

Stratigraphy, K-Ar ages, and magnetostratigraphy of the Acambay graben, central Mexican Volcanic Belt

Gerardo J. Aguirre-Diaz*

Instituto de Geología, Universidad Nacional Autónoma de México, Estación Regional del Centro, Apartado Postal 376, Guanajuato, Guanajuato 36000, México

Jaime Urrutia-Fucugauchi and Ana Maria Soler-Arechalde

Laboratorio de Paleomagnetismo y Geofísica Nuclear, Instituto de Geofísica, Universidad Nacional Autónoma de México, Delegación Coyoacan 04510 D.F., México

Fred W. McDowell

Department of Geological Sciences, P.O. Box 7909-7813, University of Texas at Austin, Austin, Texas 78713

ABSTRACT

The Acambay graben is an east-west intraarc tectonic depression in the central sector of the Mexican Volcanic Belt. The graben is 80 km long and 15–38 km wide, bounded at the south by the Pastores and Venta de Bravo faults, and at the north by the Acambay-Tixmadejé and Epitacio Huerta faults. Two representative sections were measured, one in the northern wall of the graben on the Epitacio Huerta fault (Amealco caldera section), and the other in the southern wall on the Venta de Bravo fault (Tlalpujahuá section). These two sections were documented with K-Ar ages and paleomagnetic measurements. The units exposed in the northern section are all volcanic and within a range of 4.7 to 2.2 Ma. The southern section includes metasedimentary rocks that could be Cretaceous (no fossils have been found) and the Miocene-Quaternary volcanic succession. The southern section has a K-Ar age of 4.7 ± 0.2 Ma and reverse polarity for a major ignimbrite of Las Américas Formation. This formation is correlated with the Amealco tuff of the northern section, which is the only map unit widespread enough to be exposed on either side of the Acambay graben. Paleomagnetic studies concentrated on the widespread ignimbrites, such as those within the Amealco and Huichapan tuffs, because of their potential for magnetostratigraphy. The K-Ar and paleomagnetic data are consistent within analytical uncertainties. The Amealco tuff sequence includes three major ignimbrites. The oldest ignimbrite, Amealco I, has a reverse polarity and a K-Ar age of 4.7 Ma; Amealco II has a normal polarity and a K-Ar age of about 4.7 Ma; and Amealco III has a normal polarity and a K-Ar age of about 4.6 Ma. The ignimbrite of the Huichapan tuff has a reverse polarity and a K-Ar age of 3.5 Ma. There is a predominance of reverse polarity for units within the Acambay graben. Magnetostratigraphy is used as another line of evidence for the correlation of Amealco tuff and Las Américas Formation, and proved useful to demonstrate that the Amealco caldera was the source for the Amealco tuff and Las Américas ignimbrites.

*Present address: Unidad de Investigación, Universidad Nacional Autónoma de México, en Ciencias de la Tierra, Campus Jariquilla, Apartado Postal 1-742, Centro Querétaro, Querétaro 76001, México

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INTRODUCTION

The Acambay graben is located in the central sector of the Mexican Volcanic Belt. It is one of a series of east-west-oriented grabens along the Chapala-Tula fault system (Johnson and Harrison, 1990; Suter et al., 1992, 1995), which practically coincides with the axis of the belt, and are thus interpreted as intraarc tectonic depressions (Suter et al., 1995). This study provides a brief description of the stratigraphy of the Mesozoic basement and the Tertiary-Quaternary volcanic rocks exposed in the Acambay graben region, focusing on those that are well exposed on the walls of the graben, in the vicinity of Venta de Bravo and Tlalpujahua, and near the Amealco caldera, southern and northern walls, respectively (Fig. 1). Stratigraphic interpretations are derived from detailed measured sections, K-Ar dating, and paleomagnetic studies.

This chapter is organized as follows: (1) previous works in the Acambay graben, (2) presentation of results that includes a description of the K-Ar and paleomagnetic data and of the techniques employed, (3) description of the stratigraphy at two representative sections, one per graben wall, and (4) discussion of results.

