation indicates renewed erosion of bedrock. Although the Larampuquio Formation was eroded to a greater or lesser extent before deposition of the Huayllapata Formation, the local reflection of the Quechua I tectonic pulse is significantly different from that in the region to the west (McKee and Noble, 1982; Noble et al., 2007 in press) as well as that envisioned by Mégard et al. (1984) for the Ayacucho basin. These arguments using inferred paleo-relief, composition, and syn-formational erosion indirectly establish an extensional setting in the early Miocene. It is more difficult to analyze the above-listed features in terms of contraction. Furthermore, details of the timing of uplift of the Andes remain controversial and therefore implying syn-contraction formation from the modern setting is tenuous at best.

Based on isotopic ages and the geometry of interpreted post-depositional folds, Mégard et al. (1984) concluded that the Larampuquio Formation was deformed during the regional Quechua I contraction event (ca. 17 Ma). The present geologic mapping, however, shows that that the Larampuquio Formation was not folded before deposition of the overlying middle Miocene Huayllapata Formation (Fig. 3). Stratigraphic relations based on geologic mapping provide no evidence that rocks of the Ayacucho region were significantly folded in the early Miocene. Nevertheless, because of the relatively limited exposures of the Larampuquio Formation, it is definitely possible that the rocks of the domain were affected by the Quechua I event. Even if significant folding and/or faulting did not take place, the Quechua I event may have produced uplift of the area directly west of the basin or subsidence to the east, as evinced by the erosion of the Larampuquio Formation. On the other hand, relief developed during deposition of the Larampuquio Formation is best ascribed to block faulting accompanying extensional opening of the basin.

Distribution of Quechua I deformation

Folds produced by late early Miocene Quechua I contraction are traceable over broad areas in the western part of the High Plateau province (Mégard et al., 1978a; McKee and Noble, 1982; Noble et al., 2007 in press). To the east, the continuity of Quechua I folding and faulting is more difficult to evaluate, in part because of the widespread presence of overlying middle and late Miocene volcanic rocks.

The small early Miocene Rumichaca basin, located 40 km directly west of the Ayacucho basin (Fig. 7), contains a thick wedge of boulder conglomerate composed entirely of pre-Cenozoic rock that overlies a thin sequence of interbedded lacustrine sediment, olivine basalt, and felsic tuff. The tuff has yielded K-Ar ages of 21.7±0.3 (biotite), 21.6±1.3 (plagioclase), 22.9±0.8 (plagioclase) and 20.8±3.9 Ma (plagioclase) (McKee and Noble, 1982) and the bimodal volcanism and lithologic evidence of a closed basin together imply deposition during extension (Noble et al., 1999a). In contrast, Mégard et al. (1983) interpreted the conglomerate wedge, which has been described as possessing progressively rotated beds and angular unconformities, as a syntectonic deposit formed during folding and basin closure. As based on a comparison of stratigraphic thickness and the much smaller areal extent of the basin, it appears that the early extensional phase in the Rumichaca basin was not as intense or widespread as in the Ayacucho basin during deposition of the lower Miocene Larampuquio Formation. Moreover, the Rumichaca basin is unusual in containing coarse deposits that not unreasonably (albeit not conclusively) can be interpreted as having formed during contraction. Rock units in the northern part of the basin record a history of early extension, reflected by the olivine basalt and lacustrine, volcanic-rich sediments (the rhyolitic tuff is probably a distal

