LATE PLIOCENE INCEPTION OF EXTERNAL DRAINAGE AND EROSION OF INTERMONTANE BASINS IN THE HIGHLANDS OF CENTRAL PERÚ

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Resumen: A finales del Neógeno, una gran parte de las altiplanicies del Perú Central estaban drenadas internamente, como lo demuestra la presencia de lagos en las cuencas intermontañosas. A finales del Plioceno, el río Mantaro cortó su paso a través de la Cordillera Oriental y abrió el drenaje de las cuencas intermontañosas de Ayacucho, Huancayo y Junín. Un importante resultado de la erosión en las cabeceras del Rió Mantaro fue la terminación de los drenajes internos ocupados por lagos en las cuencas de Huancayo y Ayacucho. El cañón del río Mantaro espectacularmente profundo y estrecho tanto por debajo de la cuenca intermontañosa de Ayacucho, refleja el cambio de drenaje de interno a externo. Una edad isócrona $^{40}Ar/^{39}Ar$ de 2.76±0.03 Ma de una biotita de una arenisca volcánica de la parte superior de la Formación Cachi en la parte norte de la cuenca de Ayacucho, la cual consiste de estratos lacustres y fluviales de grano fino, establece un límite superior para el inicio del drenaje externo. El río Mantaro no existió en su forma actual antes del final del Plioceno, según lo demuestra la ausencia de capas o lentejones de conglomerados de cantos gruesos en la Formación Cachi y en la Formación Ayacucho infrayacente. Después de abrir su paso a través de la Cordillera Oriental, unos 500 metros de estratos de la cuenca de Ayacucho fueron erosionados durante unos cientos de miles de años, rebajando fuertemente el nivel de base local y cortando gargantas en la superficie de erosión Huari. Los ríos Cachi y Mantaro profundizaron rápidamente cañones al Oeste y Noroeste de la cuenca de Ayacucho. La erosión en las cabeceras por encima de la cuenca de Ayacucho incrementó considerablemente la región de drenaje externo. Luego las cabeceras del río Mantaro cortaron un profundo cañón que se extiende al margen norte del lago Junín, con lo que, solo recientemente, se abre esta región al drenaje externo. El levantamiento en curso de la Cordillera Oriental reflejado en parte por un buzamiento de 5 a 8 grados hacia el Oeste de la Formación Cachi acentúa el relieve desarrollado durante la rápida incisión del río Mantaro por debajo de la cuenca de Ayacucho.

Palabras claves: Perú, Cuenca de Ayacucho, Formación Ayacucho, Formación Cachi, río Mantaro, Cordillera Oriental, desarrollo de drenaje.

Abstract: Before latest Neogene time, much of the highlands of central Perú were internally drained as shown by the presence of lakes in the intermontane basins. In the late Pliocene, río Mantaro cut across the Cordillera Oriental and opened the Ayacucho, Huancayo, and Junín intermontane basins. A significant result of headward erosion of río Mantaro was the termination of closed basins occupied by lakes in both the Huancayo and Ayacucho basins. The spectacularly deep and narrow canyon of río Mantaro below the Ayacucho intermontane basin reflects this change from internal to external drainage. A $^{40}Ar/^{39}Ar$ isochron age of 2.76±0.03 Ma on biotite from volcanic sandstone within the upper part of the Cachi Formation in the northern part of the Ayacucho basin, which consists mainly of fine-grained lacustrine and fluvial strata, provides an upper limit for the time of onset of external drainage. Río Mantaro did not exist in its present form before late Pliocene time, as shown by the absence of beds or lenses of coarse boulder conglomerate within the Cachi Formation and the underlying upper Miocene Ayacucho Formation. After erosional breaching of the Cordillera Oriental, at least 500 m of strata were removed from the Ayacucho basin within several hundred thousand years, lowering local base level and incising gorges into the Huari geomorphic surface. Ríos Cachi and Mantaro rapidly incised deep canyons west and northwest of the Ayacucho basin. Headward erosion above the Ayacucho basin breached a paleo-drainage divide between the Ayacucho and Huancayo basins, greatly expanding the region of external drainage. The upper reaches of río Mantaro then incised a deep canyon that extends north to near the north side of lago Junín, probably only recently linking this region to sea level-based external drainage. Ongoing uplift of the Cordillera Oriental, in part reflected by a 5 to 8 degree westward tilt of the Cachi Formation, accentuates the relief developed during the rapid down cutting of río Mantaro, especially downstream from the Ayacucho basin.

Keywords: Perú, Ayacucho intermontane basin, Ayacucho Formation, Cachi Formation, río Mantaro, Cordillera Oriental, drainage development.

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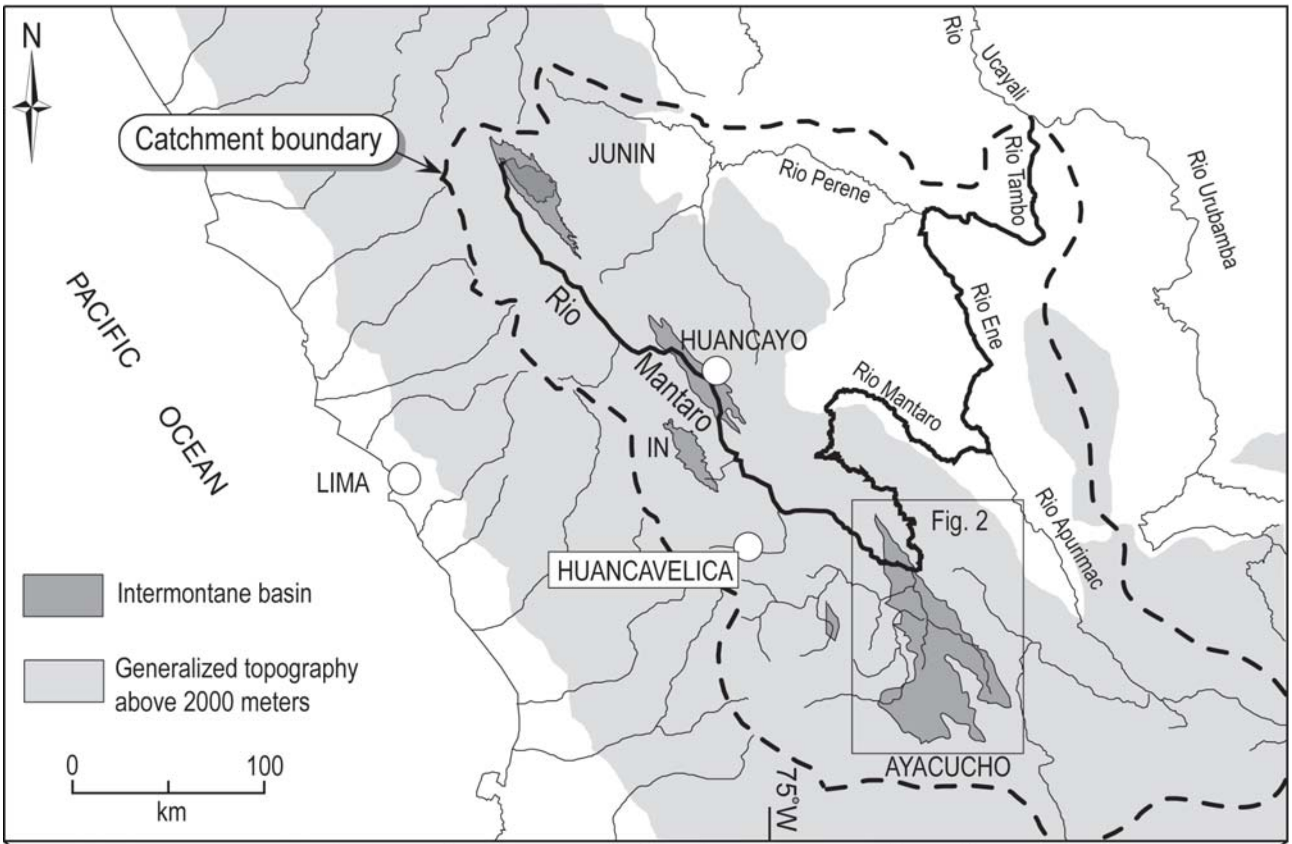
The río Mantaro drainage basin is, after the Urubamba basin, the largest hydrologic catchment draining eastward to the Amazon north of the internally-drained Altiplano that extends from Lake Titicaca southward into Bolivia, northern Chile, and northwestern Argentina (Fig. 1). We use the term *external drainage* for rivers that are not landlocked and ultimately have sea level as the base level. Río Mantaro, with its headwaters in the Junín basin, runs through the Huancayo and Ayacucho intermontane basins, making it the only river in Perú that connects three intermontane basins without being landlocked. The western limit of this catchment is defined by the Continental divide. Its southern boundary, including río



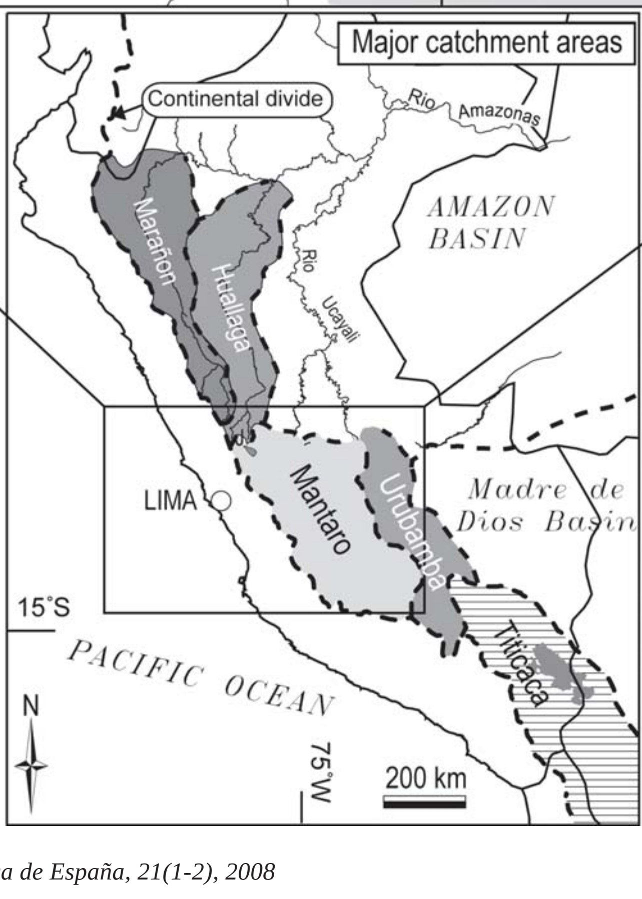


Figure 1.- The lower map illustrates the location of modern major Atlantic-flowing drainage basins and region of internal drainage of the Altiplano. Inset box area shown enlarged in the upper map gives details on the locations of major intermontane basins and river systems referred to in the text. The Mantaro drainage basin in generalized to include the major trunk river systems of ríos Perene and Apurimac.

Apurimac and tributaries, adjoins the Atlantic draining Urubamba catchment. To the north, the río Mantaro catchment is bordered by similar-sized catchments of Huallaga and Marañon (Fig. 1).

Río Mantaro, with a length of about 580 km (including major downstream segments of ríos Ene and Tambo), is characterized by a semi-trellis drainage pattern as it winds through the ranges of the Cordillera Oriental and the Subandean belt. Río Mantaro heads into the lago Junín region, which lies in a broad, nearly closed, sedimentary basin that has not yet been incised by streams. The general lack of deep incision by río Mantaro directly below lago Junín suggests that the river has only recently established a connection to this basin. The river flows generally towards the southeast, traversing the Huancayo intermontane basin. Downstream from Huancayo río Mantaro has cut a deep gorge before reaching the Ayacucho intermontane basin. Río Mantaro has cut into older (Miocene) deposits of the Ayacucho intermontane basin, entering the basin at the northern end, and exits the Ayacucho Valley north of pueblo Huanta (Fig. 2).

