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Neogene magmatism in the Bolivian Andes between 16°S and 18°S: Stratigraphy and K/Ar geochronology

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Abstract—An important characteristic of Neogene magmatism (20.0-1.6 Ma) in the Bolivian Andes is the presence of numerous pyroclastic flows. Samples collected along a west-to-east transect (Western Cordillera, Altiplano, Eastern Cordillera) have been dated radiometrically, and this information provides the basis for interpretation of these rocks within the context of the late compressive phase of the Quechuan orogeny. In the Western Cordillera, the Abaroa Formation gave Miocene ages (20.8±0.5 to 13.5±0.4 Ma). The Pliocene to latest Miocene age of Cerke volcanism has been confirmed (5.7±0.5 Ma). In the Altiplano, ash-flow deposits are clearly assigned to the Pliocene (5.2±0.3 Ma). Along the eastern boundary of the Altiplano, a widespread tuff deposit was dated as late Pliocene (2.8±0.4 Ma). In the La Paz Basin, the Patapatani tuff is Pliocene in age (2.8±0.1 Ma), and its intercalation in glacial deposits comfirms the presence of a coeval glacial event. The absence of the Quechuan phase Q2 has been confirmed. In the La Paz Basin, the Quechuan phase Q4 takes place between 2.8±0.1 Ma and 1.6±0.1 Ma.

Resumen—La presencia de numerosos flujos piroclásticos es una característica importante del magmatismo neógeno (20 a 1.6 Ma) de los Andes bolivianos. Muestras volcánicas recolectadas a lo largo de un perfil W-E (Cordillera Occidental, Altiplano, Cordillera Oriental) permitieron la determinación precisa de edades de diversas formaciones así como sus relaciones con las últimas pulsaciones de la fase tectónica compresiva Quechua. En la Cordillera Occidental, la Formación Abaroa fue datada como Miocena (20.8±0.5 a 13.5±0.4 Ma). La edad pliocena del volcanismo Cerke fue confirmada (5.7±0.5 Ma). En el Altiplano depósitos de cenizas ["ash-flow deposits"] son claramente de edad pliocena (5.2±0.3 Ma). En la parte oriental del Altiplano, una toba bien desarollada dió una edad pliocena superior (2.8±0.4 Ma). En la cuenca de La Paz, la edad pliocena de la toba Patapatani (2.8±0.1 Ma) intercalada en sedimentos glaciales demostró la existencia de una glaciación pliocena. La ausencia de la pulsación Quechua Q2 fue confirmada. En la cuenca de La Paz, la pulsación Q4 se encuentra entre 2.8±0.1 Ma y 1.6±0.1 Ma.

INTRODUCTION

WIDESPREAD Tertiary magmatism occurred in the Andean Cordillera during the late Paleogene and all of the Neogene. In Bolivia, the first isotopic dates of this age were reported by Evernden *et al.* (1966) and subsequently by Evernden *et al.* (1977), Grant *et al.* (1977,1979), Castaños and Saavedra (1979), De Pachtère *et al.* (1984), Lavenu (1986a,b), and Swanson *et al.* (1987).

During the late Paleogene and Neogene, the continental volcaniclastic deposits of the Bolivian Central Andes were affected by post-Incaic compressive deformations. Earlier studies considered that these rocks were deformed during the Quechuan phase (late Miocene or intra-Pliocene; see, for example, Steinmann, 1929; Alhfeld, 1946). However, more recent studies (Mégard, 1978; Audebaud *et al.*, 1973; Soulas, 1975; Dalmayrac *et al.*, 1980; Martinez, 1980) have shown that these rocks were deformed during several Neogene compressional episodes.

Martinez (1980) has established the following succession in Bolivia: an Oligocene phase (between 25.6 and 33.6 Ma), a late Miocene phase (7.25 to 6.4 Ma), and a late Pliocene phase (5.4 to 2.5 Ma). A similar sequence has also been established in southern Peru and northern Bolivia (Sébrier *et al.*, in press) where four pulses were defined for the Quechuan event: Q1 (~30 Ma), Q2 (~15 Ma), Q3 (~7 Ma), and Q4 (~3 Ma).

In an attempt to understand the late Oligocene-Pleistocene post-Quechuan pulse Q1 in northern Bolivia, we carried out a detailed stratigraphic and petrologic study of the volcanic rocks that are interbedded with the Tertiary continental sediments in this area. These rocks were studied along a transect from the Western Cordillera (Charaña area) to the Eastern Cordillera (La Paz Basin and Morococala Meseta), between 16°S and 18°S. Along this line, four geographic zones have been studied in detail (Fig. 1): The Western Cordillera Piedmont (Charaña-Abaroa area), the Altiplano (Tirata, Turco, Soledad, Ayo Ayo, and Villa Remedios areas), the Eastern Cordillera Piedmont (La Paz and Titicaca Basins), and the Eastern Cordillera (Morococala Meseta). The petrologic, geochemical, and geochronologic analyses of these samples permit us to determine precisely the ages of the various formations as well as the ages of the various tectonic pulses that affected them.

STRATIGRAPHIC AND GEODYNAMIC FRAMEWORK

The Western Cordillera Piedmont

Four main formations are recognized in the border area with Chile and Peru (Fig. 2): the Mauri Forma-