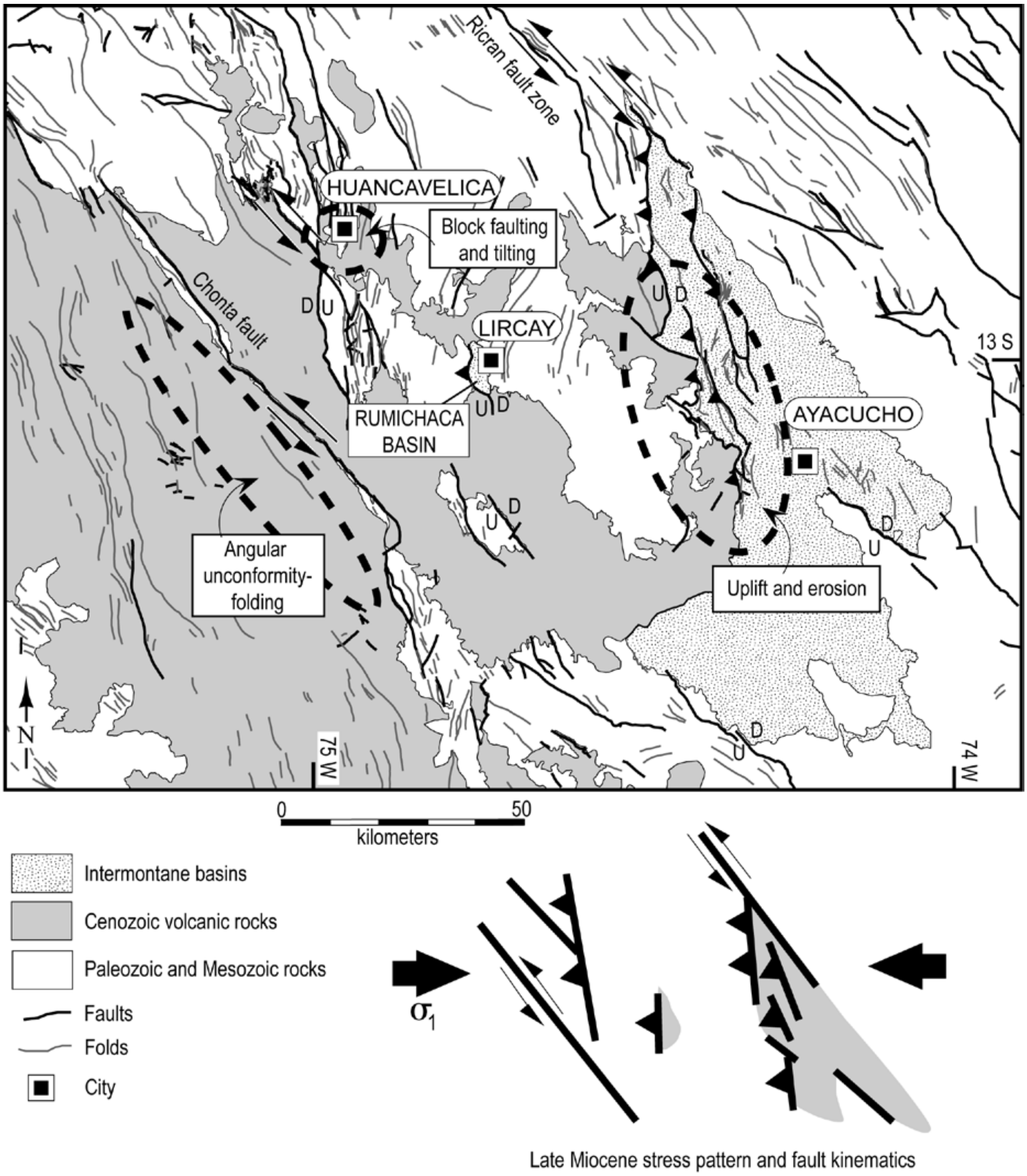

Figure 7.- *Generalized geologic map of the region surrounding the Ayacucho intermontane basin, showing the location of Huancavelica, the Rumichaca intermontane basin, and the Chonta fault. The Ayacucho basin mainly had contractional deformation reactivating faults along the western boundary, producing thrusts that represent fault. restraining bends during left-lateral slip along major NW-striking faults (see lower inset). Heavy dashed outlines mark areas with documented Quechua I deformation.*

deposit derived from a western source) followed by syn-compressional deposition of conglomerate.

In the case of both the Ayacucho and Rumichaca basins, the bounding faults record subsequent late Miocene motion, as shown by basement rock that has been juxtaposed against isotopically-dated basin-fill sections, in a combination of left-lateral strike slip reactivation and thrusts expressing strain partitioning from oblique convergence of the Nazca plate with the South American plate (Dewey and Lamb, 1992; Wise and Noble, 2001; Wise, 2005). It remains unclear if the reported internal angular unconformities in the section at the Rumichaca basin formed by syn-tectonic contraction, or deformation of divergent strata from deposition in the hanging wall of a major normal fault that is no longer exposed, having been overridden by the hanging wall rocks of the younger reverse faults. Because of the amount of late Miocene contraction, the present forms of both basins reveal little, if anything, about their geometries during deposition in the early Miocene. Mégard (1987), however, inferred that the Ayacucho basin was localized by throughgoing NW-striking faults that pass southward from the core of the Ricrán synclinorium, and that these faults most likely also responded to the lastest phases of deformation with a component of left-lateral slip (Fig. 7).