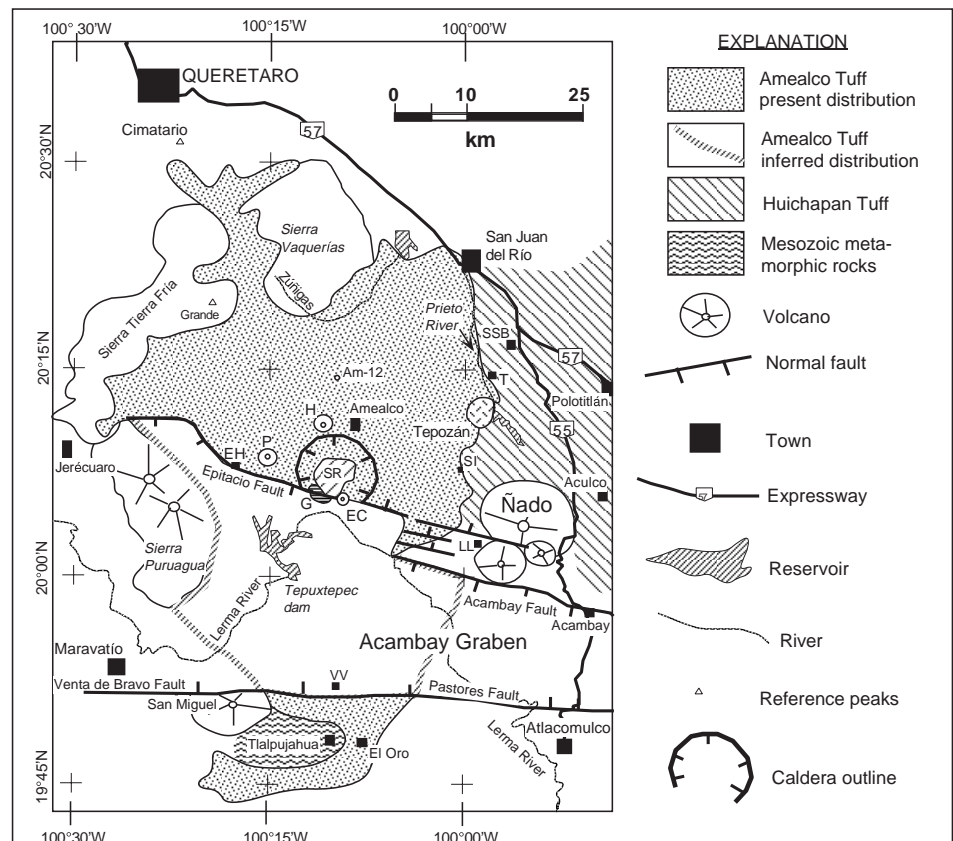
The stratigraphy is described in two parts: the southern section which includes the stratigraphy around the Tlalpujahua area; and the stratigraphy of the northern section, including the Amealco caldera. In addition to these sections, two transects gathering geologic and paleomagnetic data were carried out

within the Acambay graben, one across the central part of the graben (Temascalcingo), and the other on the eastern part, between Atzaculco and Acambay (Fig. 2). A more detailed description focused on the Amealco caldera can be found in Aguirre-Díaz and McDowell (this volume).

ACAMBAY GRABEN

Previous studies date from early in the twentieth century. Urbina and Camacho (1913) reported effects of the devastating Acambay earthquake ($M = 7$) of 1912 along the Acambay-Tixmadejé northern master fault. Flores (1920) published a description of the Mesozoic metamorphic and plutonic complex in the Tlalpujahua mining district exposed in the southern uplifted block of the Acambay graben (Fig. 1). Fries et al. (1977) reported a geologic study of the southern sector of the Acambay graben, where they defined the Las Americas Formation, a stack of four major ignimbrites mapped in the Tlalpujahua area. Most of the more recent works that investigate the stratigraphy have been conducted as thesis projects (Silva-Mora, 1979; Sánchez-Rubio, 1984; Carrasco-Núñez, 1988; Soler-Arechalde, 1990; Aguirre-Díaz, 1993). Silva-Mora (1979) did a reconnaissance mapping of the area south and southwest of the Acambay graben, which has been published recently in the 1:100,000 scale geologic map series of the Universidad Nacional Autónoma de México (UNAM) Instituto de