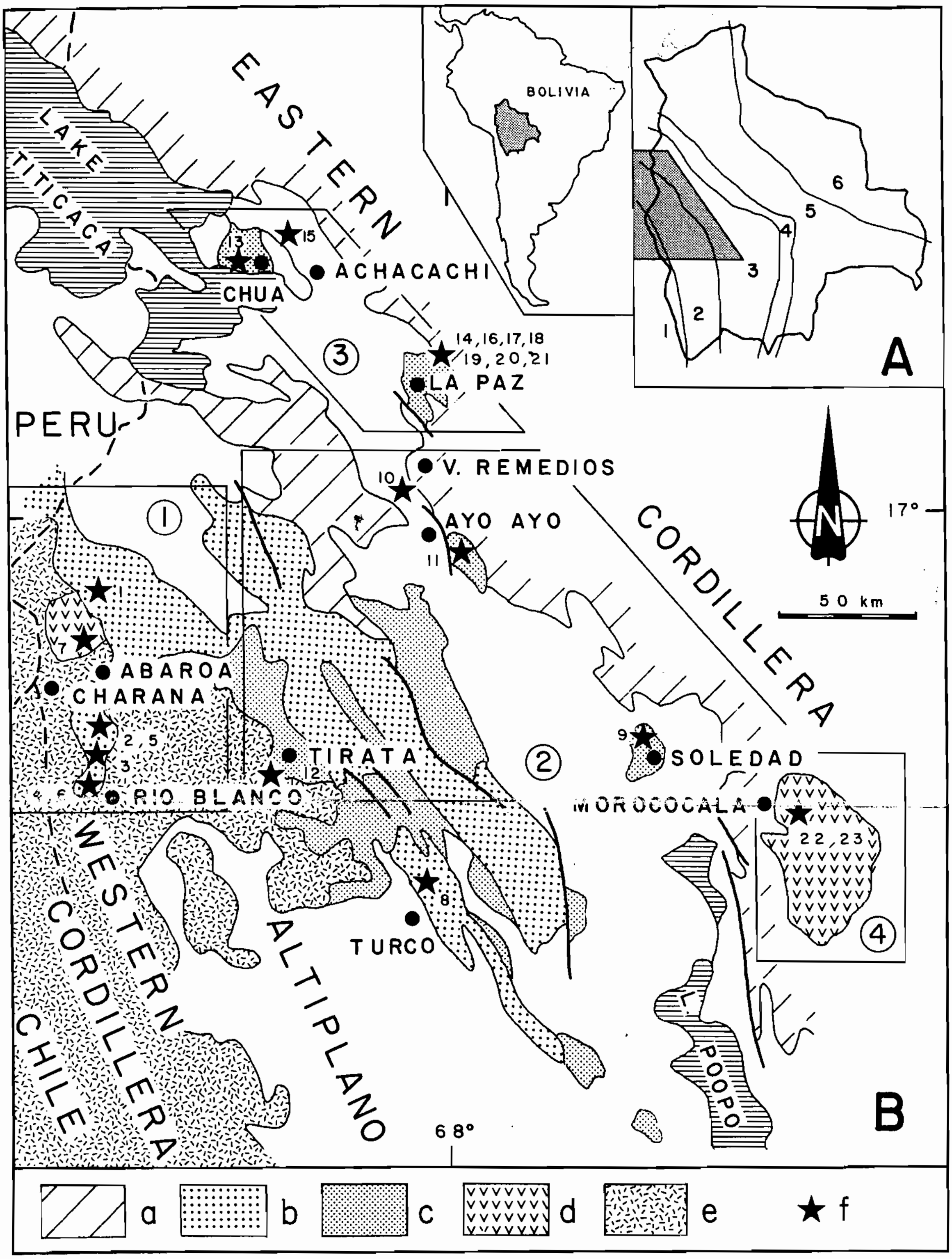

Fig. 1. Location map of studied area, central Bolivia. A, dot pattern indicates study area and numbers indicate morphostructural zonation: 1, Western Cordillera; 2, Altiplano; 3, Eastern Cordillera; 4, Subandean Zone; 5, Beni-Chaco Plain; 6, Brazilian Shield. B, simplified geologic map of the study area: **a**, pre-Miocene formations; **b**, Miocene formations; **c**, Pliocene formations; **d**, Pliocene volcanic deposits; **e**, undifferentiated Pliocene-Quaternary sediments; **f**, numbered stars indicate location of analyzed samples (1, BO3; 2, LA80-2; 3, PH43; 4, LA80-6; 5, LA80-4; 6, LA80-5; 7, BO4; 8, LA81-14; 9, PH48; 10, PH75; 11, LA82-2; 12, BO7; 13, LA82-1; 14, PH53a; 15, MB158; 16, MB161; 17, MB159; 18, MB160; 19, MB155; 20, MB154; 21, MB153; 22, PHM1; 23, PHM2). Numbered boxes delineate areas shown in other figures: Box 1, see Fig. 2, Western Cordillera study area; Box 2, see Fig. 5, Altiplano study area; Box 3, see Fig. 8, La Paz Basin; Box 4, see Fig. 9, Meseta de Morococala.

tion, the Abaroa Formation, the Cerke Formation, and the andesitic porphyritic flow.

The Mauri Formation. The Mauri Formation has been divided into six members (Sirvas and Torres, 1966), but it consists essentially of detrital volcaniclastic rocks intercalated with numerous volcanic flows. Basalts (Table 1, Sample BO3, Mbr 2) and basic andesites (Mbr 4) are common in the lower part, whereas dacitic tuffs (Mbr 5) and acidic cinerites, together with numerous dacitic pumice clasts (Mbr 6), are dominant in the middle and upper parts. These flows separate sabulitic to sandy and frequently conglomeritic beds (Fig. 2B), but no unconformity is visible between the different members of the formation (Montes de Oca *et al.*, 1963; Evernden *et al.*, 1966). This formation, which overlies the Berenguela Sandstones, has been assigned a Paleocene-Eocene age (Sirvas and Torres, 1966; Evernden *et al.*, 1966) and is correlated with the 38 Ma San Andrés Formation (Evernden *et al.*, 1966). According to Evernden *et al.* (1966), an unconformity separates the Mauri and Berenguela Formations. Lavas from the lower part of the Mauri Formation give K/Ar dates of 25.6 Ma (Table 3, Evernden *et al.*, 1966) and 25.2±0.1 Ma (Tables 1 and 2, B03), whereas a tuff from the upper part gave an age of 10.5 Ma (Table 3: Evernden *et al.*, 1966). These data indicate that the Mauri Formation ranges in age from late Oligocene to Miocene.

The Abaroa Formation. The Abaroa Formation crops out in the same area as the Mauri Formation (Fig. 2A) and consists of hornblende dacitic flows (Table 1: PH43), massive vitric clinopyroxene dacitic flows (Table 1, LA80-4 and LA80-6), and rhyolitic domes crossed by acidic or basic dikes (Table 1, LA80-2). Interbedded in these flows are thin layers of fine-grained red sandstones and conglomerates with centimeter-sized clasts set in a sandy matrix (Sirvas and Torres, 1966). The conglomerates include cobbles of red granitic gneiss as well as of various other metamorphic rocks (Nuñez, 1964). The lower and upper contacts of this formation are not exposed.

Different ages have been proposed for the Abaroa Formation. Sirvas and Torres (1966) proposed a pre-Tertiary age, whereas Evernden *et al.* (1966) suggested a Tithonian-early Neocomian age. Avila and Arduz (1975) considered a Tertiary age more likely, due to the good preservation of the volcanic edifices, but Martinez (1980) compared it to the Late Cretaceous-early Tertiary volcaniclastic formation of Peru and Chile.

One of the samples collected from the Abaroa Formation by Evernden *et al.* (1977, p. 1005; Table 3, Sample IT) gave an age of 14.6-21.6 Ma. This sample seems to have been collected near a reverse fault and in contact with a dike (Blanco, 1980). The analyzed mineral, augite, contained 12% radiogenic argon. Such a concentration is very susceptible to the presence of excess radiogenic argon (Tougarinov, 1965) which, in the Andean context, is not uncommon and therefore this date cannot be accepted with confidence.

Three lava flows and one dike were sampled during the course of this work in the Abaroa Formation (Tables 1 and 2, LA80-2, LA80-4, LA80-6, PH43). The ages obtained are in the range 17.9±0.7 Ma to 13.5±0.4 Ma, and place the Abaroa Formation in the early and middle Miocene.