Geological relations at the Rumichaca basin are consistent with the history of the Ayacucho basin and provide additional support for rapid changes between extension and compression. Following the ca. 28 Ma Aymara contraction, several apparently isolated basins with very thick sections formed in which both lacustrine deposits and units of conglomerate associated with basalt flows and rhyolite tuff were deposited. A contractional setting cannot account for the amount of subsidence in the central Peruvian basins. Similar extensional-phase assemblages dated at about 21-22 Ma in the Rumichaca basin, and of early Miocene age near Huancavelica and Lago Choclococha (McKee and Noble, 1982; Noble et al., 1999b) may reflect the same tectonic conditions under which the Larampuquio Formation was deposited. However, the early Miocene volcanic section exposed along the limbs of the Castrovirreyna synclinorium are richer in felsic pyroclastic rocks and lack the mafic lavas that erupted within the Ayacucho basin. Likewise, the time-equivalent volcanic rocks in the upper part of the Calipuy Group of the Cordillera Negra is mainly composed of andesite flows and dacitic tuff and breccia (Noble et al., 1999a), instead having bimodal mafic and felsic compositions. All of the above units bearing coarse-grained clastic deposits suggest active faulting associated with volcanism with the generation of a number of more-or-less isolated basins throughout much of the eastern part of the High Plateau province of central Perú.

For each site of more-or-less intense Quechua I deformation in the eastern part of the High Plateau province the extent or area affected remains generally undefined because the evidence is limited by the sparse preservation and exposure of rocks deposited before and after deformation. Benavides-Cáceres (1999) mentioned that the Quechua I event in the Cordillera Oriental is difficult to differentiate from folding and faulting of the earlier Incaic phases of deformation. Perhaps it would be better to acknowledge that deposits of appropriate age to place upper limits on deformation are absent or sparse in this region, and therefore that it is a matter of inference or speculation whether or not the Quechua I event produced significant deformation in the Cordillera Oriental.

Except for the limited and isolated occurrences near Huancavelica and the Rumichaca basin, there is a lack of early Miocene deposits in the region between Ayacucho and the Castrovirreyna synclinorium. Instead, where visible, pre-middle to late Miocene rocks consist of folded Paleozoic to Mesozoic strata. Because this area was eroded during the development of early Miocene erosion surface(s) (e.g., Puna surface), it remains uncertain if early Miocene deposits were eroded away or simply not deposited in this zone.

Along strike of the NW-trending Andean orogenic fabric, other intermontane basins northwest of Ayacucho (e.g., Huancayo basin) apparently do not contain and/or expose rocks old enough to record deformation from the Quechua I event. In southern Perú folding of the Quechua I phase is not present in the Crucero basin (Laubacher et al., 1988; Clark et al., 1990; Sandeman et al., 1997). Here the Quechua I event is represented by a disconformity, a geologic relationship similar to that of Ayacucho.

The Cenozoic geologic development of most of Perú generally differs significantly from that of the Bolivian orocline, upon which many Andean researchers recently have been focused. Bolivia, however, represents a special case of localized higher-magnitude contractional deformation produced by space problems resulting from the oroflexure. This domain accounts for only a short segment of the entire Andean belt. The list of differences between Perú and Chile as compared to Bolivia is long. Most importantly, deformation phases in Bolivia appear to have extended over longer periods (Lamb and Hoke, 1997) than in Perú (Wise, 2004) and apparently do not match the timing of the Quechua pulses of Perú.