Figure 1. Simplified geologic map of the Acambay graben and adjacent region in the central Mexican Volcanic Belt. The areal extent of the major ignimbrites of the Amealco and Huichapan calderas are indicated by the filled patterns. It is proposed that the Amealco Tuff extends beneath the Acambay graben volcanic-sedimentary cover. Abbreviations: EH, Epitacio Huerta; VV, Venta de Bravo; LL, Loma Linda; SSB, San Sebastián Barrancas; SI, San Ildelfonso; T, Taxhie; TR, Tlacotepec river; EC, El Comal; G, Garabato Andesite; SR, Santa Rosa Andesite. Also shown is the site of sample Am-12 (mentioned in text).



grained rocks, were analyzed with no further treatment after crushing, sieving, and washing the dust. Glass and plagioclase separates were mixed with an equivalent amount of zero-age basalt as a flux. Plagioclase and glass samples were heated to 1600 °C for 40 min. Glass, groundmass, and whole-rock samples were heated to similar temperatures but only for 25 min. Practically all K and Ar analysis were done in duplicate. A third analysis was performed in case of excessive scatter.

Standards of suitable age are not available to check directly the accuracy of these ages. An accuracy within 5% is inferred from agreement of ages for samples dated by both matrix and feldspar, for multiple samples of the same unit, and from the general consistency of K-Ar age with stratigraphic position.

Analytical uncertainty (precision) is calculated from replicate K and Ar analysis. Analytical uncertainties shown in Table 1 are given at one standard deviation. For samples in which the yield of radiogenic argon is >40% of total argon, additional error is attributable to uncertainty in the measurement of mass discrimination effects in the mass spectrometer. For some samples these discrimination factors do not account for the full scatter in replicate determinations. In such cases, the uncertainty is calculated from the replicate measurement. Generally, the uncertainties were smaller than 8% of the age, and mostly less than 5% of the age. The weighted means of the results of a single unit were computed in order to assign a representative age to the unit. Five datings were performed on different samples of the Amealco tuff, with a range from 4.54 to 4.74 Ma (Table 1); the weighted mean of the five results is 4.68 ± 0.1 Ma, which is considered the representative age of this unit.

Paleomagnetism

Analytical data for the paleomagnetic results are shown in Table 2. The locations of sites and corresponding magnetic polarity are shown in Figure 2. Six to eight samples per site were collected with a gas-powered drill with nonmagnetic drill bits, and oriented with a magnetic compass. Magnetic gradient measurements were taken to evaluate the effects of localized magnetic fields and to avoid outcrops affected by lightning strikes or with high local magnetic fields. The cores were cut in the laboratory into cylindrical specimens 2.54 cm diameter and 2.2–2.3 cm long.

The intensity and direction of natural remanent magnetization (NRM) of all specimens were measured with a Molspin spinner fluxgate magnetometer. The low-field susceptibility was measured with a Bartington MS2 susceptibility system with the dual-frequency laboratory sensor. The stability, coercivity spectrum, and vectorial composition of NRM were investigated by detailed step-wise alternating field (AF) demagnetization, with a Schonstedt AF apparatus (operated in the stationary three-orthogonal position mode).

By treating the paleomagnetic data in a way similar to that of Dunlop (1977a) and Schmidt (1982), it is observed that most samples are characterized by intermediate coercivity spectra, which indicate that remanence is mainly carried by members of the

titanomagnetite series. Further indications of the magnetic mineralogy and magnetic carriers were obtained from isothermal remanent magnetization (IRM) measurements. IRM was given in steps to 500 mT in an IRM pulse magnetizer. Samples reach saturation in low applied fields, indicating the presence of low-coercivity minerals. In some cases high coercivities are present, indicating the occurrence of other minerals such as titanohematites, in agreement with the AF coercivity spectrum analysis. These results are also consistent with the petrographic thin-section observations.