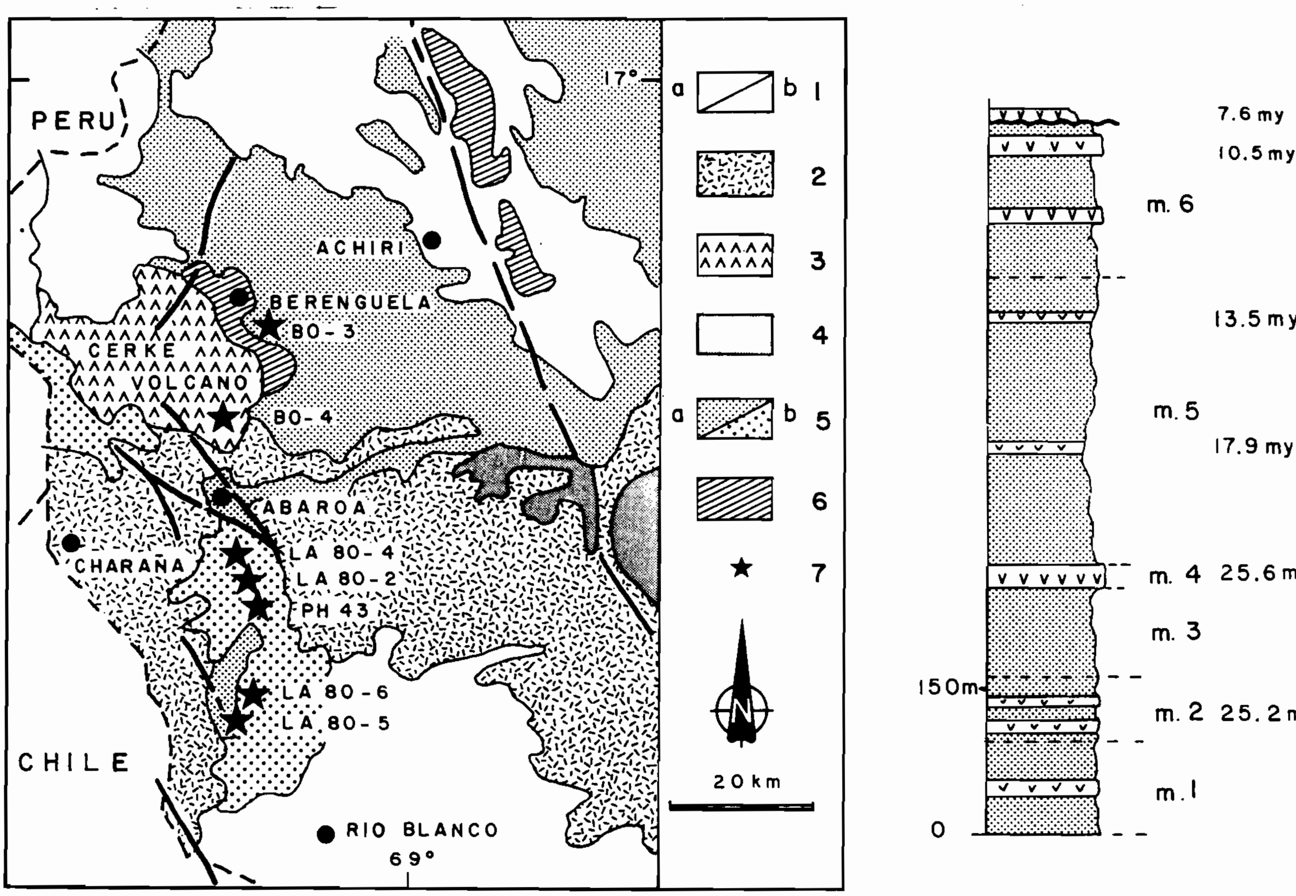

Fig. 2. The Western Cordillera and its Piedmont near Charaña. A, simplified geologic map (Box 1, see Fig. 1): 1, Quaternary deposits (a, fluvio-lacustrine deposits; b, volcanism); 2, Perez Formation; 3, Cerke Formation; 4, Pliocene sediments; 5, Oligocene-Miocene sediments (a, Mauri Formation; b, Abaroa Formation); 6, Eocene sediments; 7, analyzed samples. B, schematic stratigraphic column of the Mauri Formation.

Table 1. Location and description of analyzed samples.

No.	Sample	Location	Lat/Long	Altitude in Meters	Units	Petrographic Description
1	BO3	E. Kusima	17°14'28"S 69°14'29"W	4060	Mauri Fm Mbr 2	olivine clinopyroxene basalt lava flow
2	LA80-2	E. Abaroa	17°33'14"S 69°14'18"W	3990	Abaroa Fm	olivine clinopyroxene basalt dike
3	PH43	Co. Canasita	17°44'29"S 69°09'33"W	4580	Abaroa Fm	clinopyroxene amphibolitic dacite lava flow
4	LA80-6	E. Kolkhe Uma	17°50'49"S 69°13'07"W	4310	Abaroa Fm	porphyritic clino- and orthopyroxene andesite lava flow
5	LA80-4	C. Lupijcala	17°33'54"S 69°13'31"W	4060	Abaroa Fm	vitric amphibolitic dacite lava flow
6	LA80-5	E. Kolkhe Uma	17°52'00"S 69°13'20"W	4350	Cerke Fm	porphyritic amphibolitic andesite lava flow
7	BO4	E. Sacacani	17°25'05"S 69°18'07"W	4080	Cerke Fm	porphyritic amphibolitic andesite lava flow
8	LA81-14	Azurita Mine	18°05'25"S 68°09'00"W	3920	Turco Fm	rhyolitic pyroclastic tuff
9	PH48	Soledad	17°41'05"S 67°18'57"W	3760	Umala Fm	quartz amphibole biotite dacitic ash flow
10	PH75	V. Remedios	16°46'13"S 68°10'51"W	3920	Umala Fm	quartz biotite rhyolitic ash flow
11	LA82-2	Ayo Ayo	17°07'42"S 68°59'00"W	3900	Umala Fm	amphibole biotite dacitic ash flow
12	BO7	E. Tirata	17°53'04"S 68°36'05"W	4100	Perez Fm	vitrophiric pumice flow
13	LA82-1	Chua	16°10'21"S 68°44'21"W	3900	Umala Fm (?)	quartz biotite dacitic pyroclastic tuff
14	PH53a	Chuquiaguillo	16°27'05"S 68°05'51"W	4100	Patapatani Fm	quartz biotite rhyolitic ash fall
15	MB158	Achacachi	16°08'20"S 68°38'00"W	3870	La Paz Fm	quartz biotite rhyolitic cinerite
16	MB161	Cota Cota	16°32'00"S 68°03'30"W	3520	La Paz Fm	amphibole plagioclase biotite welded tuff
17	MB159	La Paz	16°27'40"S 69°09'20"W	3900	La Paz Fm	quartz biotite rhyolitic cinerite
18	MB160	La Paz	16°27'40"S 69°09'20"W	3900	La Paz Fm	quartz biotite rhyolitic cinerite
20	MB154	Rio Kaluyo	16°25'48"S 68°07'50"W	4160	La Paz Fm	quartz biotite rhyolitic cinerite
21	MB153	Rio Kaluyo	16°25'30"S 68°07'50"W	4160	La Paz Fm	quartz biotite rhyolitic cinerite
22	PHM1	C. Tankha Tankha	18°06'35"S 66°43'17"W	4825	Morococala	quartz biotite dacite lava flow
23	PHM2	C. Tankha Tankha	18°06'35"S 66°43'17"W	4825	Morococala	quartz biotite dacite dike

According to Evernden *et al.* (1977), a "profound unconformity" should occur between Member 6 of the Mauri Formation and the Abaroa Formation. This contention was based not only on the difference in lithologies of the two formations, but also on the presence of granitic cobbles (supposedly derived from the Abaroa Formation) in the Mauri Formation. However, detailed mapping (by A. Lavenu) has shown that the Mauri and Abaroa Formations have been folded together (Fig. 3) and that the contact between the two formations is conformable (Fig. 4).

Evernden *et al.* (1977) suggested that the Abaroa Formation is about 10 km thick; however, geologic mapping and photointerpretation indicate the presence of numerous folds and strike-slip and reverse faults. We believe, therefore, that a thickness of 1000-2000 meters is a more reasonable estimate (Fig. 4). Field and radiometric evidence also suggest that, in part, the Abaroa and Mauri Formations could be contemporaneous.

The Cerke Formation. The Cerke Formation comprises a composite andesitic volcanic edifice on top of the Mauri Formation (Montes de Oca *et al.*, 1963; Sirvas and Torres, 1966), with a diameter of 30 km and an elevation of more 5000 meters (Fig. 2). The

Table 2. New potassium-argon age determinations on volcanic rocks of northern Bolivia.

Field No.	Field Sample	Mineral Dated	K_2O (%)	Ar_{rad} (%)	$^{40}Ar_{rad}$ (mol/g 10^{-10})	Age (Ma)
1	BO3	WR	4.28	58.4	3.488	25.2 ± 1.0
2	LA80-2	Pl	4.30	89.7	2.901	20.8 ± 0.5
3	PH43	WR	3.84	38.2	2.455	17.9 ± 0.7
4	LA80-6	Pl	0.55	63.7	0.268	15.1 ± 0.8
-	LA80-6	WR	3.55	72.1	1.430	13.2 ± 0.3
5	LA80-4	WR	2.68	69.2	1.172	13.5 ± 0.4
6	LA80-5	Pl	0.77	43.6	0.189	7.6 ± 0.8
7	BO4	Pl	1.015	33.0	0.188	5.7 ± 0.5
8	LA81-14	Pl	4.51	80.7	1.701	11.7 ± 0.3
9	PH48	Pl	2.74	27.7	0.463	5.2 ± 0.3
-	PH48	Pl	2.74	22.0	0.439	5.0 ± 0.7
-	PH48	B	7.56	31.6	1.123	4.6 ± 0.2
10	PH75	Pl	5.06	36.9	0.542	3.3 ± 0.2
-	PH75	Pl	5.06	16.8	0.523	3.2 ± 0.4
11	LA82-2	Pl	1.30	58.0	0.120	2.8 ± 0.4
12	BO7	V	4.66	12.3	0.497	3.3 ± 0.3
13	LA82-1	Pl	0.87	61.7	0.215	7.6 ± 0.7
14	PH53a	Pl	4.70	19.1	0.239	1.6 ± 0.1
15	MB158	KS	10.00	89.2	0.897	2.8 ± 0.1
16	MB161	B	8.59	70.3	1.600	5.8 ± 0.1
-	MB161	B	8.59	60.8	1.520	5.5 ± 0.2
17	MB159	KS	10.38	93.0	0.929	2.8 ± 0.1
18	MB160	B	5.21	22.9	2.100	12.1 ± 1.1
-	MB160	B	5.21	18.8	1.960	11.6 ± 1.3
19	MB155	KS	10.78	98.3	66.700	182.0 ± 5.0
20	MB154	KS	9.40	85.3	0.846	2.8 ± 0.1
21	MB153	KS	10.41	87.9	0.924	2.7 ± 0.1
22	PHM1	WR	4.72	37.3	0.972	6.4 ± 0.3
-	PHM1	Pl	2.52	32.1	0.475	5.8 ± 0.3
23	PHM2	Pl	2.39	32.6	0.489	6.3 ± 0.3
-	PHM2	WR	4.36	42.8	0.850	6.0 ± 0.3