The Ayacucho intermontane basin is one of a number of Neogene intermontane basins in central Perú (Figs. 1 and 2). It records a history of deposition of volcanic and volcano-sedimentary rock within a composite basin produced by episodes of extension that were terminated by short pulses of intense compressive deformation and erosion that had begun by early Miocene time (Mégard *et al.*, 1984; Wise, 2004). Bedrock surrounding the basin consists of the Lower Permian Copacabana Group, the Permian to Lower Triassic Mitu Group, and plutons of probably Permian age. During the late Neogene, following the late Miocene (8.7 Ma) Quechua II compressive pulse (Benavides-Cáceres, 1999; Wise, 2004), a new cycle of sedimentation began within a closed basin. Almost all of these strata are included within the Ayacucho and Cachi Formations, which consist mainly of distal ash-flow units and beds of volcaniclastic sandstone and siltstone intercalated with fresh-water limestone, carbonaceous shale and other fine-grained lacustrine strata. Near the eastern margin of the basin wedges of breccia and conglomerate derived from bedrock along

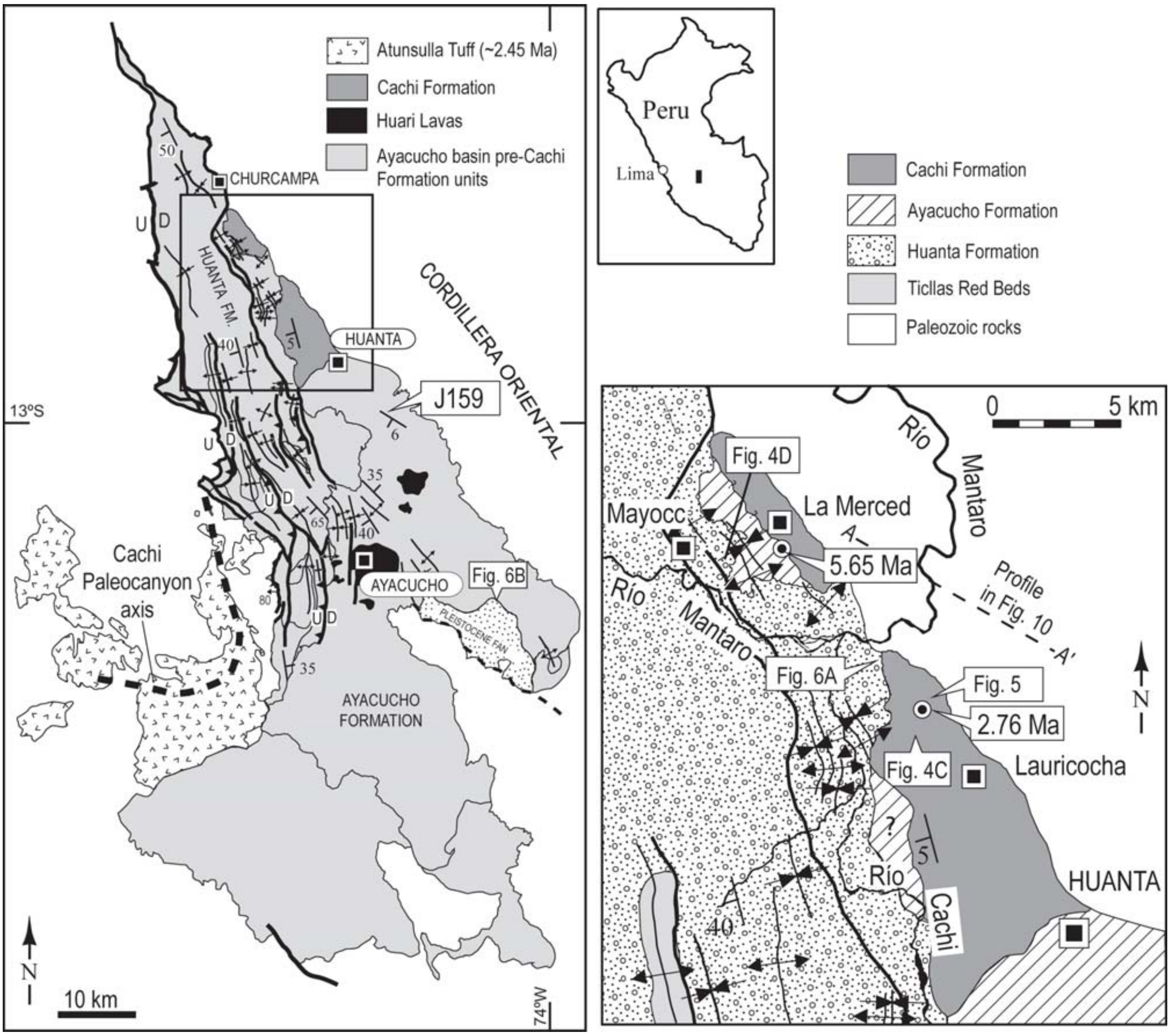


Figure 2.- Generalized geologic map of the Ayacucho intermontane basin. Inset boxes show locations of enlarged maps.

the edge of the basin interfinger with the Ayacucho Formation. There is no evidence that río Mantaro existed during the deposition of these units.

This study focuses on the younger sedimentologic, volcanic and tectonic history of the Ayacucho basin, and particularly on the northern part of the basin that is now traversed by río Mantaro. At least fifteen different stratigraphic units of Neogene age can be recognized in the Ayacucho intermontane basin (Wise, 2004). Of these, we describe the younger units that post-date the Quechua II event, including the upper Miocene Ayacucho and the Cachi Formations. Many units within these formations were deposited in lacustrine settings, demonstrating closed-basin configuration and largely, if not entirely, internal drainage in the Pliocene. The depositional environment during the latest Miocene and early Pliocene is used in conjunction with information on the geomorphic characteristics of the river and the Huancayo intermontane basin to the northwest to constrain the latest Neogene drainage evolution east of the continental divide of central Perú.

Upper Neogene stratigraphy of the Ayacucho basin

Ayacucho Formation

The Ayacucho Formation is a markedly heterogeneous unit that was deposited within a northwest-trending basin shortly after the 8.7 Ma Quechua II compressive pulse (Mégard *et al.*, 1984; Wise, 2004). The formation unconformably overlies the upper Miocene Huanta Formation (Gerth, 1915). In the central part of the basin the formation contains units of ash-flow tuff, volcanic sandstone, conglomerate, reworked tuff, and lacustrine sediments composed mostly of fine-grained volcanic material. Locally, in the center of the basin, the formation was deposited conformably on intermediate-composition lavas and lahars of the upper Miocene Puchcas volcanics that unconformably overlie the Huanta Formation (Wise, 2004). Along the eastern margin of the basin the tuffs and volcanoclastic sedimentary rocks interfinger with locally-derived conglomerate, debris flows and slide

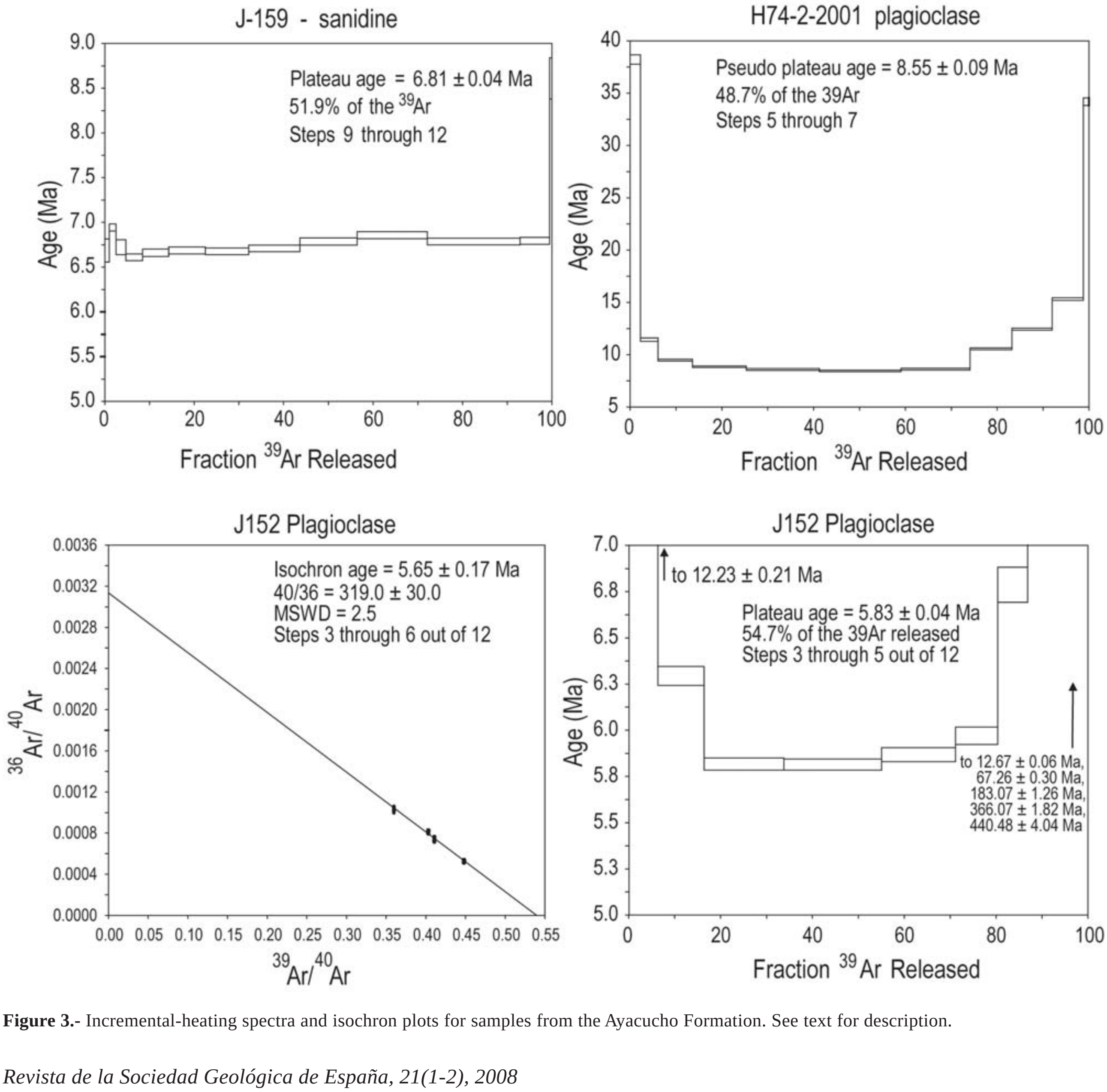


Figure 3.- Incremental-heating spectra and isochron plots for samples from the Ayacucho Formation. See text for description.

breccia sourced from rocks exposed directly northeast of the basin; to the south they are overlain by locally-erupted lava flows of intermediate composition. North of Huanta, in the northern part of the basin, the formation is thinner and composed of reworked tuff and volcanic sandstone with interbedded conglomerate and lacustrine sediments.

The upper age of the formation is refined in this study by several new $^{40}Ar/^{39}Ar$ determinations. A plateau age of 6.81±0.04 Ma incorporating 51.9% of the total released ^{39}Ar and a total-gas age of 6.77±0.03 Ma has been obtained on sanidine from a specimen (J159) collected near the top of the sequence of ash-flow units of the Ayacucho Formation exposed in the central part of the basin (Fig. 3, Table I, Appendix I). The dated unit is conformably overlain by a sequence of locally-derived conglomerate interbedded with lacustrine siltstone and shale of dominantly volcanic provenance, which in turn is capped by more conglomerate (Fig. 4A). The interval of time represented by that part of the Ayacucho Formation overlying the dated sample is not known, but at least pre-dates the eruption of the Pliocene Huari lavas.