Site-mean results were calculated by vector addition, and the angular dispersion parameters were estimated by conventional Fisherian statistics (Fisher, 1953; Tarling, 1983). A plot of site-mean directions in a stereographic projection (Fig. 3) shows the predominance of reverse polarities. Virtual geomagnetic pole (VGP) positions were calculated for the site-mean directions by assuming a central axial dipole field. The magnetic polarity is estimated from the VGP latitude (λ_p): $90^\circ \text{N} < \lambda_p > 45^\circ \text{N}$ correspond to normal (N) polarity, $45^\circ \text{N} < \lambda_p > 45^\circ \text{S}$ corresponds to intermediate (I) polarity, and $45^\circ \text{S} < \lambda_p > 90^\circ \text{S}$ corresponds to reverse (R) polarity. Magnetic polarities were initially referred to the geomagnetic polarity time scale (GPTS) of Harland et al. (1990). For the final analysis (and this chapter), we have referred the results to the recent revision of the GPTS given by Baksi (1993), which became available during the course of this study. This GPTS is based on $^{39}\text{Ar}/^{40}\text{Ar}$ plateau ages and agrees with astrochronological calibrations. Site-mean results are schematically referred to the GPTS in Figure 4.

STRATIGRAPHY OF THE SOUTHERN SECTOR OF THE ACAMBAY GRABEN

Figure 5A shows a representative composite section, with K-Ar and $^{39}\text{Ar}/^{40}\text{Ar}$ ages and paleomagnetic polarities of the southern uplifted block of the Acambay graben, in the vicinity of Tlalpujahua (Fig. 1). The sequence exposed includes Mesozoic metamorphic rocks, Tertiary volcanic rocks, and Quaternary mafic lava flows and lake deposits.

Tlalpujahua metamorphic-plutonic complex

The oldest units in the area are metasedimentary and plutonic rocks (dikes and sills) exposed near Tlalpujahua village along the southern master fault of the Acambay graben, the Venta de Bravo fault (Suter et al., 1991, 1992) (Fig. 1). These rocks were described by Flores (1920), and later by Fries et al. (1977). The metamorphic sequence consists of black, brown, yellow, or white slates or slightly metamorphosed shales that are locally interbedded with lenses of black limestone. The sequence is cut by andesitic and rhyolitic dikes and sills that do not crop out, but are only observed inside the mines (Flores, 1920). Gold and silver mineralization was related to these acid intrusions. No fossils or absolute ages have been reported for this sequence or for the plutonic rocks, and thus there are no time constraints for them. Flores (1920) inferred the metamorphic sequence to be Triassic,