K and Ar analyses were made in the laboratory of the Institut Dolomieu, Grenoble, by M. G. Bonhomme. Key: WR, whole rock; Pl, plagioclase; B, biotite; KS, K-feldspar; V, vitrophyre. Constants:

$$^{40}K\ \lambda\beta = 4.962 \times 10^{-10} yr^{-10}$$
$$^{40}K\ \lambda\varepsilon = 0.581 \times 10^{-10} yr^{-10}$$
$$^{40}K/K = 0.01167 \text{ atm } \%$$

unit is made up of pale porphyritic andesites (Tables 1 and 2, BO4) and has been assigned a Pliocene age (Martinez, 1980). The Cerke Formation is overlain by the Plio-Pleistocene Perez Formation (pumice pyroclastic flows; Table 3, IA and IB).

Sample BO4 (Tables 1 and 2) gave a date of 5.7± 0.5 Ma, which agrees with the late Miocene to early Pliocene age established by Martinez (1980). Our sample was collected from a younger eruption, however, and the root of the volcano, which is not exposed, could be considerably older.

The Andesitic Porphyritic Flow. The andesitic porphyritic flow (Tables 1 and 2, LA80-5) unconformably overlies the Abaroa strata (Fig. 4C). On the geologic map of Río Blanco (Murillo *et al.*, 1963), these rocks were mapped as the Plio-Pleistocene ignimbritic Perez Formation, but analysis of the andesite gave an age of 7.6±0.8 Ma. This unit correlates with the lower part of the Cerke Formation.

The Altiplano

The following localities have been studied and sampled in the northern portion of the Bolivian Altiplano (Fig. 5): the Tirata, Turco, Soledad, and Ayo Ayo-Villa Remedios areas.

Tirata Area. Three units are exposed at Tirata (Fig. 5B). The lower part of the sequence is composed of 20 to 30 meters of sandy clay and red sandstone that correlate with the detrital Miocene of the Altiplano (Crucero Formation; Meyer and Murillo, 1961). These deposits are overlain by a thick (80 m) ash-flow tuff that is followed by 10 to 30 meters of pale detrital sediments which correlate with the Pliocene Umala Formation. The ash-flow tuff, which conformably overlies the Miocene, is called "Toba 76" and radiometric dating gave an age of 5.4 to 5.9 Ma (Evernden *et al.*, 1966; Table 3, ID and IE).

The Pliocene Umala Formation is itself overlain by an ignimbritic tuff — the Perez Formation (Sirvas and Torres, 1966) —which gave a K/Ar age of 2.2 to 3 Ma (Table 3, IA and IB) from a sample site near the Cerke volcano. At Tirata, the Perez Formation is apparently conformable with the Umala Formation, but at Curahuara de Carangas the Umala Formation is folded and there is a clear unconformable relationship between the two units.

At Tirata, the Perez Formation contains two pumice flows. The upper flow contains a 2-meter thick basal vitrophyre with large fiamme (Tables 1 and 2, BO7). These rocks gave an age of 3.3±0.3 Ma, which indicates, therefore, that either the Perez Formation is older than 2.2 to 3 Ma or that the basal vitrophyre we dated does not belong to the Perez Formation.

Turco Area. In this zone (Figs. 1 and 6), the Turco Formation consists of a thick, reddish, detrital sequence with numerous interbedded volcanic layers, all of which have been assigned to the Miocene by Martinez and Tomasi (1978). Similarly, a volcanic horizon in the upper part of the Turco Formation gave a K/Ar age of 9.7 Ma (Evernden *et al.*, 1966; Table 3, IK). However, since this sample was collected from a "weathered red biotitic sill," it does not truly establish the age of the formation. We also sampled an interbedded tuff (Table 1, LA81-14) near the top of the Turco Formation, which yielded an age of 11.7±0.3 Ma (Table 2). According to our data, the Turco Formation is middle to late Miocene in age and hence it is coeval with the Miocene formations of the Western Cordillera (*i.e.*, uppermost Mauri and Abaroa Formations). In all three of these formations, the presence of red granitic gneiss and pegmatitic cobbles derived from the "Precambrian Arequipa Massif" also supports such a correlation, as does the

Table 3. Potassium-argon age determinations on some volcanic rocks of northern Bolivia according to various authors.

Sample	Reference	Location	Mineral Dated	Unit	Age (Ma)
IO	Evernden *et al.*, 1966, 1977	17°14'S 69°08'W	Pl	Mauri Fm Mbr 4	25.6
IL	Evernden *et al.*, 1966, 1977	17°11'S 69°10'W	B	Mauri Fm Mbr 6	10.5
IT	Evernden *et al.*, 1966, 1977	17°32'S 69°20'W	A	Abaroa Fm	14.5 to 21.6
IU	Evernden *et al.*, 1966, 1977	17°05'S 68°35'W	H	Comanche Stock	16.7 & 14.6
IK	Evernden *et al.*, 1966, 1977	18°08'S 68°20'W	KS	Turco Fm	9.7
IJ	Evernden *et al.*, 1966, 1977	17°50'S 65°26'W	KS	Crucero Fm	9.1
IS	Evernden *et al.*, 1966, 1977	18°03'S 68°10'W	B	Umala Fm	6.4
IE	Evernden *et al.*, 1966, 1977	17°52'S 68°26'W	B	Umala Fm	5.9
ID	Evernden *et al.*, 1966, 1977	17°51'S 68°00'W	B	Umala Fm	5.5
IC	Evernden *et al.*, 1966, 1977	17°29'S 68°28'W	B	Umala Fm	5.4
IB	Evernden *et al.*, 1966, 1977	17°24'S 69°24'W	B	Perez Fm	3.0
IA	Evernden *et al.*, 1966, 1977	17°24'S 69°24'W	KS	Perez Fm	2.2
IV	Evernden *et al.*, 1966, 1977	La Paz	B	La Paz Fm	6.0
NG1	Grant *et al.*, 1977	Japo	B	Morococala Meseta	6.3 ± 0.1
NG2	Grant *et al.*, 1977	Japo	B	Morococala Meseta	6.4 ± 0.1
	Clapperton, 1979	La Paz	B	La Paz Fm	3.27 ± 0.14
	Clapperton, 1979	La Paz	B	La Paz Fm	3.38 ± 0.13
	Swanson *et al.*, 1987	Altiplano	S	Azurita Conglomerate	18.9 ± 0.5
	Swanson *et al.*, 1987	Altiplano	CS	Azurita Conglomerate	24.5 ± 0.6

Key: A, augite; B, biotite; H, hornblende; KS, K-feldspar; Pl, plagioclase; S, sanidine; CS, contaminated sanidine.

occurrence of dacitic dikes and sills in both the Abaroa and Turco Formations. The Ulloma tuff dated by Evernden *et al.* (1966, 1977) also appears to be of a similar age (Sample IJ, Table 3).

The sabulitic and conglomeratic Azurita Formation overlies the Turco Formation; an interbedded rhyolite gave an age of 6.4 Ma (Table 3, IS) which is equivalent to that of the "Toba 76." Swanson *et al.* (1987) assigned a questionable age of 18.9 to 24.5 Ma (contaminated sanidine) to the Azurita Formation.