Two additional $^{40}Ar/^{39}Ar$ ages show that rocks in the northernmost part of the basin that had been in part provisionally assigned to the Cachi Formation by Wise (2004) in fact belong to the Ayacucho Formation. Mégard and Paredes (1972) and Mégard *et al*. (1984) considered these units to be part of the Mayocc Member of the Huanta Formation. A thin flow of latite lava overlies strata of the Ayacucho Formation north of pueblo La Merced in the northern part of the basin. This lava is mineralogically and chemically very similar to latite of the Huari lavas (see below). A new $^{40}Ar/^{39}Ar$ date from sample J152 on a separate of potassium-rich groundmass feldspar, consisting of a mixture of anorthoclase, plagioclase and compositionally intermediate ternary feldspar separated from a latite flow, contains a large amount of excess argon (Kelly, 2002), as is clearly shown by the pronounced U-shape of the incremental-heating spectrum (Fig. 3). The two youngest steps, incorporating 38.6% of the released ^{39}Ar, result in an age of 5.82±0.03 Ma, and three steps incorporating 54.7% of the released ^{39}Ar give a plateau age of 5.83±0.04 Ma. An isochron plot (Fig. 3) based on four points yielded an age of 5.65±0.17 Ma with a MSWD (Mean Sum Weighted Deviates) of 2.5; the

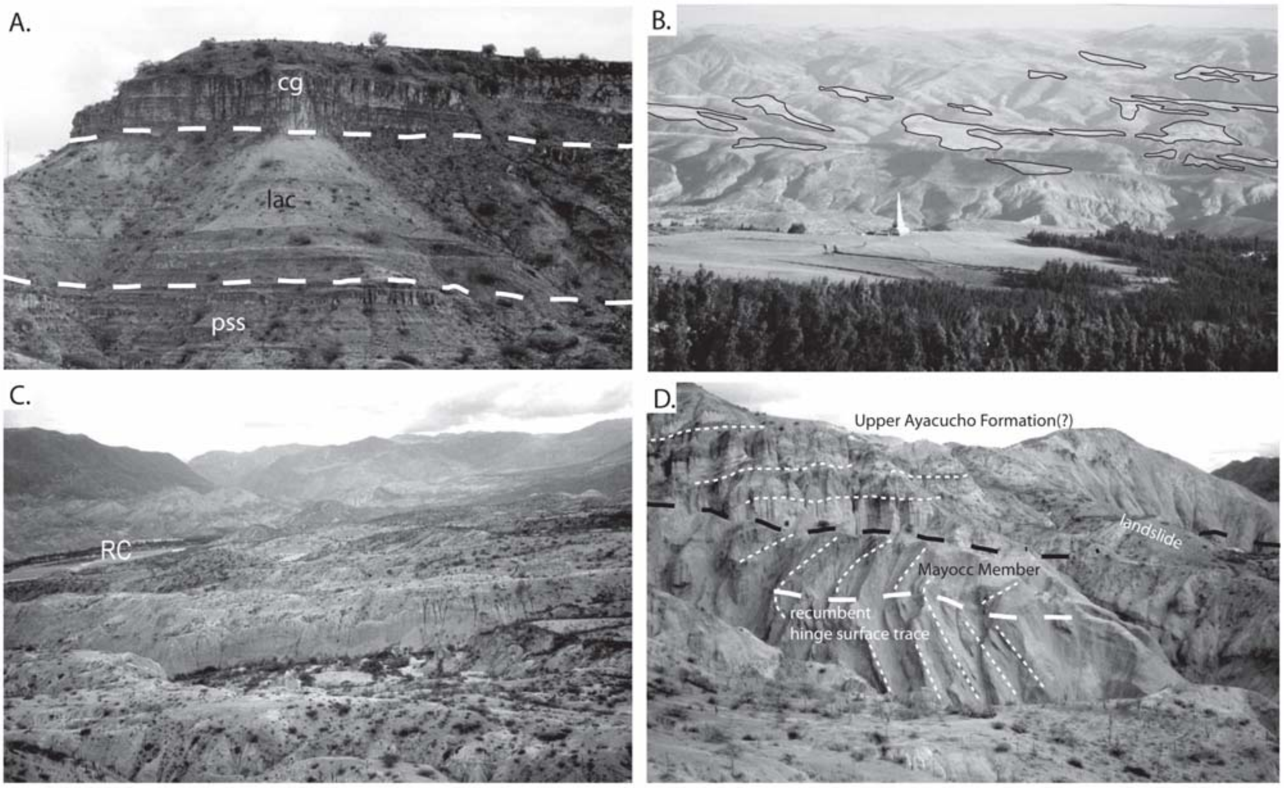


Figure 4.- A) Photograph of a partial stratigraphic section in the Ayacucho Formation directly southwest of Pampa de la Quinua. View is towards the east. Lowermost unit is composed of medium- to thick-bedded cross-stratified sandstone, pebbly sandstone, and pebble conglomerate interpreted as braided stream facies. The middle unit is composed of laminated silty mudstone and mudstone interpreted as lacustrine facies. The uppermost unit has very thick-bedded, channeled clast-supported conglomerate. These units overlie tuff dated at 6.81±0.04 Ma (see text) and are older than the overlying Huari lavas. The lacustrine unit may in part correlate with the Cachi Formation, although additional refinement in the geochronology is needed. **B)** Photograph looking south towards Pampa de Quinua, showing flat-topped interfluves that preserve part of the Huari geomorphic surface. **C)** Photograph looking toward the northwest showing gently west-dipping beds of the Cachi Formation exposed south of río Mantaro and west of pueblo Lauricocha. Río Cachi (RC) is on the left and the canyon of río Mantaro can be seen in the left-central part of the photograph. **D)** Photograph of strong angular unconformity (dashed line) between the Ayacucho Formation and the underlying tan-weathering Mayocc Member of the upper Miocene Huanta Formation. A recumbent fold is present in the Mayocc Member (thick dashed line shows hinge surface trace and bedding is indicated by dashed white lines). Photograph was taken from the unpaved road between Mayocc and La Merced, looking to the southeast.

calculated $^{40}Ar/^{36}Ar$ ratio is 319±30. Considering the presence of excess argon, we interpret the isochron age as being the most accurate.

Mégard *et al*. (1984) reported a preferred K-Ar age of 11.2±0.4 Ma for plagioclase (sample H74-2) from a unit of volcanic sandstone exposed south of río Mantaro a short distance east of the road that connects pueblos Mayocc and Huanta. Redating the mineral separate (new laboratory number H74-2-2001) using $^{40}Ar/^{39}Ar$ methods yielded a highly discordant spectrum with a pronounced saddle shape (Fig 3, Table I). The total-gas age of 10.74±0.09 Ma is close to that of the earlier K-Ar age. The age of the lowest step of the spectrum, involving 17.8% of the released ^{39}Ar, is 8.45±0.08 Ma; the three lowest steps define a pseudo-plateau involving 48.7% of the released ^{39}Ar of 8.55±0.09 Ma. These maximum ages are about 0.9 Ma older than the oldest age obtained for the basal unit of the Ayacucho Formation (Wise, 2004). Some uncertainties remain in the geologic context of the sample. The new age suggests that either there may be additional presence of older units beneath the Cachi Formation or older material was reworked into deposits of the Cachi Formation. The age for sample H74-2-2001 is within analytical uncertainty of dates yielded from the Puchcas Formation (Wise, 2004). Regardless of the sample context, the redated material shows that the sample site does not belong to the Huanta Formation as originally reported in Mégard *et al*. (1984).

Huari lavas

Pyroclastic rocks and lava of latitic to low-silica latitic composition were erupted in several isolated areas after deposition of the Ayacucho Formation (Noble *et al.*, 1975; Morche *et al*., 1995; Wise, 2004). The largest and most readily accessible exposures are in the vicinity of the city of Ayacucho and at the archeological site of Huari below Pampa de la Quinua. The section of Huari lavas at Ayacucho appears to fill a low region centered on the hinge line of a major upright syncline in the Ayacucho Formation. In contrast, the Pampa de la Quinua section of the Huari lavas was deposited on a very gently WSW-dipping tableland formed upon the uppermost conglomerate beds of the Ayacucho Formation. This contact along with the planar upper surface of the lavas together generally parallels a broad geomorphic surface here named the *Huari geomorphic surface*. This surface is preserved on wide interfluves throughout the southeastern part of the basin (Fig. 4B).

Only one isotopic age has been obtained on the Huari lavas. Noble *et al*. (1975) presented a K-Ar age of 3.8±0.4 Ma obtained on a whole-rock specimen of low-silica latite lava (AYA-1A) collected from exposures near Huari. As discussed above, we have obtained a $^{40}Ar/^{39}Ar$ age of about 5.65±0.17 Ma on groundmass feldspar from lava (J152) exposed north of La Merced. The total-gas age of this specimen, which is petrographically similar to that the Huari lavas, is 12.78±0.03 Ma. The excess Argon in the latite specimen increased its apparent age by more than 7 million years. In view of the presence of a considerable amount of excess argon in specimen J152, it is not unreasonable to suspect that a significant amount of excess argon may be present in the petrographically similar specimen AYA-1A. If so, the lavas in the vicinity of Huari would be appreciably younger than 3.8 Ma.

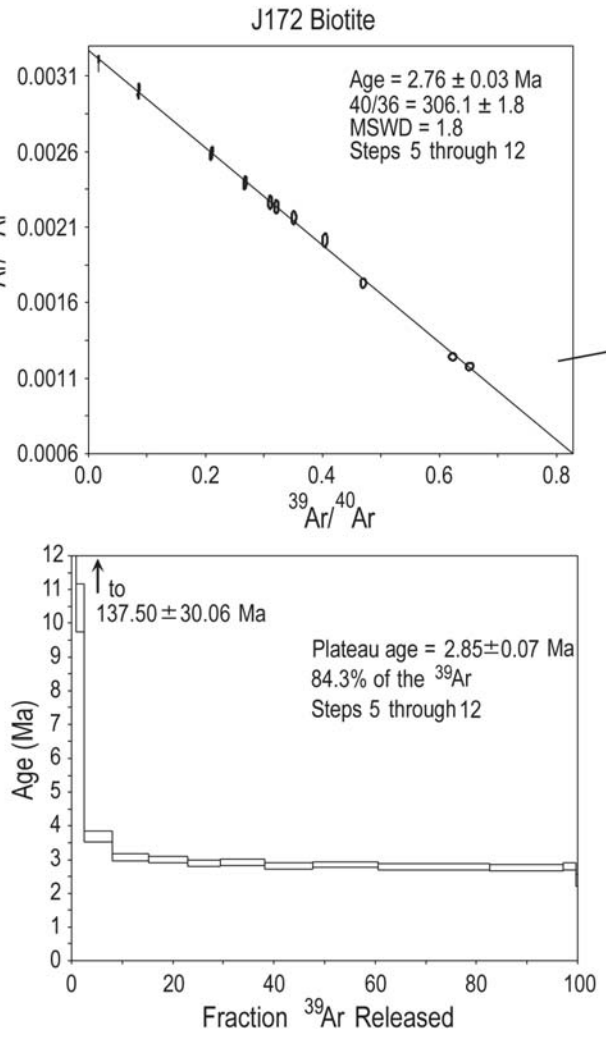
The lavas exposed near Ayacucho and Huari are underlain and surrounded by tuff rings of fine-grained, typically tabular bedded, pyroclastic rocks with well-developed surge structures. The particles consist mostly of angular fragments of volcanic glass. These features strongly suggest that fragmentation was produced by the contact of magma with water. It is not clear whether standing water was present or if the water was saturating the porous Ayacucho Formation, or some combination of the two. In any case, the nature of eruption suggests that the Ayacucho basin may have been closed or undrained during early Pliocene time, or at least that erosion had not proceeded sufficiently to markedly lower the water table.