TABLE 1. K-Ar AGES OF AMEAICO CALDERA REGION

| Unit | Sample | Location | | Mat.* | K (%) | Weight (g) | Ar x 10 ⁻⁶ (scc/g) [†] | ⁴⁰ Ar [§] (%) | Age (Ma) | ±1σ ^{**} (Ma) | Assigned Age [‡] (Ma ± 1σ) |
|--------------------|--------|-------------|-------------|-------|----------|---------------|---|--------------------------------------|-------------|---------------------------|---|
| | | Lat. (N) | Long (W) | | | | | | | | |
| Pre-Amealco | am-67 | 20°21'8" | 100°6'50" | Wr | 1.27 | 0.611 | 0.269 | 33.2 | 5.69 | 0.35 | 5.69 ± 0.35 |
| | | | | | 1.26 | 0.611 | 0.294 | 31.8 | | | |
| | am-84 | 20°10'33" | 100°27'54" | Fsd | 0.97 | 0.261 | 0.175 | 27.4 | 4.70 | 0.19 | 4.70 ± 0.19 |
| | | | | | 0.99 | 0.327 | 0.183 | 38.5 | | | |
| Ameaico Tuff | am-1 | 20°8'3" | 100°18'10" | Gl | 4.64 | 0.263 | 0.854 | 18.5 | 4.74 | 0.15 | 4.68 ± 0.10 |
| | | | | | 4.61 | | | | | | |
| | | | | | 4.63 | | | | | | |
| | am-1 | | | Fds | 0.53 | 0.316 | 0.094 | 19.9 | 4.54 | 0.28 | |
| | | | | | 0.53 | | | | | | |
| | am-12 | 20°16'36" | 100°9'7" | Fds | 0.46 | 0.301 | 0.082 | 13.1 | 4.55 | 0.40 | |
| | | | | | 0.46 | | | | | | |
| | am-22 | 20°8'1" | 100°18'8" | Gl | 3.62 | 0.432 | 0.640 | 35.9 | 4.71 | 0.14 | |
| | | | | | 3.53 | 0.277 | 0.664 | 31.1 | | | |
| | | | | | 3.56 | | | | | | |
| | | | | | 3.53 | | | | | | |
| | am-208 | 19°50'45" | 100°11'15" | Gl | 2.90 | 0.606 | 0.542 | 34.4 | 4.71 | 0.19 | |
| | | | | | 2.91 | 0.278 | 0.524 | 38.8 | | | |
| | | | | | 2.86 | | | | | | |
| Amealco Andesite | am-62 | 20°10'16" | 100°10'17" | Gms | 2.00 | 0.668 | 0.342 | 58.0 | 4.42 | 0.21 | 4.31 ± 0.12 |
| | | | | | 1.97 | | | | | | |
| | am-58 | 20°10'13" | 100°9'23" | Wr | 2.31 | 0.579 | 0.385 | 45.3 | 4.30 | 0.24 | |
| | | | | | 2.29 | | | | | | |
| | am-46 | 20°6'38" | 100°7'0" | Wr | 3.42 | 0.588 | 0.519 | 16.6 | 4.14 | 0.36 | |
| | | | | | 3.41 | 0.459 | 0.584 | 18.6 | | | |
| | am-195 | 20°7'54" | 100°6'55" | Wr | 2.28 | 0.666 | 0.371 | 22.3 | 4.30 | 0.15 | |
| | | | | | 2.30 | 0.440 | 0.395 | 21.7 | | | |
| Palomas Andesite | am-41b | 20°9'19" | 100°16'8" | Gms | 0.58 | 0.546 | 0.096 | 16.9 | 3.96 | 0.40 | 3.96 ± 0.40 |
| | | | | | 0.57 | 0.461 | 0.083 | 14.7 | | | |
| | | | | | 0.429 | | 0.089 | 14.2 | | | |
| Sta. Rosa Andesite | am-61 | 20°8'49" | 100°10'7" | Gms | 3.36 | 0.552 | 0.474 | 13.6 | 2.69 | 0.25 | 3.74 ± 0.25 |
| | | | | | 3.31 | 0.681 | 0.478 | 13.0 | | | |
| | | | | | 3.30 | | | | | | |
| | am-51 | 20°7'32" | 100°9'43" | Gms | 2.82 | 0.723 | 0.374 | 19.2 | 3.79 | 0.26 | |
| | | | | | 2.72 | 0.353 | 0.423 | 20.2 | | | |
| | | | | | 2.69 | 0.494 | 0.416 | 17.3 | | | |
| Coronita Rhyolite | am-179 | 20°7'7" | 100°19'33" | Gl | 3.83 | 0.518 | 0.524 | 42.8 | 3.52 | 0.10 | 3.72 ± 0.27 |
| | | | | | 3.82 | | | | | | |
| | | | | | 3.83 | | | | | | |
| | am-179 | | | Fds | 4.20 | 0.285 | 0.627 | 54.0 | 3.90 | 0.10 | |
| | | | | | 4.15 | 0.493 | 0.642 | 61.5 | | | |
| | | | | | 4.30 | | | | | | |
| Huichapan Tuff | am-81 | 20°8'38" | 99°58'36" | Gl | 3.96 | 0.604 | 0.553 | 48.4 | 3.59 | 0.09 | 3.52 ± 0.16 |
| | | | | | 3.96 | | | | | | |
| | am-81 | | | Fds | 3.58 | 0.274 | 0.443 | 23.3 | 3.36 | 0.21 | |
| | | | | | 3.52 | 0.414 | 0.482 | 58.0 | | | |
| | | | | | 3.54 | | | | | | |
| | | | | | 3.50 | | | | | | |
| El Rincón Rhyolite | am-122 | 20°14'15" | 100°14'25" | Gl | 4.86 | 0.664 | 0.555 | 4.5 | 2.92 | 0.44 | 2.92 ± 0.59 |
| | | | | | 4.89 | | | | | | |
| Garabato Andesite | am-18 | 20°6'0" | 100°11'50" | Wr | 2.39 | 0.558 | 0.252 | 19.8 | 2.54 | 0.26 | 2.54 ± 0.26 |
| | | | | | 2.37 | 0.588 | 0.218 | 29.0 | | | |
| El Comal Andesite | am-19b | 20°5'59" | 100°9'48" | Gms | 1.91 | 0.779 | 0.161 | 31.3 | 2.18 | 0.07 | 2.18 ± 0.07 |
| | | | | | 1.90 | 0.647 | 0.163 | 24.9 | | | |