Soledad Area. Near Soledad (Fig. 5) in the eastern part of the Altiplano, there is a complex volcanic structure which is surrounded by lacustrine detrital deposits of supposed Pliocene-Pleistocene age (Misión Geológica Alemana, 1972; Martinez and Tomasi, 1978; Pareja and Ballon, 1978).

At Cerro Pucara north of Soledad, unconsolidated ashy pyroclastic deposits are interbedded with the lacustrine sediments and ages of 4.6±0.2 Ma to 5.2±0.3 Ma (Table 2) obtained from these deposits (Table 1, PH48) confirm their Pliocene age. The radiometric ages place these sediments near to the base of the Pliocene and, as such, they may be correlated with the Umala Formation. Thus, therefore, the existence of Pliocene-latest Miocene deposits in the Altiplano is more widespread than previously supposed — a fact which is also emphasized by the discovery of a Pliocene fauna within the Remedios Formation near Lake Poopo (Lavenu, 1984; Fig. 1).

Ayo Ayo and Villa Remedios Area. These areas are located near the boundary between the Altiplano and the Eastern Cordillera (Fig. 5); both sites have comparable sections. A detailed study of the Ayo Ayo section has been made by Hoffstetter *et al.* (1971). The lower part consists of flat-lying lacustrine and fluvio-lacustrine silty and sandy sediments. The thick Ayo Ayo pyroclastic ash-flow tuff (Table 1, LA82) overlies these sediments; above the tuff, the top of the section consists of sandy fluvio-lacustrine sediments that contain numerous fossil vertebrates.

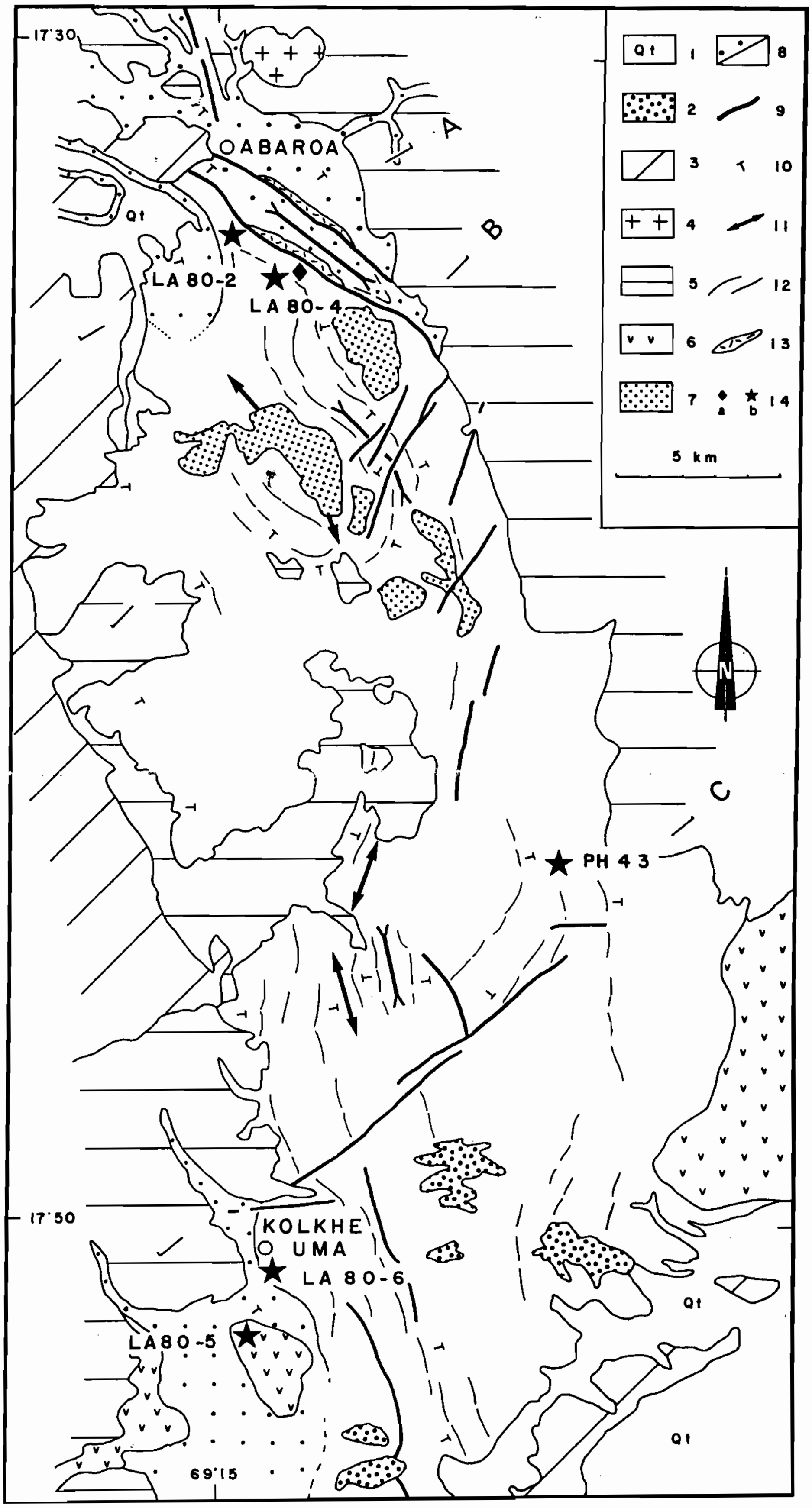

Fig. 3. Schematic geologic map of the Abaroa Formation between Abaroa and Kolkhe Uma (detail of Fig. 2): 1, undifferentiated Quaternary deposits; 2, Quaternary moraines; 3, Charaña Formation; 4, Quaternary intrusive rocks; 5, Perez Formation; 6, undifferentiated volcanism; 7, Tertiary intrusive rocks; 8, Oligocene-Miocene sediments (dotted, Member 6 of Mauri Formation; white, Abaroa Formation); 9, faults; 10, dip; 11, folds; 12, bedding; 13, Tertiary dikes; 14, samples (a, Evernden *et al.*, 1966; b, this paper); A, B, C, locations of cross-sections shown in Fig. 4.