Cachi Formation

Newly recognized lacustrine and fluvial sedimentary rocks exposed in the northern part of the Ayacucho intermontane basin (Fig. 2) are here named the Cachi Formation after the nearby río Cachi. These rocks were considered to belong to the lower part (Mayocc Member) of the Huanta Formation by previous researchers (Mégard and Paredes, 1972; Mégard *et al*., 1984; López *et al*., 1996; see discussion by Wise, 2004). Both the Mayocc Member of the Huanta Formation and the Cachi Formation share a common dominantly lacustrine depositional environment, resulting in similar weathering features and color. The Cachi Formation, however, is considerably less folded than the Mayocc Member, the criterion that in this study initially suggested that two different units were present.

Both the Cachi Formation and the Mayocc Member weather to an identical yellowish- to tan color. Preserved thickness of the Cachi Formation is approximately 80 m north of río Mantaro, and more than 150 m to the south. This formation is recessive weathering or, in other words, a slope-forming unit that developed rounded topographically low-profile hills. The formation onlaps Paleozoic bedrock along the eastern margin of the Ayacucho basin. It is best exposed from Lauricocha northward (Fig. 4C). In contrast, the region southwest of Huanta is heavily cultivated and here the formation has limited exposures, the best of which are close to río Cachi. Based on isotopic dating (see below), the upper part of the formation south of río Mantaro is of late Pliocene age. The rest of the unit is probably also of late Pliocene age, although the possibility exists that the lower part of the formation includes strata of early Pliocene age.

East of pueblo Mayocc, the Cachi Formation overlies beds that we now assign to the Ayacucho Formation, which in turn has its base well exposed along a well-developed angular unconformity cut upon the Mayocc Member of the Huanta Formation (Fig. 4D). The Ayacucho Formation here consists of subhorizontal beds of lithic-rich tuff and pebble conglomerate that have been deformed into very open NS-trending upright folds. Several thick units of thin-bedded organic-bearing, laminated mudstone indicate intermittent anoxic conditions, similar to lacustrine



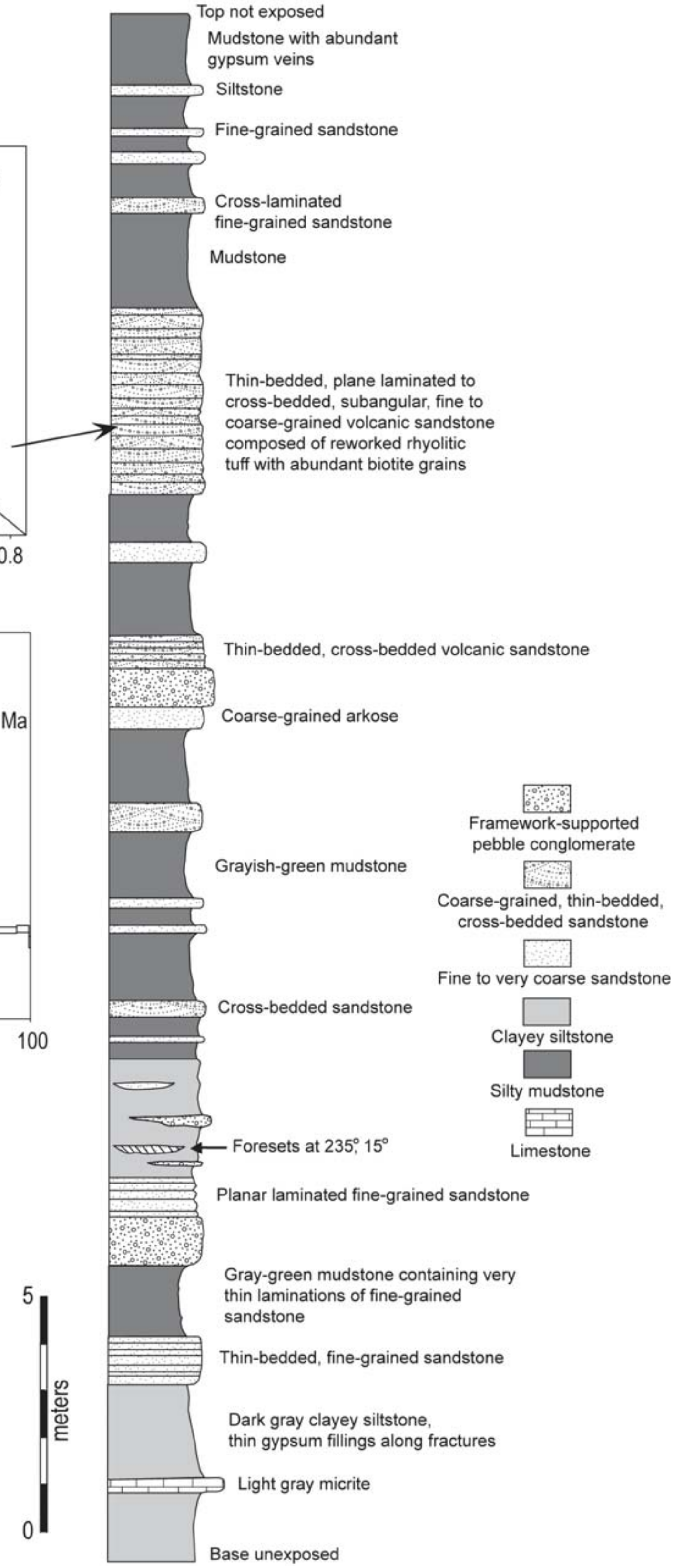


Figure 5.- Partial measured section of the Cachi Formation. Section is located at 575,189E, 8,578,734N (zone 18 of the 1956 South American provisional UTM grid), near the location of isotopically dated specimen J172. On the left side of the section are incremental-heating and isochron plots for $^{40}Ar/^{39}Ar$ age determinations on rocks from the Cachi Formation. See text and Table I for discussions and locations of samples.

units in the Ayacucho Formation west of Pampa de Quinua. Higher in the section, south of pueblo La Merced, a bed of fresh-water limestone and very minor amounts of thin-bedded chert contain snail and reed fossils. As discussed above, latite lava of limited areal extent overlies a limestone bed in the Ayacucho Formation. Although this unit of lava underlying the Cachi Formation has yielded a latest Miocene age (see above), the contact relation with the Cachi Formation is poorly exposed. Although we interpret the Ayacucho and Cachi Formations as two distinct stratigraphic units, the similar depositional settings of both units would allow a prolonged closed-basin depositional environment and a transitional contact between the two units. Although, based on cross cutting relationships at Pampa de Quinua, it is equally likely that the Ayacucho-Cachi Formation contact at La Merced is an angular unconformity related to the ~5.3 Ma Quechua III contractional event. A complete vertical section of the formation is not available. We therefore propose that the area a short distance north of pueblo Lauricocha, within which the partial measured section in figure 5 is located, be taken as the type area of the Cachi Formation.

South of río Mantaro, in the type area, the Cachi Formation consists of parallel-layered, yellow-weathering mudstone, siltstone, and channeled clast-supported sandstone and gravel, with some beds composed mostly to entirely of reworked silicic pyroclastic material (Fig. 5). Overall, beds average between 20 and 80 cm in thickness. The formation dips 5 to 8 degrees to the west-southwest. The fine-grained beds are laminated and are gray to green where unweathered. Fractures in the mudstone are lined with gypsum, suggesting that the unit once contained evaporites. Sandy beds are planar-laminated to cross-bedded. There are also a few tabular layers of fine-grained, medium gray, fresh-water limestone in 20 cm-thick beds, and intervals of thin-bedded, planar-laminated, well-sorted, coarse-grained sandstone about 4 m thick. All the above units are in the partial measured section (Fig. 5), located near sample site J172. Most of these beds are interpreted as lacustrine deposits based on the abundance of laminated silty mudstone and subordinate thin beds of micritic limestone. Interbedded channelized pebble conglomerate and cross-stratified sandstone may represent a near-shore facies, either beach deposits, or braided-stream gravels possibly formed during low stands.

Biotite from a unit of cross-stratified, medium-bedded, medium to coarse grained, poorly cemented, volcanic sandstone near the top of the Cachi Formation south of río Mantaro (sample J172) yielded an excellent (MSWD = 1.8) $^{40}Ar/^{39}Ar$ isochron age of 2.76±0.03 Ma calculated using incremental heating steps 5 through 12, which account for 84.3% of the released ^{39}Ar (Table I, Fig. 5). The form of the incremental-heating spectrum suggests the inclusion of a minor amount of excess argon (Kelly, 2002), as does the calculated $^{40}Ar/^{36}Ar$ ratio of 306.1±1.8. The slightly younger isochron age is preferred over the plateau age of 2.85±0.07 Ma, which was also obtained using steps 5 through 12.

Sandstone sample J172 is composed of moderately-sorted, angular grains of plagioclase, quartz, biotite and volcanic glass, with no lithic material derived from older units. There is no evidence for multiple populations of plagioclase, biotite or other minerals or for the incorporation of older epigenetic volcanic material, and the rock is interpreted as reworked pyroclastic debris from a single eruptive event; the source area for which is not known. The isochron age of sample J172 therefore is taken as the age of the volcanic eruption and, by extension, the time of deposition of the volcanic sandstone. The isotopic age and the absence of sanidine indicate that the Cachi Formation is not correlative with the younger Atunsulla Tuff (see below), outcrops of which are found southwest of the basin.

The Cachi Formation is preserved on both the north and south sides of the present río Mantaro, which has cut a prominent gorge through the Cordillera Oriental (Fig. 6A). These deposits demonstrate a minimum of 500 m of canyon incision since the deposition of the unit.

Atunsulla Tuff

The Atunsulla Tuff is a multiple-flow or composite ash-flow sheet of uppermost Pliocene age. The rhyolitic ash-flow tuff contains abundant large clasts of pumice and phenocrysts of sodic plagioclase, quartz, sanidine and biotite. The unit is in part preserved within a deep paleocanyon west of the Ayacucho basin (Fig. 2). The Atunsulla Tuff can be traced continuously for 40 km along the río Cachi drainage from its source, the Cerro Sagollan caldera within the Nevado Portugueza volcanic center, to the western margin of the Ayacucho basin (Noble and McKee, 1982). The difference in elevation between the caldera margin and the base of exposures in the lower part of the río Cachi drainage is about 1,600 m. The modern drainage system has mostly eroded through the thick canyon-filling tuff, and in places remnants of the outflow sheet are locally perched as much as 650 m above the present río Cachi. Although the unit is not preserved within the Ayacucho basin, distal ash flows undoubtedly reached the northern part of the basin.

Noble and McKee (1982) reported K-Ar ages on biotite of 2.23±0.3 Ma, 2.34±0.2 Ma, and 2.76±0.3 Ma for the Atunsulla Tuff. They gave greater weight to the first two ages, suggesting a preferred age of about 2.4 Ma. This interpretation is supported by a whole-rock K-Ar age on the Atunsulla Tuff of 2.45±0.06 Ma reported by Kaneoka and Guevara (1984, their sample A-116).