*Material used for K-Ar analyses: Gl = glass; Wr = whole rock; Gms = groundmass; Fds = feldspar.

[†]Scc/g = standard cubic cm³.

[§]⁴⁰Ar = radiogenic argon content of sample, in percent of total ⁴⁰Ar.

**Error of age at one sigma, see text for details.

[‡]Assigned age = weighted mean of the different ages obtained for a particular unit.

⁴⁰K/K = 1.167 x 10⁻⁴ mol/mol; λβ = 4.963 x 10⁻¹⁰/yr; λε + ε = 0.581 x 10⁻¹⁰/yr.

TABLE 2. PALEOMAGNETIC DATA, ACAMBAY GRABEN

| Site | Number | Dec. | Inc. | r | k | α_{95} |
|------|--------|-------|-------|---------|-----|---------------|
| n1 | 8 | 190.1 | -11.5 | 7.9740 | 269 | 2.7 |
| n2 | 6 | 135.1 | 9.7 | 5.9173 | 60 | 7.0 |
| n3 | 4 | 158.9 | -29.6 | 3.9828 | 174 | 5.6 |
| n4 | 5 | 181.9 | -45.0 | 4.8985 | 39 | 9.9 |
| n7 | 5 | 161.8 | -45.1 | 4.8854 | 35 | 10.0 |
| n10 | 7 | 155.1 | -43.8 | 6.7438 | 23 | 10.2 |
| n11 | 7 | 147.4 | -37.9 | 6.8431 | 38 | 7.9 |
| n15 | 6 | 353.3 | 24.2 | 5.9369 | 79 | 6.1 |
| n16 | 6 | 358.2 | 35.8 | 5.9740 | 192 | 3.8 |
| n17 | 8 | 183.5 | -21.6 | 7.9529 | 149 | 3.7 |
| n18 | 9 | 193.8 | -34.3 | 8.6646 | 24 | 8.6 |
| n23 | 6 | 173.1 | -15.3 | 5.8435 | 32 | 9.6 |
| l1 | 6 | 164.7 | -48.6 | 5.8688 | 38 | 8.8 |
| l2 | 6 | 167.9 | -46.2 | 5.9689 | 161 | 4.2 |
| l3 | 6 | 192.7 | -20.2 | 5.9431 | 88 | 5.8 |
| l4 | 4 | 192.3 | -32.1 | 3.9788 | 141 | 6.2 |
| l5 | 8 | 125.0 | -71.8 | 7.9818 | 384 | 2.2 |
| l6 | 8 | 183.5 | -39.1 | 7.9867 | 528 | 1.9 |
| am1 | 12 | 190.9 | -35.5 | 11.9268 | 150 | 2.9 |
| am3 | 8 | 351.4 | 29.3 | 7.9485 | 136 | 3.8 |
| am4 | 9 | 351.2 | 21.0 | 8.9621 | 211 | 2.9 |
| am5 | 4 | 191.9 | -33.4 | 3.9656 | 87 | 7.9 |
| am7 | 4 | 161.4 | -69.3 | 3.9487 | 58 | 9.7 |
| am8 | 11 | 172.8 | -43.6 | 10.9657 | 289 | 2.2 |
| mn1 | 24 | 173.5 | -35.5 | 22.3146 | 23 | 6.7 |