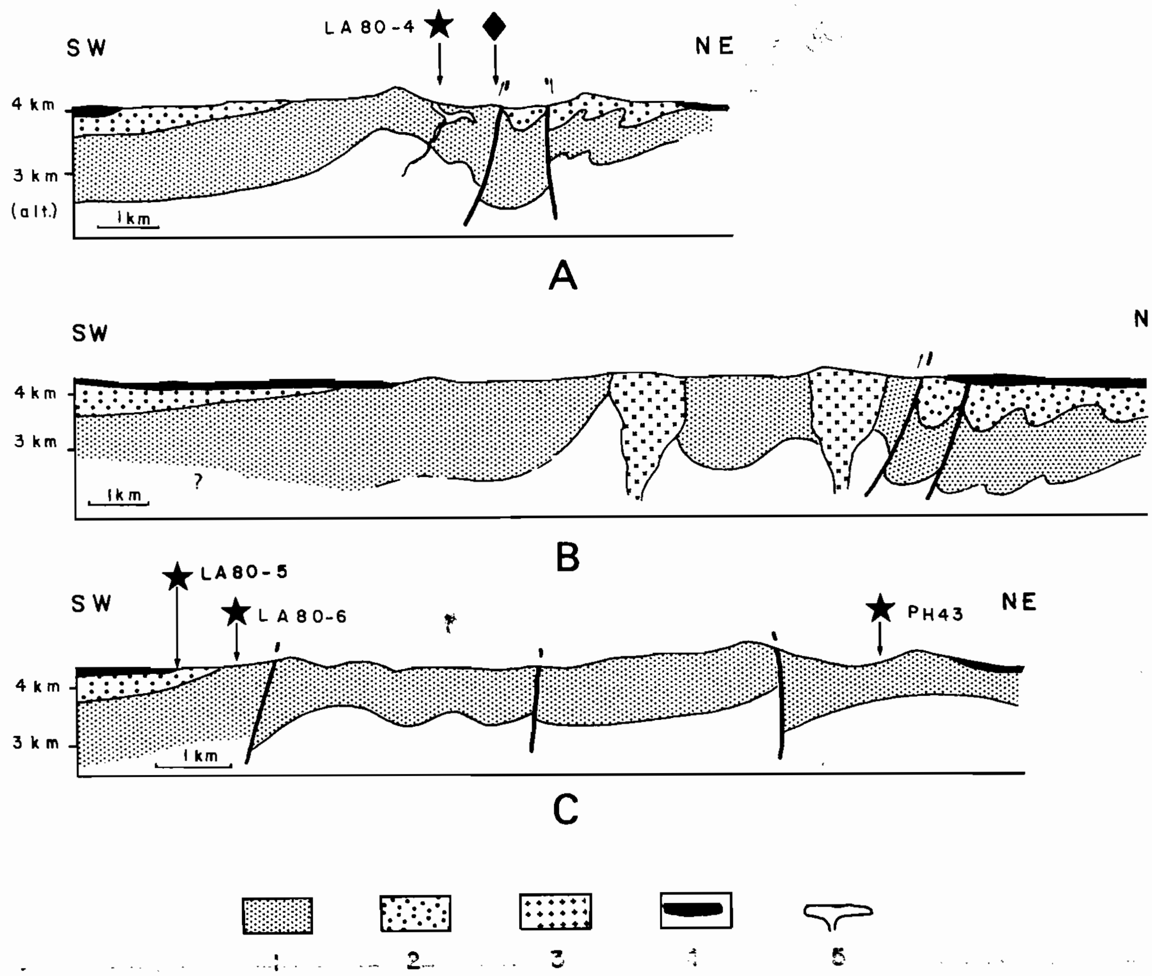

Fig. 4. Schematic cross-sections of the Abaroa zone showing the conformity between the Abaroa Formation and Member 6 of the Mauri Formation. A, B, C, The locations of cross-sections A, B, and C are shown in Fig. 3. Key: 1, Abaroa Formation; 2, Member 6 of the Mauri Formation; 3, intrusive rocks; 4, Perez Formation; 5, dikes or sills.

According to Hoffstetter *et al.* (1971), the assemblage beneath the tuff is definitely Pliocene in age and that above is Pleistocene in age. The tuff, which outcrops between Ayo Ayo and Villa Remedios (Table 1, PH45) along the main La Paz-Oruro road, gave ages of 3.3±0.4 Ma (Table 2, PH75) and 2.8±0.4 Ma (Table 2, LA82-2).

The Eastern Cordillera Piedmont

More than 1000 meters of Pliocene and Quaternary sediments crop out in the Eastern Cordillera Piedmont (Fig. 7). The fossiliferous, Pliocene La Paz Formation (complete references in Marshall *et al.*, 1983) consists of 600 meters of fluvial to fluviolacustrine sediments, including conglomerates in the east but finer grained sediments in the center of the basin. Radiometric dates were obtained from various tuffs interbedded within these sediments. The Cota Cota tuff from the lower part of the La Paz Formation gave an age of 5.3±0.2 Ma (Tables 1 and 2, MB161), which confirms the early Pliocene age for the basal part of La Paz Basin sediments. The Chijini tuff from the upper part of the La Paz Formation gave an age of 2.8±0.1 Ma (Tables 1 and 2, MB159), which confirms the late Pliocene age of the upper part of the La Paz Basin sediments (Evernden *et al.*, 1977; Clapperton, 1979) (Table 3).

Biotite ages obtained from the tuffs of the La Paz area are difficult to interpret. One of us (MGB) has observed that, for a given sample, biotites always give older ages than feldspars. An example is provided by Samples MB159 and MB160 (Table 2) which were taken from the same tuff layer along the La Paz-El Alto road; the feldspars gave an isotopic age of about 2.8 Ma, but the biotites gave an age of 12.1 Ma. This observation suggests that the biotites may contain excess radiogenic argon which, therefore, would cast doubts on all the isotopic results obtained from this mineral. Two possible explanations can be proposed to explain this phenomenon: either the tuffs contain a significant proportion of older biotites derived from the pre-Andean substratum, or there was an argon-rich, possibly glassy, inclusion with the biotite crystals. The varying ages obtained from biotites by Evernden *et al.* (1977) would also support the idea that, at least in this instance, biotite ages are less reliable than those obtained from feldspars.

The Patapatani tuff overlies sediments belonging to the first stage of Plio-Pleistocene glaciation (Patapatani Drift; Table 1, MB153 and MB154; Fig. 7). This tuff crops out in the Río Kaluyo north of La Paz

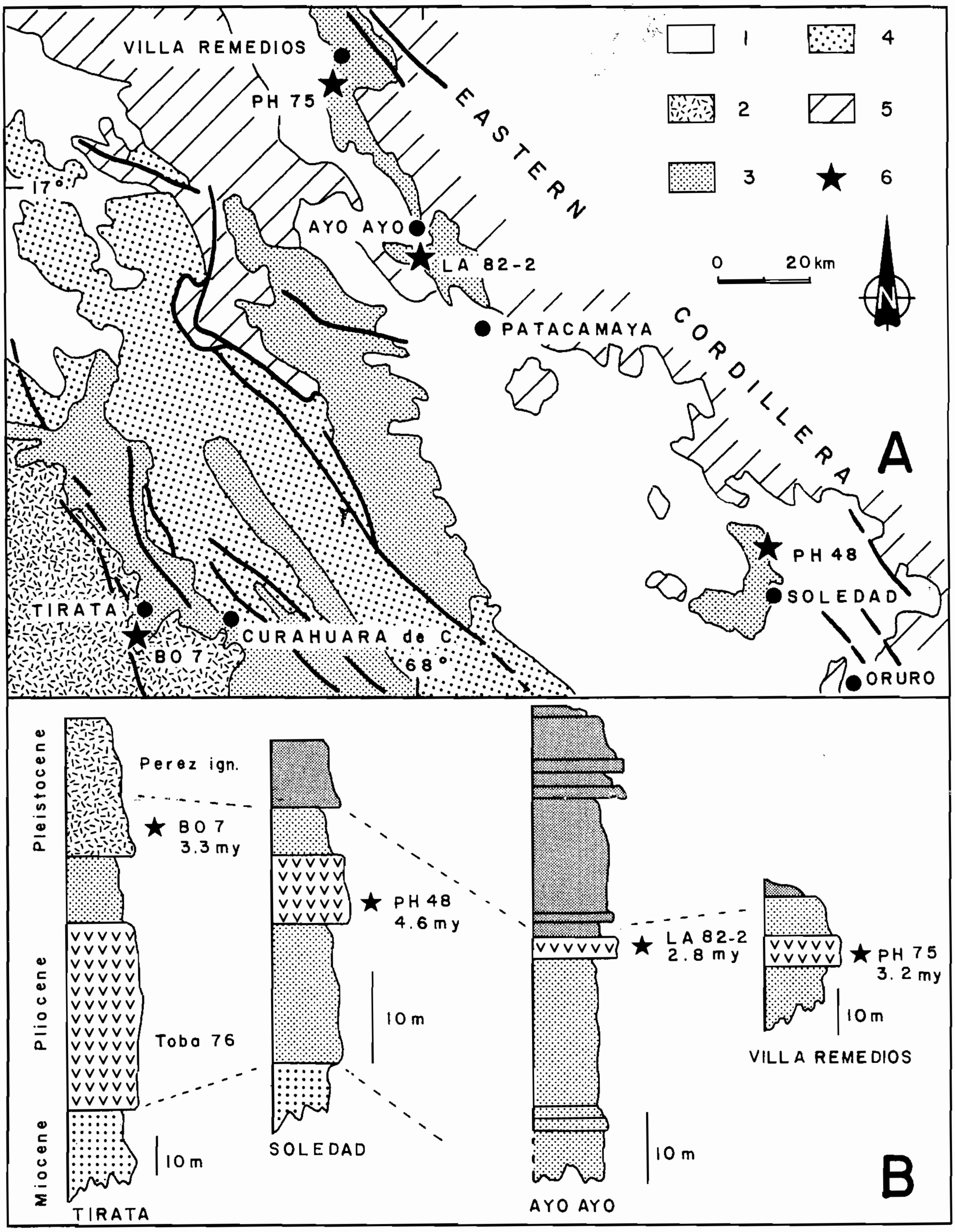

Fig. 5. The northern part of the central Altiplano. A, geologic map: 1, Quaternary deposits; 2, Perez Formation; 3, Pliocene sediments; 4, Oligocene-Miocene sediments; 5, pre-Oligocene-Miocene substratum; 6, location of analyzed samples. B, columnar sections.