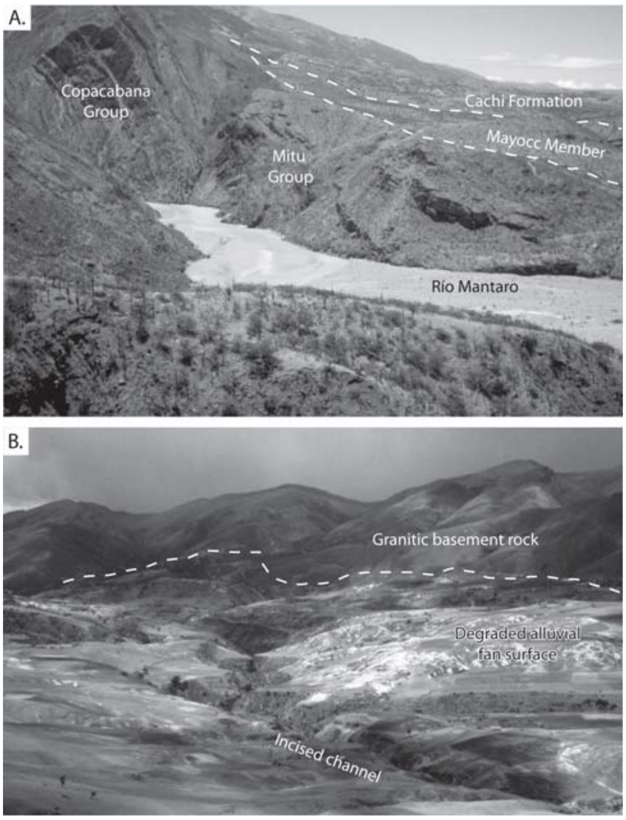


Figure 6.- A) Photograph with view towards the southeast showing the río Mantaro at the exit point from the Ayacucho basin. The Cachi Formation forms the unit on the skyline south of the river. **B)** View to the southwest toward reddish-weathering Pleistocene(?) alluvial fan deposits southeast of Ayacucho. Land surface is cultivated. Note the deeply incised gully at the center of the photograph. Clasts are composed of Permian (?) granitic rock that crops out in the dark, shadowed hills.

Pleistocene to Recent deposits

Quaternary Lacustrine Beds

Flat-lying, tabular-bedded mudstone and siltstone deposits of very limited areal extent fill paleo-depressions near the confluence of ríos Mantaro and Cachi. These lacustrine deposits unconformably overlie the Pliocene Cachi Formation and the Mayocc Member of the Huanta Formation, and are exposed at elevations that extend higher than the onlapping river terraces (see below). Maximum thickness is approximately 100 m. These deposits most likely were deposited in a short-lived lake formed by blockage of the río Mantaro by a landslide perhaps located not far downstream from where the river now exits the Ayacucho basin.

Recent river terraces

A series of depositional river terraces are found along both ríos Mantaro and Cachi. The older terraces have cut banks about 5 m high and form large areas of flat land at the mouths of minor tributary canyons. At least four terraces are discontinuously preserved as patches along río Mantaro. The two innermost sets of terraces have lower cut-bank height and are very young. These younger terraces correlate with morphologically similar inset terraces along río Cachi and the local río Urubamba. River terraces are found discontinuously along río Mantaro upstream of the Ayacucho basin, and Blanc (1984) describes three main terraces where the river passes through the Huancayo intermontane basin. Most of the terrace deposits probably represent river aggradation during the last glacial stage and subsequent incision. However, the most recent, and lowest, terraces along río Mantaro downstream from pueblo Mayocc may have been deposited from large debris flows generated by landslides into the canyon upstream (Fig. 7).

Pleistocene alluvial fans

Southeast of Ayacucho, monolithic reddish-weathering alluvial-fan deposits of probable Pleistocene age cap now-dissected Huari surface plateaus underlain by the Ayacucho Formation (Fig. 6B). The alluvial fans are composed entirely of debris derived from granitic rock that forms a basement high in the south-center part of the Ayacucho basin (Fig. 2). Similarly, young alluvial fans also partially onlap the Cachi Formation north of Huanta. These very coarse alluvial fan deposits are very poorly sorted and contain large angular boulders. These deposits generally drape the eastern side of the Ayacucho basin and onlap the

Figure 7.- Photograph of the Mayunmarca landslide along río Mantaro between Huancayo and Ayacucho.

pre-Cenozoic basement rock of the Cordillera Oriental. Deep incision or even possibly channel entrenchment of these fans demonstrate the recent development of headward erosion into the Huari geomorphic surface.

Huancayo and Ingahuasi intermontane basins

The NW-elongate Huancayo intermontane basin (Fig. 1) was closed during the late Miocene and subsequently was integrated into the río Mantaro drainage system. The basin is presently bounded on the eastern margin by the Huaytapallana massif, a subrange of the Cordillera Oriental, which is being actively thrust to the west (Mégard and Philip, 1976). Along the western margin of the basin active east-vergent reverse faults place basement rock over basin-fill units, and pre-Cenozoic basement rock makes a prominent divide farther to the west. During the late Miocene and probably into the Pliocene the basin held a large lake that is represented by certain sedimentary units of the Jauja Group (Dollfus and Mégard, 1968; Mégard, 1968; Blanc, 1984), which is comprised of the Ushno and Mataula Formations (Fig. 8). The combined minimum preserved thickness of the Jauja Group is about 200 m (Dollfus and Mégard, 1968). The lower Ushno Formation is composed mainly of alluvial fan deposits that contain conglomerate beds rich in clasts of Paleozoic and Mesozoic basement rock. This formation is overlain by the mainly lacustrine deposits of the Mataula Formation. The paucity of Tertiary volcanic clasts in the conglomerate beds of the Jauja Group indicates that east-flowing streams did not transport material from the main volcanic arc into the basin. Rather, the clasts of weakly metamorphosed Paleozoic to Mesozoic sedimentary and volcanic rock of the Permian to Lower Triassic Mitu Group demonstrate that the conglomerates were sourced from exposures directly surrounding the basin.

Blanc (1984) reported a K-Ar age of 5.64±0.20 Ma for a unit of silicic tuff intercalated within the sedimentary sequence of Mataula Formation in the Jauja Group. A more precise and accurate $^{40}Ar/^{39}Ar$ plateau age of 5.39±0.05 Ma on phenocrystic biotite from the same unit has been obtained by Wise (2004). Although these isotopic determinations provide the only age control available for the unit, it is not unreasonable to assume that the upper part of the Mataula Formation extends into the Pliocene. The source area for the waterlain tuffaceous material has not been positively identified, but a new age determination reported by Bissig *et al*. (2008) from a dacite dome located 46 km to the southwest is a likely candidate (see additional discussion below).

The deep and narrow nature of the canyon where río Mantaro now exits at the southeastern end of the Huancayo basin strongly suggests that the canyon is a relatively young feature. Moreover, farther upstream, río Mantaro heads in lago Junín, which lies in a broad and nearly closed basin containing sediments that have not yet been incised by streams. This lack of deep erosion also argues that río Mantaro has only recently established a connection to this basin.

Recent headwater erosion in the vicinity of Huancayo is affirmed by the drainage pattern affecting the Ingahuasi basin. The Ingahuasi basin, centered about 14 km west of the Huancayo basin, is a broad depression

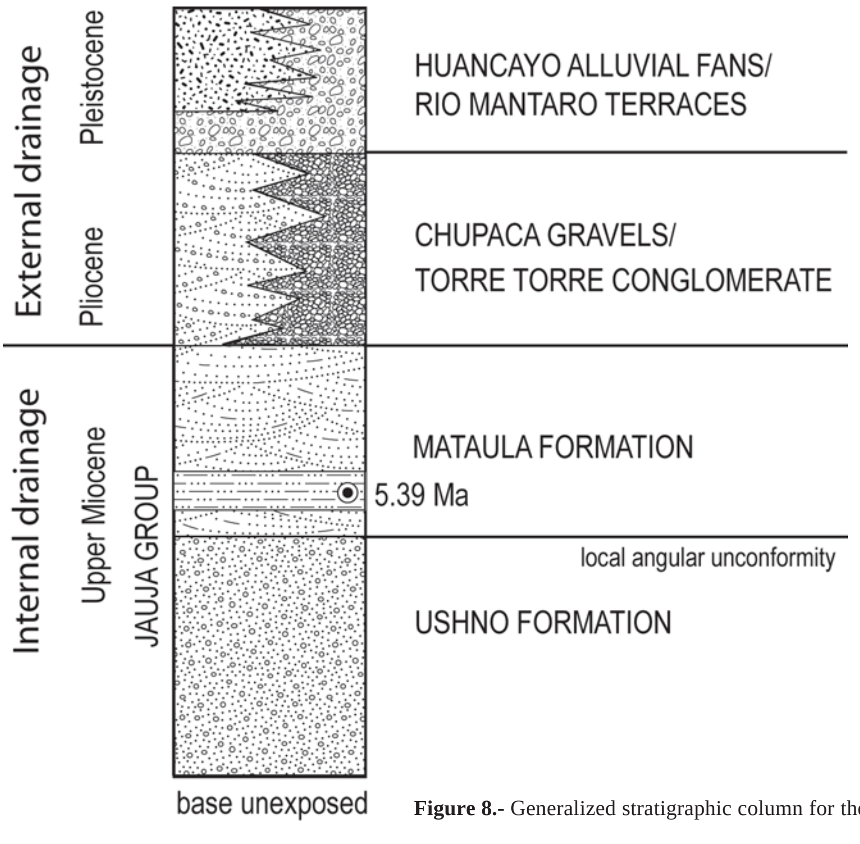


Figure 8.- Generalized stratigraphic column for the Huancayo intermontane basin.

surrounded mainly by Mesozoic rocks. This basin has only just begun to be incised at its southern end by río Canipaco, a major tributary to río Mantaro (Fig. 9). Flat-lying deposits of travertine, tuff, and lacustrine-deposited tuff of Pliocene age capped by sheets of gravel comprise the basin fill (Mégard, 1968). Deep gorges are just now eroding into dacite flows, which constrain the timing of rio Mantaro tributaries to be similar as that observed in the Huancayo basin. Bissig *et al.* (2008) dated the domes at 5.4±0.25 Ma (their sample 2PYB514), an age that is analytically indistinguishable from the above described age on sample J152.

The northern two-thirds of the Ingahausi basin, however, drains to the northwest along a gentle river system that joins Quebrada Chupaca, which then flows eastwards, cutting across the western divide of the Huancayo basin to join the río Mantaro. This drainage pattern is probably somewhat older than the canyon advancing into the southern part of the basin, and indeed may have directed outflow ash from the dacite dome complex into the paleo-lake in the Huancayo basin. Additional petrographic and geochemical data needs to be examined to test this hypothesis.

Geomorphic features of the Río Mantaro drainage

Both upstream and downstream of where the river passes through the northern part of the Ayacucho basin, the canyon of río Mantaro is geomorphologically very young; the canyon is very deep and narrow and the river is actively eroding bedrock. The precipitous canyon walls are extremely prone to landslides. Similarly, major rivers in other parts of Perú, such as río Urubamba, have carved spectacular canyons where they transverse the Cordillera Oriental. Multiple slope angles that steepen closer to the river bed, as apparent in cross profile, imply increasing rates of incision (e.g., Garner, 1959, his figure 8; our observations). Drainage divides in the Cordillera Oriental and Subandean belt are characterized by steep slopes and sharp crests, readily observed in such accessible areas as Macchu Picchu and Cobriza. The extremely narrow gorges indicate more rapid latest Neogene uplift and erosion along the eastern margin of the Cordillera Oriental as compared to the wider canyons of the Cordillera Occidental.

