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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-

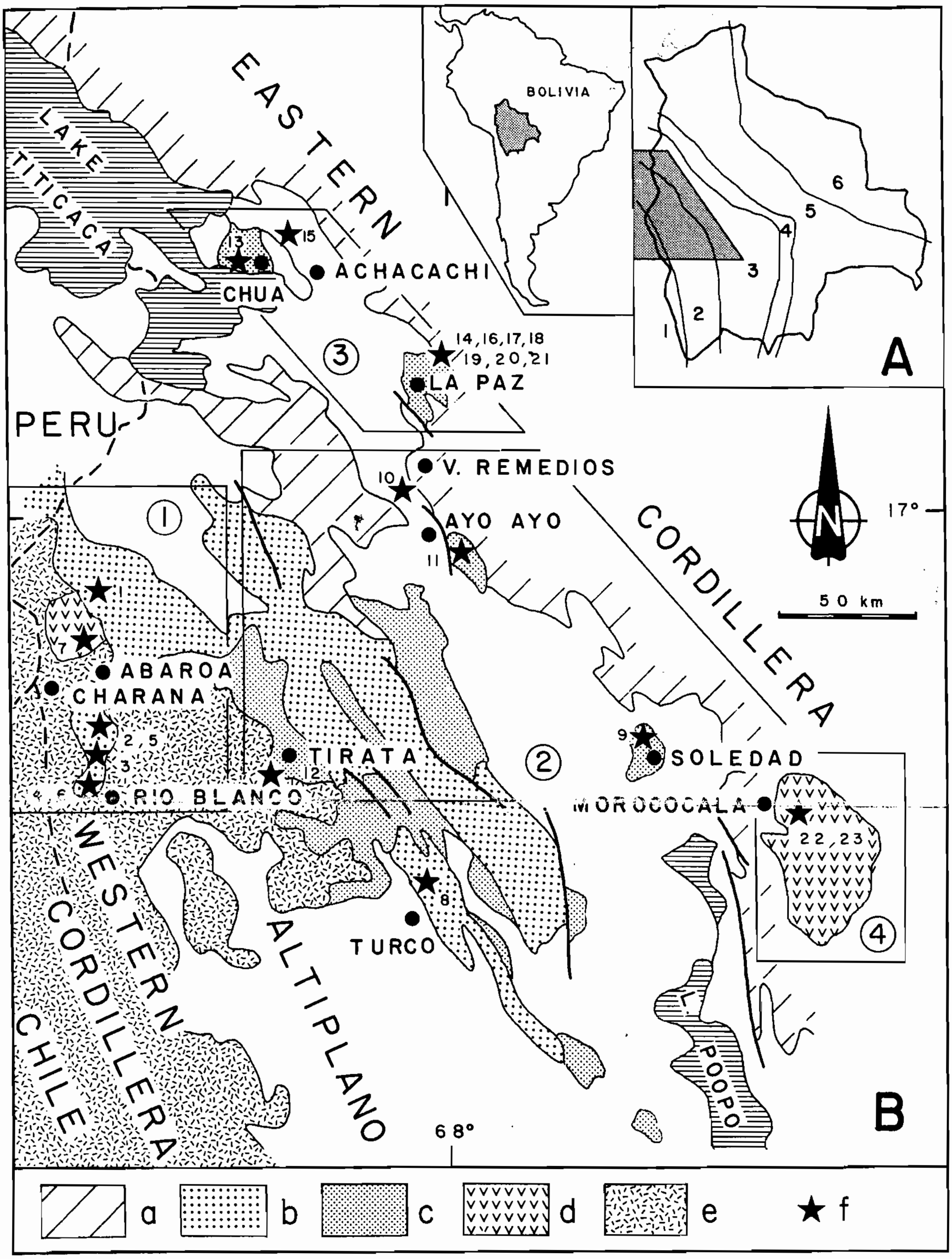

Fig. 1. Location map of studied area, central Bolivia. A, dot pattern indicates study area and numbers indicate morphostructural zonation: 1, Western Cordillera; 2, Altiplano; 3, Eastern Cordillera; 4, Subandean Zone; 5, Beni-Chaco Plain; 6, Brazilian Shield. B, simplified geologic map of the study area: 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