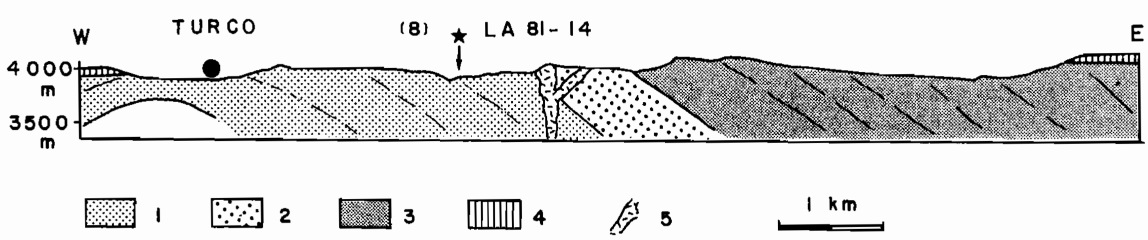

Fig. 6. E-W cross-section near Turco showing the interbedded rhyolitic tuffs. Sample LA81-14 (11.7±0.3 Ma; point 8 in Fig. 1). Key: 1, Turco Formation; 2, Azurita Formation; 3, Crucero Formation; 4, Umala Formation; 5, dike.

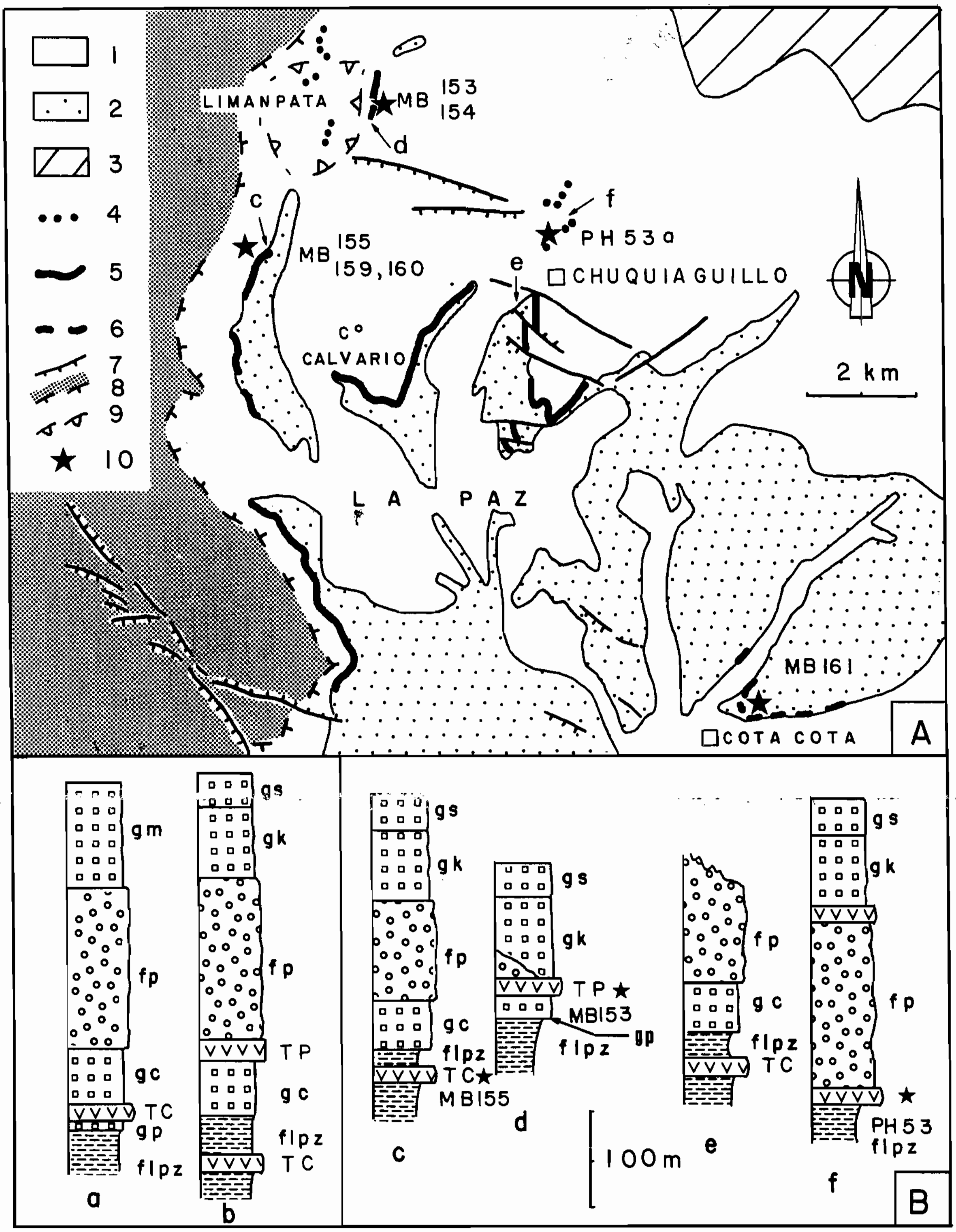

Fig. 7. The La Paz Basin. A, generalized map of the La Paz Basin: 1, Quaternary alluvium; 2, La Paz Formation; 3, Eastern Cordillera substratum; 4, undated interglacial tuff; 5, Patapatani or Chijini tuff; 6, Cotacota tuff; 7, normal faults; 8, edge of the Altiplano; 9, landslide of Limanpata; 10, location of analyzed samples. B, columnar sections: a, interpretative section according to Dobrovolny (1962); b, interpretative section according to Servant (1977) and Ballivian *et al.* (1978); c, d, e, f, sections located on the map (gs, Sorata moraine; gm, Milluni Drift; gk, Kaluyo Drift; fp, Purapurani Formation; TP, Patapatani tuff; gc, Calvario Drift; TC, Chijini tuff; gp, Patapatani drift; flpz, La Paz Formation).

and has been interpreted as being of either Pliocene (Dobrovolny, 1962) or Quaternary age (Servant, 1977; Ballivian *et al.*, 1978). Our 2.8±0.1 Ma date (Table 2), however, confirms the hypothesis of Dobrovolny and suggests a correlation with the Chijini tuff. The tuff sampled near Achacachi, Lake Titicaca (Table 1, MB158; Fig. 1) also gave an isotopic age of 2.8±0.1 Ma (Table 2). Samples MB153, M 154, MB158, MB159, and MB160 are all very similar petrographically but, in contrast, MB155 (Chijini tuff, Tables 1 and 2) is compositionally distinct — which could suggest a possible reworking. The Purapurani tuff (Table 1, PH53a) is interbedded within the glacial and interglacial deposits that overlie the Calvario Drift. It gave an age of 1.6±0.1 Ma (Table 2), confirming the early Quaternary age for the

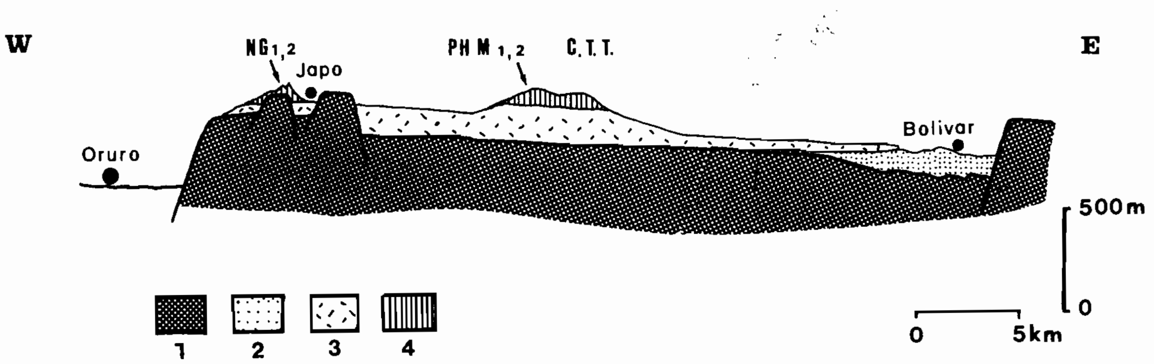

Fig. 8. Cross-section of the Meseta de Morococala: 1, Paleozoic substratum; 2, Mesozoic-Cenozoic sediments; 3, Miocene volcanic meseta; 4, Cerro Tankha Tankha volcanoes.

second stage of glaciation in this area. Near Lake Titicaca, the Chua dacitic welded tuff (Table 1, LA82-1), which is overlain by Pliocene sediments, gave an age of 7.6±0.7 Ma — identical with the andesitic porphyritic flow (LA80-5) of the Western Cordillera.