A longitudinal profile of río Mantaro (Fig. 10), extending from its headwater at lago Junín to the confluence with río Ene, a strongly meandering major tributary to the Amazon river, was drawn using topographic data from 1:100,000-scale maps. Rivers typically develop a concave-upwards profile when at equilibrium with sediment input, uplift, and erosion; this pattern is known as a graded river profile. Río Mantaro exhibits the opposite pattern- convex upward, suggesting disequilibrium in which erosion has not kept

Figure 9.- NASA photograph taken from space shuttle of the Huancayo and Ingahuasi basins showing the location of río Mantaro, major divides, and tributary canyon eroding into the young flat-lying deposits of the Ingahuasi basin. Río Mantaro flows southward from the top of the image towards the bottom. Peaks of the Cordillera Huaytapallana, part of the Cordillera Oriental, reach an elevation of 5,600 m.

pace with uplift and/or that there was insufficient time since the canyon began to be eroded for the river to establish a graded profile (Fig. 10A). Slopes of río Mantaro are mostly below one percent, although within the Ayacucho and Huancayo intermontane basins the river flows in a braided alluvial channel running at slopes between 0.4 and 0.6 percent. The channel has a greater slope where cut in bedrock between these two basins. Pronounced local changes in slope where the river crosses the Subandean fold and thrust belt, well downstream from Ayacucho, probably reflect active faulting. The lowermost reach of the river, at about 550 m elevation, returns to an alluvial channel of lower gradient.

Stream-gradient index numbers, defined as the distance from the headwater divided by the river slope along a section of the channel, for río Mantaro range from 10 to 680, increasing downstream (Fig. 10B). Segments of greater stream-gradient indices may reflect areas of more rapid tectonism and uplift or knickpoints

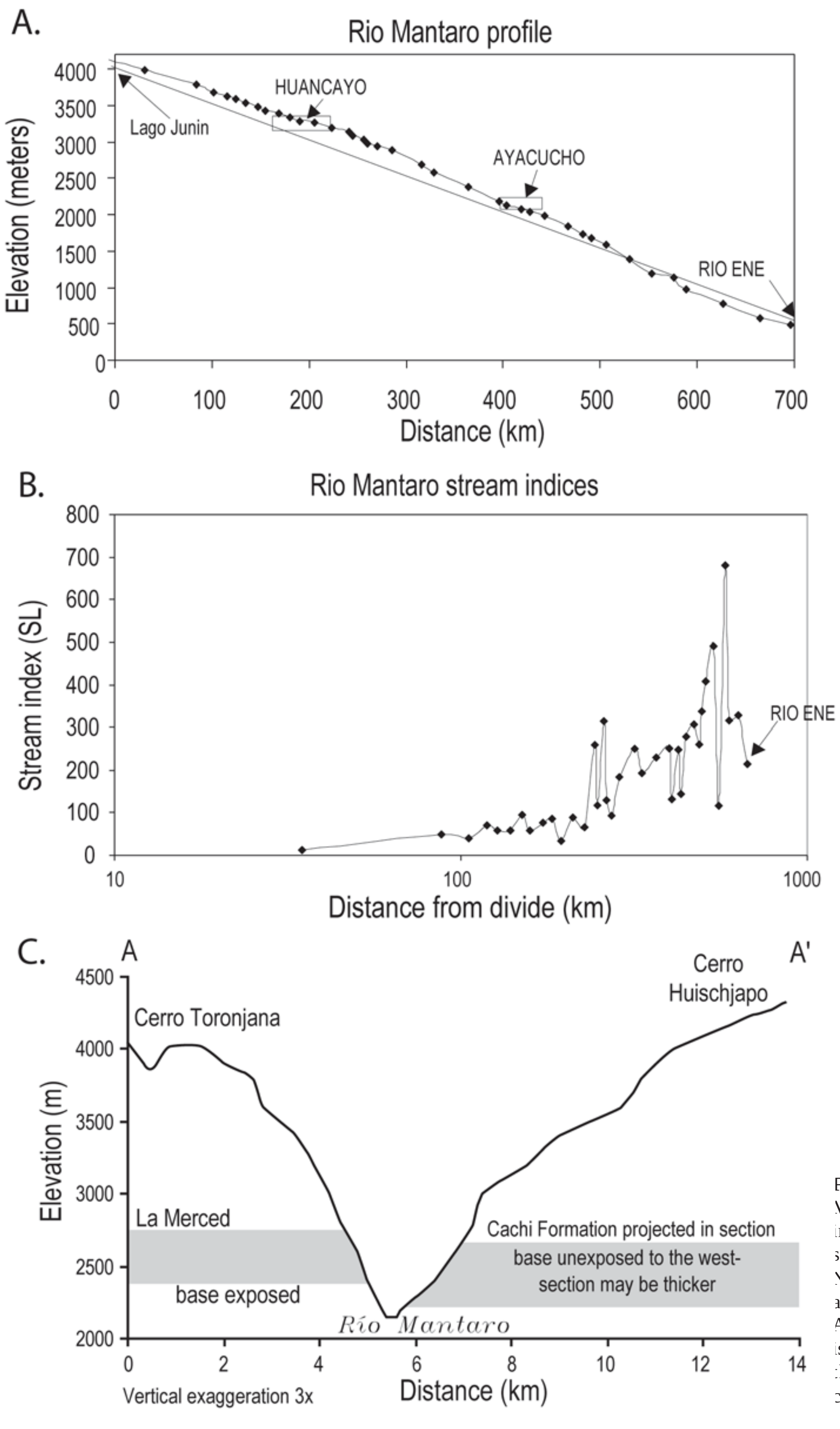


Figure 10.- A) Longitudinal profile for río Mantaro showing the location of major intermontane basins. **B)** Graph showing stream indices of río Mantaro. **C)** Northwest to southeast topographic profile across the río Mantaro where it exits the Ayacucho intermontane basin; section view is towards the northeast. Upper elevation of the Cachi Formation marked for comparison with divide slopes.

developed on resistant rock types (Hack, 1973). The overall convex-up pattern of río Mantaro is of a much longer wavelength than the outcrop extent of any resistant rock type intersected by the river. In addition, the eastward-directed rivers commonly alternate between alluvial and bedrock bases, and especially the latter where crossing the hanging walls of exposed thrust faults, and at more resistant rock types. Likewise, preliminary examination of río Urubamba reveals a similar convex-up river profile. We relate the broad convex-up profiles to active uplift, for which seismicity in the Subandean belt provides strong indirect evidence. Similar arguments were made by Seeber and Gornitz (1983), who demonstrated that in the Himalayas regions of steeper river gradients correspond to a belt of modern seismicity.

Within both the Huancayo and Ayacucho intermontane basins, the river is bordered by a series of at least three major depositional terraces that appear to have been produced by Pleistocene to post-Pleistocene erosion of the aggraded channel. Care must be used, however, in interpreting terraces along rivers such as the Mantaro. As discussed above, the very steep canyon walls of río Mantaro, like many other similar young canyons in the Andes of Perú, are in a state of almost continual landsliding. Major landslides block drainages, producing temporary lakes. A good present example is lago Pías in the vicinity of Parcoy in the upper part of the río Marañon drainage system in northern Perú. Likewise, a major lake existed in the upper reaches of río Cañete at the latitude of pueblo Yauyos in central Peru. Remnants of sediments deposited in this lake were mapped by Mégard *et al*. (1996) as Formación Mataula, although it has no relation whatsoever to Formación Mataula as mapped in the Huancayo basin. The lake sediments, which are crossed by the road from the canyon of río Cañete to Yauyos, are locally preserved some 500 m above the present river. A much smaller recent example is present 19 km to the east, where pueblo Laraos is built upon a small landslide that blocks in lagunita Cochapampa. In another example, breaching of the dam produced by the relatively small 1974 Mayunmarca landslide (Fig. 7), which formed a 30 km-long temporary lake in río Mantaro above the Ayacucho basin, resulted in a major debris flow triggered by the rupture of the dam (Lee and Duncan, 1975; Kojan and Hutchinson, 1978). In conclusion, some river terraces may reflect such massive influx of sediments caused by landslides or the catastrophic breaching of ephemeral landslide-produced lakes instead of ongoing downcutting.

Below where río Mantaro crosses the Ayacucho intermontane basin, the river has cut a deep valley across the Cordillera Oriental. Directly east of the Ayacucho basin, the maximum local relief between río Mantaro and the divide of the Cordillera Oriental is about 2,100 m (measured from Cerro Huischjapo about 7 km to the northeast of Lauricocha northward to río Mantaro). Farther south, the divide climbs to slightly less than 5,000 m elevation east of Huanta. The interfluves between Cerro Huischjapo and Cerro Toronjana give the overall impression of steeper slopes as the river is approached (Fig. 10C). Steeper inner gorges have been recognized regionally throughout Perú (Garner, 1959); at least at Ayacucho the inner steep slopes are constrained to be younger than the late Pliocene Cachi Formation. Three cross-valley topographic profiles did not reveal stair-stepped strath terraces. However, the valley walls are mainly cut into argillite of upper Paleozoic formations, which both landslide and shed talus that drapes the hillslope. Moreover, the detail provided by the 1:100,000-scale topographic maps probably is too low to reveal such terraces, if they do exist. The point of exit from the Ayacucho basin is also critical because in the Ayacucho basin post-Cachi lacustrine deposits of probable late Pliocene age are present on either side of the river about 500 m above the current river channel. This not only places a limit on downcutting, but also shows that río Mantaro did not contribute significant amounts of coarse detritus to the generally fine-grained deposits of the Cachi Formation.

Major tributary canyons to río Mantaro

The drainages tributary to río Mantaro also show the effects of very rapid downcutting. For example, at and above the city of Huancavelica río Ichu flows in a well-preserved U-shaped glacial valley. In contrast, below Huancavelica río Ichu flows in a steep, V-shaped valley that drops 270 m over a distance of 13 km, suggesting increased incision from rapid post-Cachi downcutting of río Mantaro.

West of Huanta, río Urubamba-Huachocolpa cuts a deep gorge that near Julcamarca is inset into a region of flat-lying tuff. These tuffs are apparently of similar late Miocene age as that of the Ayacucho Formation, and cap fluvial gravels that overlie what may be part of the early middle Miocene regional Puna erosion surface. The río Urubamba-Huachocolpa valley, therefore, appears to have been mainly eroded during the late Miocene to present.

Discussion

Change from internal to external drainage in latest Neogene time

The Ayacucho basin is one of four internally-drained intermontane basins that existed in central Perú during late Miocene and early Pliocene time (Fig. 11). Of these basins, the Huancayo basin is the second best known (Blanc, 1984). Both the Ayacucho and Huancayo basins held large lakes in the late Miocene. A lake was present in the Ayacucho basin in late Pliocene time, and lacustrine conditions in the Huancayo basin may have extended into the Pleistocene. At Huancayo, río Mantaro runs from the north to the south end of the basin, and a considerable amount of the late Neogene basin fill has been eroded. Similarly, the Ingahuasi basin to the west has only just recently started to be eroded by a tributary of río Mantaro. It is not clear to what extent the Ingahuasi and Huancayo basins were integrated at various times. To the north, the smaller Junín basin contains the significantly large lago Junín, which is situated a short distance to the south of the present headwaters of the Mantaro drainage. The Huancayo, Ingahuasi and Junín basins appear to have been completely closed or isolated, although we cannot rule out the possibility that lakes within one or more of the basins occasionally overflowed.