Note: Dec. = declination (in degrees); Inc. = inclination (in degrees);

and Fries et al. (1977) proposed a Triassic-Cretaceous age based on possible correlation with a similar metamorphic sequence in the mining districts of Taxco, Guerrero State, and Guanajuato, Guanajuato State. Suter et al. (1995) proposed an Early Cretaceous age based on correlation with the Trancas Formation.

Mio-Pliocene volcanic rocks

Undated volcanic rocks of intermediate and mafic composition unconformably overlie the metamorphic rocks. They are not cut by dikes, as is the case with the metamorphic sequence. Because of this, a younger age is suggested, possibly Miocene or Pliocene. Some of these volcanic rocks were probably derived from the San Miguel volcano, which is one of the largest volcanoes in the area, with a base diameter of about 9 km and an elevation of 3000 m asl. This volcano was cut at its northern flank by the Venta de Bravo fault (Fig. 1). Other mafic lava flows, that are exposed along the Tlacotepec River and near the Venta de Bravo fault, contain relatively abundant xenoliths of felsic coarse-grained igneous rocks (Pantoja-Alor, 1994). These lava flows are covered by the Amealco Tuff in the vicinity of the Tlacotepec River, or by layered lake deposits, presumably Quaternary, to the east of this river.

Andesita Yondeje

Named by Sánchez-Rubio (1984), this is one of the larger andesitic structures and bounds to the east the Acambay graben,

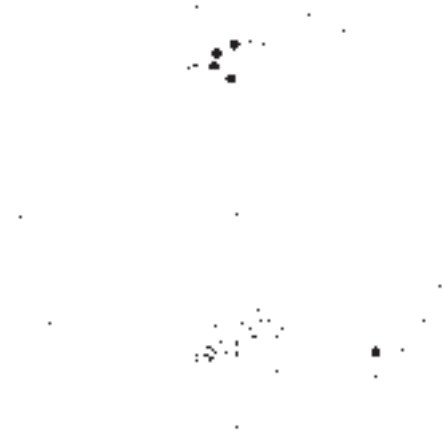


Figure 3. Equal-area stereographic diagram of site-mean directions. Data are shown in Table 2 (see text for explanation of units studied). Filled circles correspond to positive downward inclinations (normal polarity) and open circles correspond to negative upward inclinations (reverse polarity). Note the predominance of reverse polarity. The larger circle labeled Mn1 represents the overall site-mean direction with $n = 24$, declination = 173.5, inclination = -35.5, $k = 23$ and $\alpha_{95} = 6.7$.

where it forms a range about 35 km long at an altitude of 3300 m asl. It is undated but was inferred as Miocene by Sánchez-Rubio (1984). It has a reverse polarity observed at site i2 (Fig. 2). It is characterized by porphyritic flows with a massive appearance and, at some localities, with well-preserved flow structures. Flows are rich in plagioclase, hornblende, biotite, quartz and in some units, orthopyroxene, in a groundmass of plagioclase and orthopyroxene (Sánchez-Rubio, 1984).