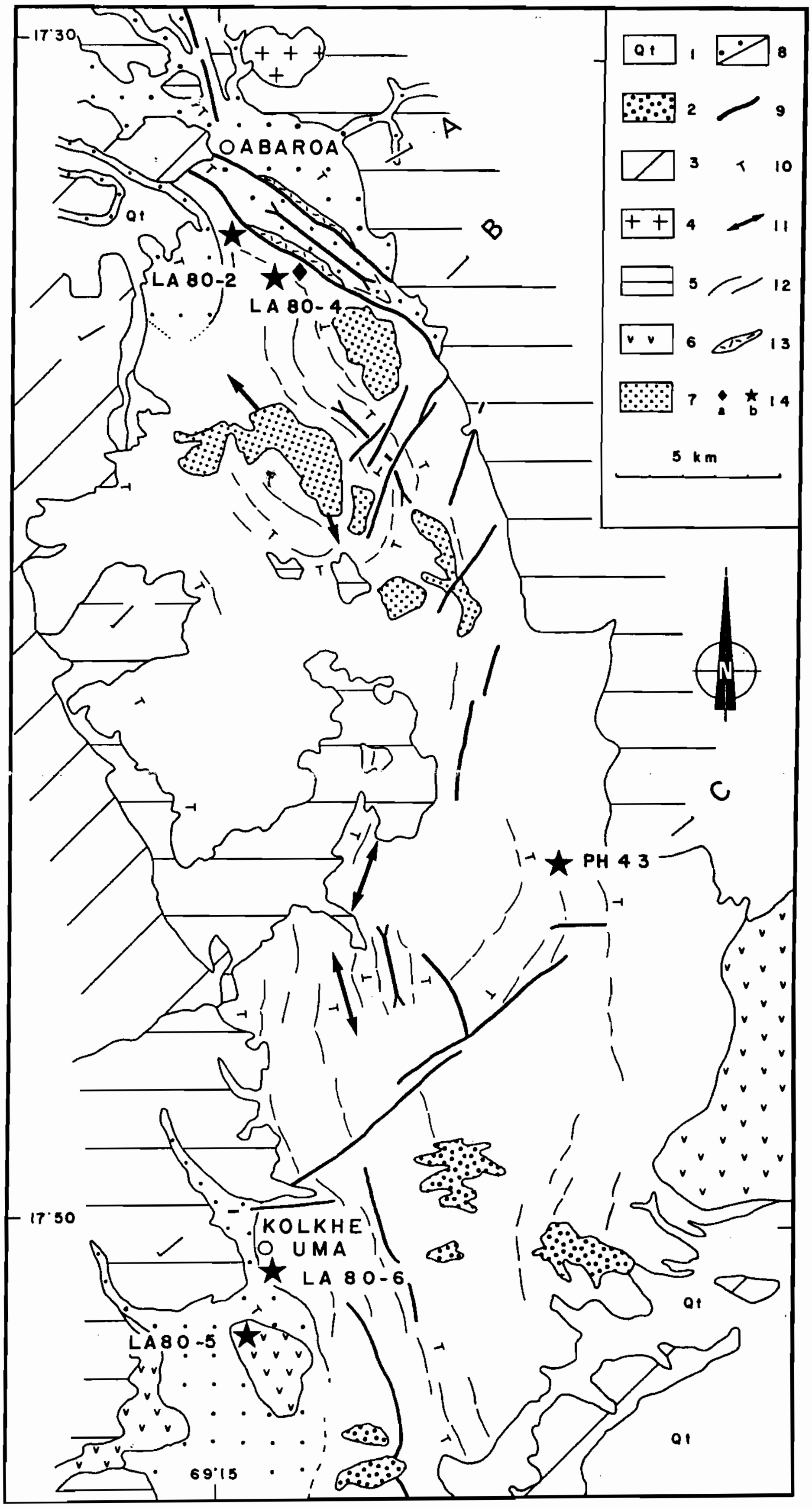

Fig. 3. Schematic geologic map of the Abaroa Formation between Abaroa and Kolkhe Uma (detail of Fig. 2): 1, undifferentiated Quaternary deposits; 2, Quaternary moraines; 3, Charaña Formation; 4, Quaternary intrusive rocks; 5, Perez Formation; 6, undifferentiated volcanism; 7, Tertiary intrusive rocks; 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.

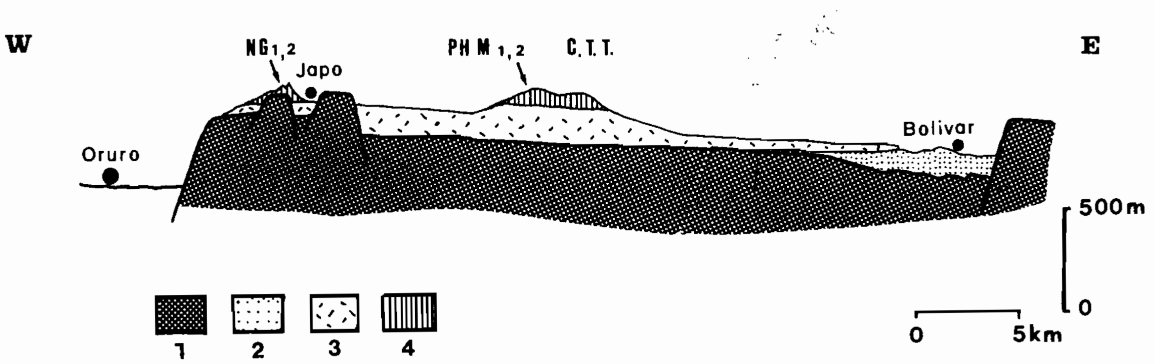

Fig. 8. Cross-section of the Meseta de Morococala: 1, Paleozoic substratum; 2, Mesozoic-Cenozoic sediments; 3, Miocene volcanic meseta; 4, Cerro Tankha Tankha volcanoes.

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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