The Andes outside of Bolivia is certainly more dominated by domainal deformation characterized by distinct phases of more-or-less spatially localized extensional tectonism in the highlands (Bonnot et al., 1988; Flint et al., 1993; Dávila and Astini, 2003) interspersed by periods of contraction (Szekely, 1969; Mégard, 1989; Noble et al., 1999b; Giambiagi et al., 2003). In some cases, thrusts have reactivated normal faults (Kley and Monaldi, 2002) and in others reverse faults have been reactivated

***Table 1.-** Appendix: Analytical data for $^{40}Ar/^{39}Ar$ age determinations.*

Summary of 40Ar/39Ar age determination						
Sample Number	UTM Coordinates		Rock type	Mineral	Age (Ma)	Type
	East	North			(± 1 Sigma)	
J127	568486	8555118	Lithic-rich tuff	bio	22.0 ± 0.5	I
					21.85 ± 0.17	P
					23.64 ± 0.17	TG
J130b	568650	8553218	Pumice clast,	plag	18.68 ± 0.41	I
					21.38 ± 0.13	TG
BOL	574305	8531371	Ash-flow tuff	plag	20.42 ± 0.12	I
					21.26 ± 0.10	P
					21.82 ± 0.16	TG
TOL	574364	8535622	Ash-flow tuff	san	19.69 ± 0.10	I
					19.71 ± 0.12	P
					19.69 ± 0.12	TG
I = isochron, P = plateau, and TG = total gas. Bio = biotite, plag = plagioclase, and san = sanidine.						

Preferred age marked in bold.

with strike-slip movement (Wise and Noble, 2001). Kley (1996) emphasized the lateral variations with the Andean orogen and this important observation should not be overlooked. Within central Perú, we have demonstrated that the Quechua I event in the eastern part of the High Plateau province has a fundamental domainal pattern with regard to the presence or absence of folds. Backarc bimodal volcanism in central Perú is interpreted to represent extension. In contrast, similar compositional associations in Bolivia, although present, need not necessarily have resulted from the same process because of lateral variation in subduction geometry, thickness of the crust, and perhaps even special cases of complex ascension of evolved and unevolved magmas. Quechua I deformation in places may have reactivated older normal and strike-slip faults with reverse slip.

The general vague nature on the importance of and the area affected by the Quechua I event in the eastern part of the orogen reflects a general lack of systematic regional mapping in which unconformities and other structural and stratigraphic features are isotopically dated and integrated to arrive at a regional structural synthesis. Previous studies have used tectonic-stratigraphic columns (e.g., Noblet et al., 1996; Sandeman et al., 1995) to summarize and interpret the timing of events, but do not present maps showing structural domains. We remain skeptical that poorly-described geologic features in Bolivia interpreted as having formed during Quechua I tectonism (Sébrier et al., 1988; Lavenu et al., 1989; Sandeman et al., 1995) were indeed formed by the same process and perhaps at the same time as folds and faults in the type area in central Perú (e.g., Steinmann, 1929; McKee and Noble, 1982).

CONCLUSIONS

Mafic to intermediate lava flows and rhyolitic tuffs and lavas of the Larampuquio Formation represent early Miocene bimodal volcanism that occurred under extensional conditions along the boundary between the eastern part of the High Plateau province and the Cordillera Oriental. The Larampuquio Formation is a tectono-stratigraphic correlative of calc-alkalic intermediate to silicic volcanic rocks and plutons that were erupted during the same period along the main magmatic arc to the west before the Quechua I compressive pulse.

The Larampuquio volcanic complex and underlying basement were then eroded, as indicated by the voluminous conglomerate both comprising

Appendix I

BOL, plagioclase, 24.97 mg, J = 0.001553 ± 0.5%

4 amu discrimination = 1.01941 ± 0.42%, 40/39K = 0.02282 ± 136.0%, 36/37Ca = 0.0002897 ± 4.07%, 39/37Ca = 0.0006991 ± 6.99%

step	T (C)	t (min.)	36Ar	37Ar	38Ar	39Ar	40Ar	%40Ar*	% 39Ar rlsd	Ca/K	40Ar*/39ArK	Age (Ma)	1s.d.
1	650	12	3.287	3.857	0.7076	8.178	1077.273	12.4	2.3	5.710134387	15.5057	42.93	1.48
2	730	12	0.965	6.281	0.333	12.011	375.644	31.6	3.4	6.332491059	8.2751	23.04	0.38
3	810	12	0.547	11.635	0.369	20.232	308.864	63.3	5.8	6.965223069	7.7306	21.53	0.22
4	890	12	0.45	20.324	0.52	33.362	374.608	81.2	9.6	7.379357585	7.6287	21.25	0.20
5	960	12	0.412	26.447	0.627	42.298	430.787	87.8	12.1	7.57431641	7.6768	21.38	0.19
6	1030	12	0.417	30.629	0.707	48.833	479.255	89.3	14.0	7.598176604	7.6540	21.32	0.19
7	1100	12	0.406	31.209	0.734	50.5	479.639	90.1	14.5	7.486241888	7.4767	20.83	0.18
8	1170	12	0.379	25.47	0.603	42.465	420.753	90.8	12.2	7.265146487	7.6262	21.24	0.19
9	1235	12	0.361	18.635	0.491	31.637	337.02	88.8	9.1	7.13450144	7.6493	21.31	0.19
10	1400	12	0.407	36.413	0.836	59.604	556.378	92.6	17.1	7.400230094	7.6627	21.34	0.19
								Cumulative %39Ar rlsd =	100.0		Total gas age =	21.82	0.16
											plateau age =	21.26	0.16
											steps 3-10		