As discussed in previous sections, the Ayacucho basin contained a lake in late Pliocene time. Moreover, it is not known if the lake in which the Ayacucho Formation was deposited persisted into Pliocene time, or whether they were two distinct lakes – a late Miocene Lake Ayacucho and an early(?) and late Pliocene Lake Cachi. The lake(s) do not appear to have had external drainage. However, it is possible that one (or both) lake(s) at least intermittently drained to the southeast. The present pass separating the Mantaro and the Apurimac catchment is at an elevation of 4,200 m, which is 1,500 m higher than the present elevation of the Huari geomorphic surface at the latitude of

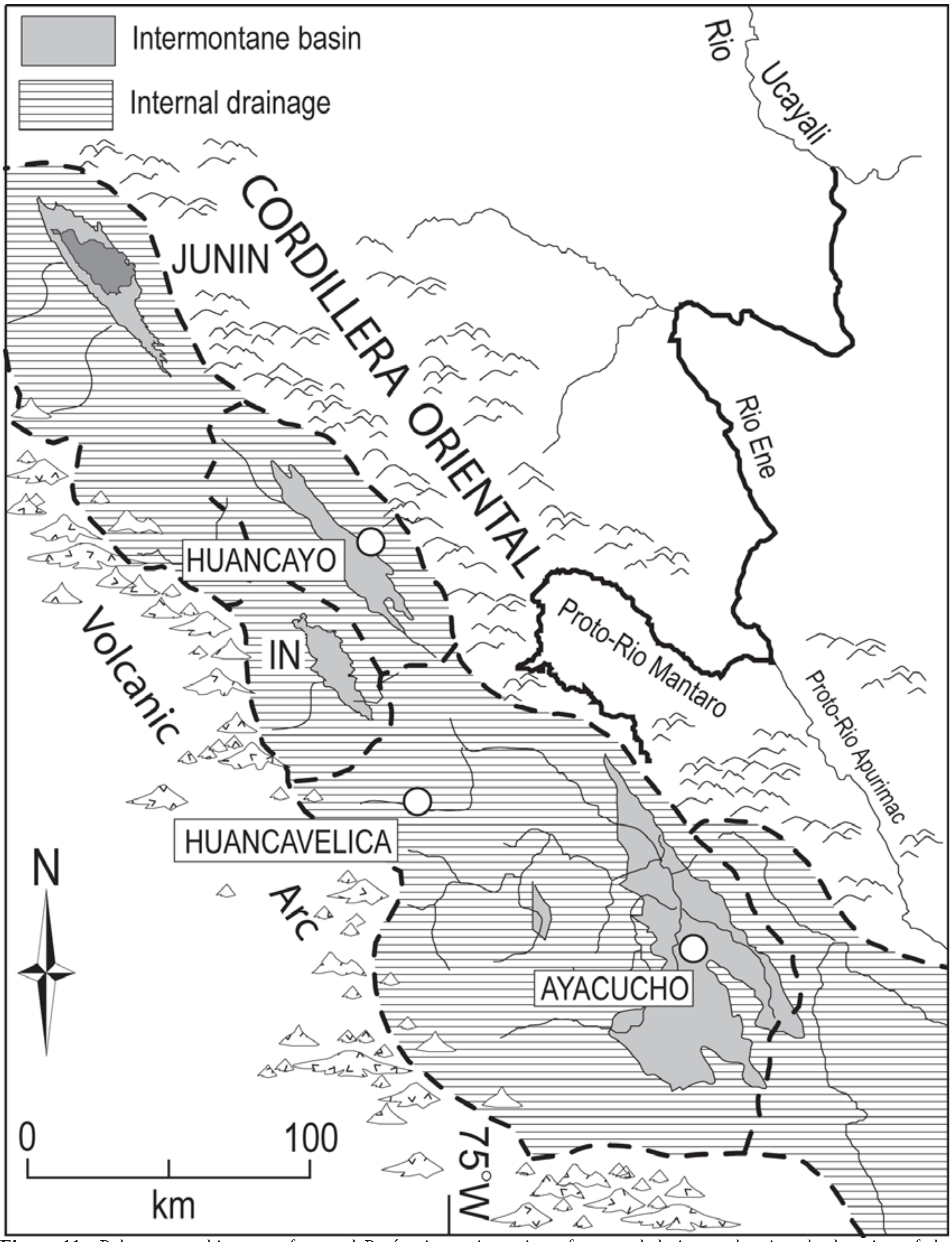


Figure 11.- Paleogeographic map of central Perú prior to inception of external drainage showing the location of the intermontane basins and their approximate paleo-catchment areas.

Ayacucho. The divide presently is underlain by large volumes of lava of intermediate to mafic composition that are younger than the Ayacucho Formation, and were erupted from nearby vents. These volcanic rocks would have blocked any outflow to the southeast, although it is possible that some of these volcanic centers post-date Lake Cachi.

As we have emphasized above, the absence of coarse conglomerate in the Ayacucho and Cachi Formations in the immediate vicinity of the río Mantaro shows that the river as it is presently developed was not extant in late Miocene and late Pliocene time. That is to say, the río Mantaro drainage unquestionably is a very young feature.

Prior to the establishment of the present Mantaro drainage system, a drainage divide must have existed between the Ayacucho and Huancayo basins. North of the divide, water drained into lake Huancayo. Part of this northward-flowing drainage is represented today by the canyon running between the pueblo of Pucará and río Mantaro. To the south, various streams, including the drainage of the present río Ichu, which now flow in deep canyons, drain to the southeast into the northern part of the Ayacucho basin.

The most probable scenario is that in late Pliocene time the lower part of río Mantaro, which previously had headed in the Cordillera Oriental, breached the Ayacucho basin by headward erosion. Breaching may have been facilitated by tectonic movements and/or by increased precipitation. Most likely the Cordillera Oriental was rising rapidly. Although a system of normal faults earlier existed along part of the eastern margin of the Ayacucho basin (Wise, 2004), there was essentially no fault movement after deposition of the Cachi Formation, and little, if any, movement after deposition of the Ayacucho Formation. Where the Cachi Formation onlaps basement rock of the Cordillera Oriental, the upper surface of the Cachi Formation presently is about 500 m above the valley of río Mantaro (Fig. 10C). Both the Cachi Formation and the younger lacustrine beds show that río Mantaro was not integrated with the Ayacucho basin at the time when they were deposited because there are no coarse deltaic or channel deposits within the units. The minor streams that form the upper part of the present río Mantaro drained small catchment basins and were at relatively low grade. For the same reason, it is unlikely that the drainage divide between the Ayacucho and Huancayo basin was breached before the capture of the Ayacucho basin by río Mantaro.

Erosion proceeded rapidly, removing most of the Cachi and Ayacucho Formations from the northern end of the Ayacucho basin and in the process developing badlands topography upon these and older units. Breaching the Cordillera Oriental and draining the basin triggered downcutting of many canyons into the

Summary of new $^{40}Ar/^{39}Ar$ age determinations

Sample Number	UTM Coordinates East	North	Rock type	Mineral	Age (Ma) (± 1 Sigma)	Type
Ayacucho Formation						
J159	584790	8563953	ash flow tuff	san	**6.81 ± 0.03**	**P**
					6.77 ± 0.03	TG
J152	571433	8588973	ash flow tuff	k-spar	**5.65 ± 0.17**	**I**
					5.83 ± 0.04	P
					12.78 ± 0.03	TG
H74-2-2001	572998	8578280	volcanic sandstone	plag	**~8.0**	**I***
					~8.55 ± 0.09	~P
					10.74 ± 0.09	TG
Cachi Formation						
J172	575155	8578661	volcanic sandstone	bio	**2.76 ± 0.03**	**I**
					2.85 ± 0.07	P
					4.21 ± 0.07	TG

I = Isochron age, P = plateau age, TG = total gas age, bold indicates preferred age, san = sanidine, k-spar = groundmass potassium feldspar dominated by plagioclase, plag = plagioclase, and bio = biotite.
* Based on isochron calculations that have MSWD values lower than generally considered acceptable.
UTM coordinates in zone 11 of the 1956 provisional grid.

Table I. Locations, in UTM coordinates, and descriptions of isotopically dated samples.

Huari geomorphic surface in the southeastern part of the basin. The pronounced downcutting by río Mantaro in the northern part of the Ayacucho basin rejuvenated the drainages that fed the northern part of the Ayacucho basin, including the present ríos Cachi and Mantaro, producing the steep canyons that now characterize these drainages. Steep canyons and drainages are incised through the probable Pleistocene alluvial fans that line the eastern margin of the Ayacucho basin, and generally dissect the Huari geomorphic surface. The age and form of this geomorphic surface may also place constraints on the reorganization of the drainage system around Ayacucho.

Factors that overrode the tectonic conditions that created and sustained the internally drained High Plateau province probably include increased erosion rates during latest Neogene time. We speculate that a change to wetter climate may have increased the rate of erosion on the eastern flank of the Cordillera Oriental.

The distal portions of the ash flows that comprise the Atunsulla Tuff must have reached the Ayacucho basin at about 2.4 Ma. However, this unit is nowhere preserved above the Cachi Formation or elsewhere around the margins of the northern part of the Ayacucho basin. These relations provide evidence that there was major reorganization and incision of the regional drainage system between about 2.8 and 2.4 Ma, with the formation and marked incision of río Mantaro and río Cachi allowing the ash flows to be channeled down río Cachi and largely pass down the río Mantaro drainage rather than being deposited in the Cachi basin on top of the Cachi Formation. In short, the exact time of drainage reorganization appears to be constrained between the age of the Cachi Formation (2.76±0.03 Ma) and that of the Atunsulla Tuff (about 2.4 Ma).

Río Mantaro cut through the drainage divide between the Ayacucho and Huancayo intermontane basins, and lowered the local base level, resulting in formation of the canyon between the Huancayo and Junín basins. The youngest depositional river-terrace deposits along rios Cachi and Mantaro are inset along these drainages, and represent the latest post-glacial aggraded channel incisement, which is prevalent in most of the canyons on both flanks of the Peruvian Andes (Garner, 1959). One or more of the terraces in the Ayacucho basin may correspond to certain of the prominent terraces in the Huancayo basin, but additional geochronologic data on the terraces is needed.

Earlier occurrences of interior drainage in central Perú

We have focused on the existence of interior drainage in central Perú during latest Neogene time and on the manner and timing of the opening of the internally drained hydrologic basins. A related question is when and to what degree the region was internally drained in earlier times.

The Ayacucho basin must have been externally drained immediately after the Quechua II compressive event at 8.7 Ma, as shown by the very rapid erosion of large portions of the late Miocene Huanta Formation and older units. An earlier episode of exterior drainage is suggested by the paleocanyon of the río Opamayo in the vicinity of Lircay, west of the Ayacucho basin, which was filled by pyroclastic rocks dated at 11 Ma erupted from the Julcani volcanic center (Petersen *et al.*, 1977; D.C. Noble, unpublished data).

There is also good evidence for the existence of closed basins at earlier times. The presence of fresh-water limestone and black shale suggests that a large closed basin existed in the region northeast of Castrovirreyna in late middle Miocene time (Wise and Noble, 2001). Sequences containing fresh-water limestone of early Miocene age are present over a broad area extending west from Huancavelica and Lircay to the region of Castrovirreyna (Noble and McKee, 1982; Salazar and Landa, 1993; D.C. Noble, unpublished data). However, to some extent these deposits may reflect inter-volcano depressions. Similar, although thinner, lacustrine units are locally present in the early Miocene Calipuy Group section of the Cordillera Negra. Redbeds containing fresh-water limestone, gypsum and halite west of Huancayo and in the vicinity of Ayacucho suggest the existence of closed basins and arid climate during the Eocene (Noble *et al.*, 1979; Mégard *et al.*, 1996; Wise, 2004). The age, extent and details of connection of such paleohydrologic catchment basins are together a largely untouched field of investigation.

Conclusions

Until latest Neogene time, drainage in the High Plateau province of central Perú was in large part internal. Recognition of this region of internal drainage shows that the «Altiplano», defined as a region of internal drainage, until recently extended well to the northwest. Both the Cachi Formation and younger lacustrine beds show that río Mantaro was not integrated with the Ayacucho basin at this time because of the absence of coarse deltaic deposits within the units. Likewise, the Mataula Formation of the Huancayo intermontane basin demonstrates the río Mantaro did not exist in its present form at about 5.4 Ma.