The Eastern Cordillera

At the western boundary of the Eastern Cordillera, the large, essentially Paleozoic Meseta de Morococala is covered by volcanic deposits (Figs. 1 and 8). Miocene plutons (23-27 Ma; Grant *et al.*, 1977, 1979) intrude the Paleozoic rocks and are associated with important mineralizations. The volcanic cover consists of a succession of late Miocene-Pliocene ignimbrites (6.2 and 6.4 Ma, Grant *et al.*, 1977, 1979; Table 3). Samples of two dacitic volcanoes (Cerro Tankha Tankha; Table 1, PHM1 and PHM2) gave ages of 5.8±0.3Ma to 6.3±0.3 Ma (Table 2). These results, as well as those of Evernden *et al.* (1966) obtained from the Meseta de Los Frailes (6.4 Ma, Table 3), place the last volcanic emissions in the latest Miocene or in the earliest Pliocene, just after the tectonic Quechuan pulse Q3. This volcanism has roughly the same age as the "Toba 76" that forms the base of the uppermost Miocene-Pliocene Altiplano deposits.

SUMMARY AND CONCLUSIONS

The schematic stratigraphic diagram of Fig. 9 shows the relationships of the units discussed in the text.

In the Western Cordillera and its Piedmont, an isotopic age of 25.2±1.0 Ma confirms that the lower part of the Mauri Formation is of early Oligocene age. Four isotopic ages — 20.8±0.5, 17.9±0.7, 15.1 ±0.8, and 13.5±0.4 Ma — obtained from lavas of the Abaroa Formation place this unit in the Miocene. No unconformities were found within the Mauri Formation or between the Mauri and Abaroa Formations. The Cerke Formation, 5.7±0.5 Ma, is assigned to the latest Miocene to earliest Pliocene. In the southern part of the Abaroa area, a dark colored lava (7.6±0.8 Ma) was incorrectly assigned to the Perez ignimbrite. This lava unconformably overlies the Mauri and Abaroa Formations and represents the base of the latest Miocene-Pliocene sequence in this area.

Southeast of Lake Titicaca near Chua, a volcanic flow has an isotopic age of 7.6±0.7 Ma that is coeval with the andesitic porphyritic lava of the Abaroa area. In the Altiplano, Pliocene deposits include a tuff that yielded an age of 5.2±0.3 Ma at Soledad and another tuff that yielded an age of 3.3±0.3 Ma at Tirata. In the La Paz Basin, the lower part of the La Paz Formation is dated at 5.5±0.2 Ma. In the Eastern Altiplano and Piedmont of the Eastern Cordillera, widespread ash-flow tuff extends from Ayo Ayo to Achacachi. This unit yielded ages of 2.8±0.1 Ma to 3.3±0.2 Ma, which places it in the Pliocene. In the La Paz area, the same ash-flow tuff is interbedded in the Pliocene lacustrine deposits of the La Paz Formation. On the east side of the basin, this ash-flow tuff overlies the first glacial sediments of the Patapatani Formation — a fact which confirms the existence of a Pliocene glaciation in the Bolivian Andes.

In the Western Cordillera Piedmont, The Quechuan pulse Q3 took place at roughly 8 Ma (7.6±0.8 Ma), before the deposition of an andesitic lava. However, it has not been possible to date precisely the Q3 pulse in the Altiplano and in the La Paz Basin, except that it must be older than 5.5 Ma. In the La Paz Basin, the late Quechuan pulse Q4 took place between 2.8 and 1.6 Ma and, therefore, the uppermost Miocene-Pliocene sedimentary sequence (dated 8-3 Ma) was laid down between the Q3 and Q4 Quechuan pulses.

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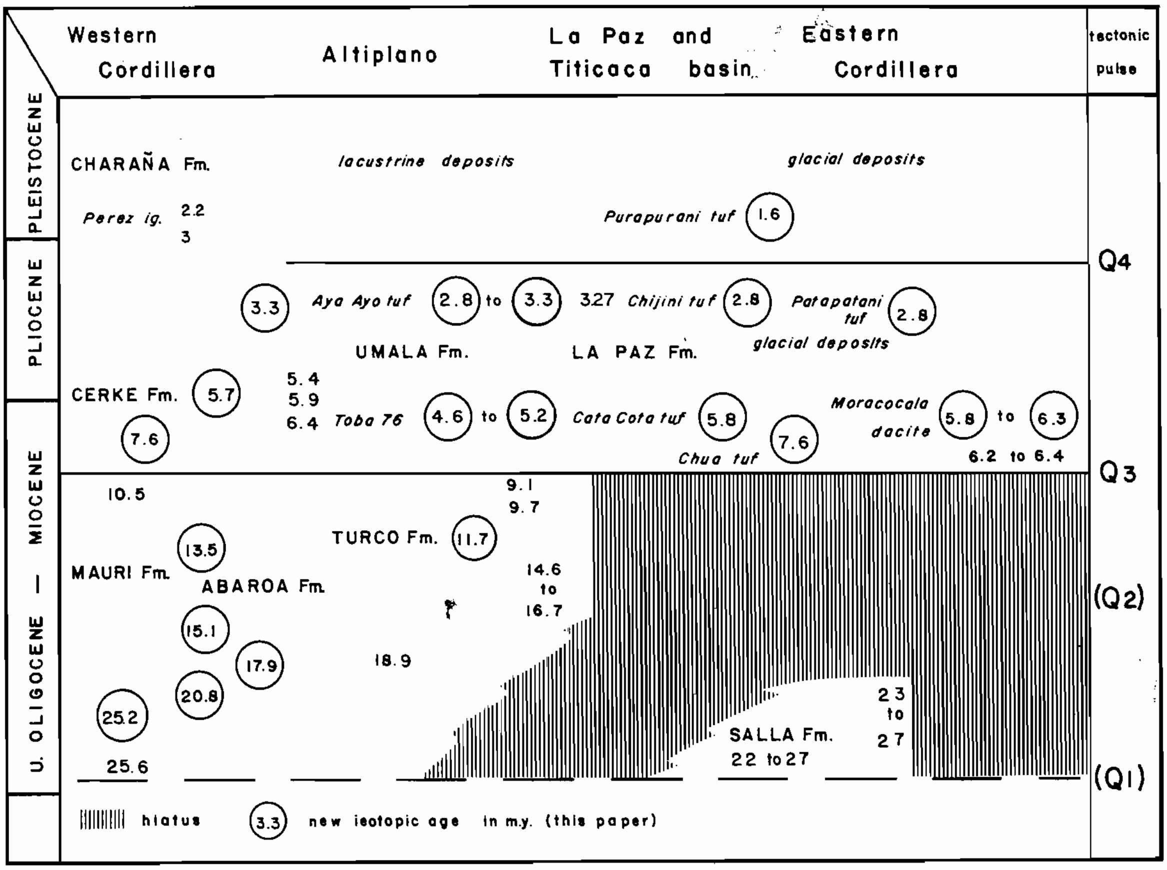

Fig. 9. Stratigraphic correlations and new isotopic ages. In this northern Bolivian Altiplano study area, the Q2 tectonic pulse does not appear as it does in Peru (Sébrier *et al.* 1979), and the age of the Q1 tectonic pulse is doubtful (Noble *et al.*, 1985; Swanson *et al.*, 1987).

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