note: isotope beams in mV rlsd = released, error in age includes 0.5% J error, all errors 1 sigma
(Not corrected for decay)

TOL , sanidine, 6.24 mg, J = 0.001553 ± 0.5%

4 amu discrimination = 1.01263 ± 0.04%, 40/39K = 0.02282 ± 136.0%, 36/37Ca = 0.0002897 ± 4.07%, 39/37Ca = 0.0006991 ± 6.99%

step	T (C)	t (min.)	36Ar	37Ar	38Ar	39Ar	40Ar	%40Ar*	% 39Ar rlsd	Ca/K	40Ar*/39ArK	Age (Ma)	1s.d.
1	600	12	1.846	0.049	0.366	2.139	555.209	3.0	0.1	0.254056909	7.6804	21.39	0.39
2	700	12	1.465	0.072	0.406	8.51	487.412	12.7	0.5	0.093826976	7.0205	19.56	0.44
3	800	12	0.936	0.102	0.516	28.036	474.845	43.9	1.7	0.040346133	7.1847	20.02	0.17
4	900	12	0.757	0.182	1.109	72.296	733.912	71.4	4.5	0.027917292	7.0897	19.76	0.14
5	1000	12	0.34	0.29	2.175	162.788	1244.86	93.1	10.1	0.019755622	7.0324	19.60	0.13
6	1090	12	0.346	0.329	3.195	242.392	1809.24	95.0	15.0	0.015051927	7.0425	19.62	0.13
7	1155	12	0.343	0.332	3.328	250.793	1865.517	95.4	15.5	0.014680374	7.0425	19.62	0.13
8	1210	12	0.336	0.409	3.944	299.7	2215.657	96.2	18.5	0.015133907	7.0695	19.70	0.13
9	1255	12	0.336	0.474	4.686	358.926	2630.125	96.7	22.2	0.014644949	7.0569	19.66	0.13
10	1295	12	0.312	0.24	2.353	176.909	1349.086	94.4	10.9	0.015044432	7.1204	19.84	0.13
11	1400	12	0.318	0.061	0.273	16.178	207.529	62.3	1.0	0.041814123	7.1453	19.91	0.27
								Cumulative %39Ar rlsd =	100.0		Total gas age =	19.69	0.12
											plateau age =	19.71	0.12
											steps 2-11		

note: isotope beams in mV rlsd = released, error in age includes 0.5% J error, all errors 1 sigma
(Not corrected for decay)

J127, biotite, 12.73 mg, J = 0.001504 ± 0.5%

4 amu discrimination = 1.01941 ± 0.42%, 40/39K = 0.02282 ± 136.0%, 36/37Ca = 0.0002897 ± 4.07%, 39/37Ca = 0.0006991 ± 6.99%