In the late Pliocene headward erosion by río Mantaro cut through the Cordillera Oriental, opening the Ayacucho basin. Breaching of the Cordillera Oriental took place after deposition of the Cachi Formation, the upper part of which has yielded a $^{40}Ar/^{39}Ar$ isochron age of 2.76±0.03 Ma. The *ca.* 2.4 Ma Atunsulla Tuff, distal portions of which were channeled down río Cachi and thence into the canyon of río Mantaro, appears to place an upper limit on the hydrologic opening of the basin. The marked lowering of local base level produced strong erosion upstream west of the Ayacucho basin. The badlands topography found throughout much of the Ayacucho basin, strongly incising the local Huari geomorphic surface, is a product of this recent capture, separating the region from what was previously part of an internally-drained province. Incision of río Mantaro through the Cordillera Oriental was caused by headward erosion, during which canyon relief was enhanced by the ongoing uplift of the Cordillera Oriental and, to a lesser extent, of the region to the west.

The north-flowing drainage into the Huancayo basin was rapidly captured, and much of the late Neogene lacustrine and fluvial sediments within the basin eroded. Río Mantaro has downcut north of the Huancayo basin, producing the present canyon that extends north of La Oroya. Eventually the Junín basin will be deeply eroded, either by further erosion of río Mantaro or possibly by headwater erosion of río Tarma-Perene from the east.

Regions of internal drainage existed at various times in central Perú before the late Miocene. The formation of closed hydrologic basins was probably mainly related to generally more rapid uplift of the Cordillera Oriental and Cordillera Occidental at various times in the Cenozoic relative to the High Plateau Province. The existence of regions of interior drainage both allowed accumulation of sediments within basins and reduced the degree of erosion of exposed rocks. The latter is well shown by the preservation over broad areas of rocks of Eocene, Oligocene and Miocene age (e.g., Noble *et al*., 1979; McKee and Noble, 1982; Salazar and Landa, 1993; Noble and McKee, 1999). The intense pulses of Cenozoic compressive deformation (e.g., Benavides-Cáceres, 1999) and attendant uplift did not result in wholesale stripping of the dominantly volcanic Cenozoic cover from the High Plateau Province.

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J-159, sanidine, 14.03 mg, J = 0.001706 ± 0.41%

4 amu discrimination = 1.01463 ± 0.28%, 40/39K = 0.0001 ± 100.0%, 36/37Ca = 0.000262 ± 2.28%, 39/37Ca = 0.000659 ± 0.44%

step	T (C)	t (min.)	^{36}Ar	^{37}Ar	^{38}Ar	^{39}Ar	^{40}Ar	%^{40}Ar*	% ^{39}Ar rlsd	Ca/K	^{40}Ar*/^{39}ArK	Age (Ma)	1s.d.
1	675	12	0.346	0.105	0.452	23.597	152.870	34.4	1.0	0.0656398	2.17639	6.69	0.13
2	750	12	0.034	0.134	0.483	35.871	92.111	92.1	1.5	0.0551055	2.26054	6.94	0.04
3	810	12	0.032	0.174	0.697	54.210	128.927	94.9	2.2	0.0473481	2.18813	6.72	0.08
4	870	12	0.041	0.269	1.144	90.045	206.396	95.6	3.7	0.0440682	2.15161	6.61	0.04
5	930	12	0.039	0.361	1.741	141.288	317.594	98.3	5.8	0.0376906	2.16791	6.66	0.04
6	990	12	0.038	0.456	0.249	198.481	442.563	98.8	8.2	0.0338904	2.17639	6.69	0.04
7	1045	12	0.042	0.494	2.911	234.799	521.749	98.8	9.7	0.0310357	2.17313	6.68	0.04
8	1100	12	0.051	0.557	3.460	275.735	616.012	98.6	11.4	0.0297984	2.18389	6.71	0.04
9	1150	12	0.058	0.596	3.881	310.122	700.773	98.4	12.8	0.0283494	2.20900	6.79	0.04
10	1200	12	0.055	0.754	4.728	379.611	861.718	98.8	15.7	0.0292997	2.23216	6.86	0.04
11	1250	12	0.073	0.965	6.242	502.190	1127.680	98.7	20.8	0.0283458	2.20933	6.79	0.04
12	1310	12	0.064	0.312	1.946	158.470	365.835	98.1	6.6	0.0290428	2.21129	6.79	0.04
13	1400	12	0.049	0.040	0.174	12.667	47.638	93.1	0.5	0.0419238	2.80353	8.61	0.23

Cumulative %^{39}Ar rlsd = 100.0

Total gas age = 6.77 0.03

note: isotope beams in mV, rlsd = released, error in age includes J error, all errors 1 sigma

(^{36}Ar through ^{40}Ar are measured beam intensities, corrected for decay for the age calculations)

Plateau age = 6.81 0.04
(steps 9-12)
no isochron age

J-152, plagioclase, 13.85 mg, J = 0.001714 ± 0.34%

4 amu discrimination = 1.01593 ± 0.12%, 40/39K = 0.0001 ± 100.0%, 36/37Ca = 0.000262 ± 2.28%, 39/37Ca = 0.000659 ± 0.44%

step	T (C)	t (min.)	^{36}Ar	^{37}Ar	^{38}Ar	^{39}Ar	^{40}Ar	%^{40}Ar*	% ^{39}Ar rlsd	Ca/K	^{40}Ar*/^{39}ArK	Age (Ma)	1s.d.
1	650	12	2.903	1.818	1.000	27.902	950.99	11.6	6.4	1.4547550	3.9695	12.23	0.21
2	730	12	0.247	2.670	0.591	44.188	158.704	58.4	10.1	1.3490387	2.0390	6.29	0.05
3	810	12	0.184	3.368	0.982	76.299	193.372	76.0	17.4	0.9854242	1.8842	5.82	0.03
4	890	12	0.137	2.435	1.184	93.161	212.002	84.4	21.2	0.5834214	1.8836	5.82	0.03
5	960	12	0.152	1.170	0.948	70.731	177.416	78.1	16.1	0.3692033	1.9009	5.87	0.04
6	1020	12	0.138	0.590	0.615	40.266	117.368	69.6	9.2	0.3270375	1.9339	5.97	0.05
7	1080	12	0.153	0.444	0.529	28.503	106.701	62.0	6.5	0.3476795	2.1990	6.79	0.10
8	1150	12	0.432	0.546	0.730	32.059	251.897	53.6	7.3	0.3801313	4.1115	12.67	0.06
9	1220	12	1.377	0.850	0.796	20.199	841.084	53.5	4.6	0.9394054	22.1635	67.26	0.30
10	1290	12	0.722	0.612	0.277	3.569	425.643	52.7	0.8	3.8313023	62.3111	183.07	1.26
11	1350	12	0.589	0.176	0.175	1.255	333.426	50.7	0.3	3.1327037	131.2509	366.07	1.82
12	1400	12	0.363	0.073	0.098	0.622	203.68	51.6	0.1	2.6212962	161.3438	440.48	4.04

Cumulative %^{39}Ar rlsd = 100.0

Total gas age =12.78 0.03

note: isotope beams in mV, rlsd = released, error in age includes J error, all errors 1 sigma

(^{36}Ar through ^{40}Ar are measured beam intensities, corrected for decay for the age calculations)

Plateau age = 5.83 0.04
(steps 3-5)
Isochron Age = 5.65 0.17
(steps 3-6)

H74-2-2001, plagioclase, 22.60 mg, J = 0.001870 ± 0.5%

4 amu discrimination = 1.01331 ± 0.37%, 40/39K = 0.0132 ± 89.00%, 36/37Ca = 0.0002770 ± 2.28%, 39/37Ca = 0.0007435 ± 0.37%

step	T (C)	t (min.)	^{36}Ar	^{37}Ar	^{38}Ar	^{39}Ar	^{40}Ar	$\%^{40}Ar^*$	$\%\,^{39}Ar$ rlsd	Ca/K	$^{40}Ar^*/^{39}ArK$	Age (Ma)	1s.d.
1	650	12	0.744	5.530	0.308	11.893	353.632	39.2	2.3	2.3628116	11.4487	38.22	0.45
2	730	12	0.131	9.751	0.269	20.006	106.911	68.7	3.8	2.4768469	3.4006	11.44	0.17
3	810	12	0.110	19.273	0.520	39.353	142.123	82.6	7.5	2.4887616	2.8201	9.49	0.09
4	890	12	0.122	31.031	0.764	61.511	194.455	86.6	11.7	2.5636846	2.6309	8.85	0.08
5	960	12	0.136	42.530	1.061	83.489	245.491	89.7	15.9	2.5887553	2.5517	8.59	0.08
6	1030	12	0.127	47.541	1.162	93.611	263.931	91.8	17.8	2.5808649	2.5100	8.45	0.08
7	1100	12	0.123	38.372	0.979	78.628	230.836	90.4	15.0	2.4799783	2.5621	8.62	0.09
8	1170	12	0.132	22.751	0.608	47.970	185.540	86.5	9.1	2.4100848	3.1396	10.56	0.10
9	1240	12	0.225	22.099	0.625	45.980	232.441	77.0	8.8	2.4423585	3.7052	12.46	0.10
10	1320	12	0.230	18.704	0.489	35.630	227.024	76.5	6.8	2.6678037	4.5619	15.33	0.13
11	1400	12	0.154	3.961	0.123	6.504	111.422	69.0	1.2	3.0953896	10.2308	34.19	0.37

Cumulative $\%^{39}Ar$ rlsd = 100.0 Total gas age = 10.74 0.09

note: isotope beams in mV rlsd = released, error in age includes 0.5% J error, all errors 1 sigma Pseudo plateau age = 8.55 0.09

(Not corrected for decay) (steps 5-7, 48.7% ^{39}Ar rlsd)

J-172, biotite, 15.11 mg, J = 0.001551 ± 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.)	^{36}Ar	^{37}Ar	^{38}Ar	^{39}Ar	^{40}Ar	$\%^{40}Ar^*$	$\%\,^{39}Ar$ rlsd	Ca/K	$^{40}Ar^*/^{39}ArK$	Age (Ma)	1s.d.
1	600	12	36.615	11.633	7.8794	27.111	11989.0	11.5	0.9	5.6561128	51.0624	137.5	30.06
2	650	12	9.580	24.696	2.493	48.603	2947.71	6.3	1.6	6.6999496	3.7448	10.45	0.72
3	725	12	6.271	8.245	3.410	169.71	2040.686	11.3	5.5	0.6394332	1.3179	3.68	0.17
4	800	12	3.021	1.572	3.500	224.10	1125.264	23.1	7.3	0.0923100	1.0992	3.07	0.11
5	875	12	2.346	1.207	3.514	234.49	934.825	28.7	7.6	0.0677381	1.0716	3.00	0.10
6	930	12	1.614	0.742	2.869	197.48	675.416	33.3	6.4	0.0494438	1.0358	2.90	0.10
7	985	12	2.231	1.269	3.932	272.13	935.002	32.5	8.9	0.0613661	1.0440	2.92	0.10
8	1030	12	2.038	1.370	4.184	291.05	888.152	35.4	9.5	0.0619427	1.0061	2.81	0.10
9	1075	12	1.694	2.075	5.479	394.28	899.278	47.9	12.9	0.0692561	1.0197	2.85	0.09
10	1120	12	1.590	3.940	9.174	676.70	1145.499	62.0	22.1	0.0766200	0.9961	2.79	0.09
11	1160	12	1.048	5.905	6.047	445.77	747.241	64.1	14.5	0.1743285	0.9836	2.75	0.09
12	1200	12	0.606	3.535	1.122	74.410	249.425	40.5	2.4	0.6252783	1.0022	2.80	0.10
13	1400	12	0.506	0.966	0.263	12.284	156.448	11.6	0.4	1.0351567	0.8536	2.39	0.17

Cumulative $\%^{39}Ar$ rlsd = 100.0 Total gas age = 4.21 0.07

note: isotope beams in mV rlsd = released, error in age includes 0.5% J error, all errors 1 sigma plateau age = 2.85 0.07

(Not corrected for decay) steps 5-12

Isochron age 2.76 0.03

Steps 5-12

Appendix I. Analytical data for isotopically dated specimens.

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