step	T (C)	t (min.)	36Ar	37Ar	38Ar	39Ar	40Ar	%40Ar*	% 39Ar rlsd	Ca/K	40Ar*/39ArK	Age (Ma)	1s.d.
1	650	12	50.779	0.341	10.485	30.74	16373.529	10.0	1.2	0.136430932	53.8304	140.45	5.77
2	725	12	7.024	0.146	1.838	33.722	2462.866	17.7	1.4	0.053246491	12.6762	34.07	0.86
3	800	12	4.463	0.249	1.939	79.945	2002.282	36.5	3.3	0.038305184	8.6317	23.27	0.32
4	875	12	4.167	0.383	3.16	174.808	2680.82	56.1	7.1	0.026945453	8.4380	22.75	0.23
5	930	12	3.536	0.377	4.022	246.985	3050.467	67.6	10.0	0.018772311	8.2118	22.15	0.21
6	985	12	4.058	0.547	6.38	423.746	4620.701	75.4	17.2	0.015875532	8.1391	21.95	0.20
7	1030	12	4.51	1.515	6.05	388.002	4447.117	71.4	15.8	0.048020806	8.1037	21.86	0.20
8	1075	12	4.3	7.089	4.693	290.725	3580.761	66.3	11.8	0.29990678	8.0507	21.71	0.21
9	1105	12	3.846	8.185	3.712	222.389	2888.183	62.7	9.0	0.452698471	8.0015	21.58	0.21
10	1145	12	3.871	7.798	4.749	296.327	3515.812	69.2	12.0	0.323667279	8.1007	21.85	0.21
11	1185	12	3.453	6.088	3.734	227.607	2840.357	66.2	9.3	0.328985316	8.1051	21.86	0.21
12	1235	12	2.266	2.707	0.836	32.166	930.169	31.7	1.3	1.035311275	8.5582	23.07	0.38
13	1400	12	2.105	0.648	0.555	12.22	713.529	16.0	0.5	0.652279179	8.5179	22.97	0.81
								Cumulative %39Ar rlsd =	100.0		Total gas age =	23.64	0.17
											plateau age =	21.85	0.17
											steps 5-11		

note: isotope beams in mV rlsd = released, error in age includes 0.5% J error, all errors 1 sigma
(Not corrected for decay)

J130b, plagioclase, 14.59 mg, J = 0.001515 ± 0.5%

4 amu discrimination = 1.01263 ± 0.04%, 40/39K = 0.02282 ± 136.0%, 36/37Ca = 0.0002897 ± 4.07%, 39/37Ca = 0.0006991 ± 6.99%

step	T (C)	t (min.)	36Ar	37Ar	38Ar	39Ar	40Ar	%40Ar*	% 39Ar rlsd	Ca/K	40Ar*/39ArK	Age (Ma)	1s.d.
1	600	12	2.019	0.746	0.4	2.272	623.631	5.7	0.9	3.790341303	15.3339	41.43	1.20
2	680	12	1.066	1.945	0.243	5.077	353.52	12.8	2.1	4.423263862	8.4975	23.08	0.19
3	760	12	0.719	4.817	0.288	10.945	299.075	32.3	4.5	5.082498856	8.3334	22.63	0.42
4	840	12	0.479	9.371	0.339	19.225	288.332	56.1	7.9	5.629987249	7.9322	21.55	0.18
5	920	12	0.418	15.875	0.514	32.639	360.595	71.3	13.4	5.617759162	7.5188	20.43	0.14
6	995	12	0.428	19.99	0.629	42.286	427.612	75.6	17.4	5.459863955	7.3615	20.01	0.14
7	1070	12	0.416	22.271	0.707	48.409	468.607	78.8	19.9	5.313248342	7.3704	20.03	0.14
8	1140	12	0.355	19.169	0.644	44.241	425.37	80.7	18.2	5.003577563	7.4618	20.28	0.14
9	1210	12	0.341	10.883	0.372	25.378	300.621	73.5	10.4	4.952114031	8.2093	22.30	0.14
10	1400	12	0.406	6.948	0.247	12.908	255.862	60.4	5.3	6.218210042	10.9732	29.75	0.21
								Cumulative %39Ar rlsd =	100.0		Total gas age =	21.38	0.13
											no plateau		

note: isotope beams in mV rlsd = released, error in age includes 0.5% J error, all errors 1 sigma
(Not corrected for decay)

parts of the Larampuquio Formation and the lower member of the overlying Huayllapata Formation. The concordant or sub-parallel nature of the Larampuquio and Huayllapata Formations shows that this portion of the Ayacucho basin was not folded during Quechua I contraction. Erosion and paleotopography developed in the Larampuquio Formation and preserved by the overlying Huayllapata Formation nevertheless show that the region had significant relief and perhaps was uplifted during the Quechua I event. The size of structural domains affected by the Quechua I deformation event remains poorly defined throughout much of the eastern part of the Andean orogen of Perú, and casual assumptions should not be made about the universal presence of this Quechua I deformation in this region.

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