Amealco Tuff (Las Americas Formation)

A pyroclastic sequence, named Las Américas Formation by Fries et al. (1977), overlies either intermediate-mafic lavas or the metasedimentary sequence described above. The bulk of this sequence was interpreted by Aguirre-Díaz (1990, 1995) as the southern distal facies of pyroclastic flows and fallouts emitted during the climatic phases of the Amealco caldera, which is 30 km to the north of these outcrops. Aguirre-Díaz (1990) named this pyroclastic sequence the Amealco Tuff. Three of the ignimbrites in the Tlalpujahuá sequence are intermediate in composition and are dark gray to reddish-brown. One of the ignimbrites, the second from the base, is felsic and light pink. The three dark ones correspond to the major ignimbrites Amealco I, Amealco II, and Amealco III, using the nomenclature of Aguirre-Díaz (1990). They contain plagioclase, augite, hypersthene, ilmenite, titanomagnetite, and accessory apatite. The pink ignimbrite, or "Segundo Derrame" of Fries et al. (1977), is nearly aphyric, containing to 5 vol% of quartz and sanidine. In contrast to the Amealco ignimbrites, it only contains white pumice lumps. The felsic ignimbrite was probably derived from a caldera located south of the Venta de Bravo fault,

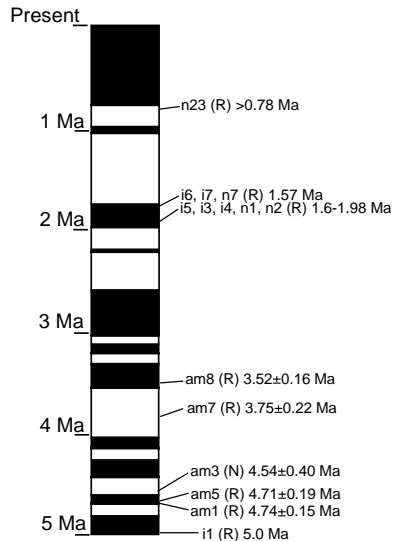


Figure 4. Schematic geomagnetic polarity time scale for the past 5 m.y. showing the approximate distribution of studied units (refer to Table 2 for data). Black represents normal polarity and white represents reverse polarity (after Baksi, 1993). Magnetostratigraphic results have been grouped and referred to major polarity chrons. The K-Ar ages permit a finer definition of age relationships, which are discussed in the text. See Table 1 for the K-Ar ages of the units.

perhaps from the depression where the Brockmann dam is, as suggested by Fries et al. (1977).

The main characteristic of the Amealco ignimbrites is the mingling of glasses; they contain black, white, light gray, and pale yellow, collapsed or uncollapsed, pumice fragments, corresponding to different compositions, from andesite to rhyolite (Aguirre-Díaz, 1993). This feature was recognized by Fries et al. (1977); their study focused on this characteristic of the ignimbrites. Black pumices or fiamme predominate; white pumices are generally small (<3 cm), and make up to 20 vol% of the ignimbrites, although more commonly, they make up less than 5 vol%. The Amealco ignimbrites at Talpujahu are generally columnar jointed, and individual flows are as thick as 10 m. Thickness decreases to the south; for example, the top ignimbrite, Amealco III, has a thickness of 10 m near the Venta de Bravo fault, and only 2 m near Chincua Lake, which is 15 km to the southwest of the Venta de Bravo site (Fig. 2).

A single K-Ar age and paleomagnetic data are available from the Amealco ignimbrites in the southern wall of the Acambay graben, and these are indicated in Figure 5A. The K-Ar glass age is from a sample of the basal vitrophyre of the lowermost ignimbrite, Amealco I, which yielded an age of 4.7 ± 0.2 Ma (sample Am-208, Table 1). This age is in agreement with the reverse paleomagnetic polarity of the sample that corresponds to the geomagnetic reverse chron between normal chrons C3n.2n and C3n.3n, that according to the geologic time scale of Baksi (1993), has a range between 4.55 and 4.74 Ma.

Other paleomagnetic-sampling sites on the Amealco ignimbrites that crop out in the southern shoulder of the graben are

n15, n16, n17, and n18 (Fig. 2), which yielded both normal and reverse polarities. It was not determined to which of the Amealco tuff ignimbrite episodes these sites correspond (Amealco I, Amealco II, or Amealco III), but based upon the polarity, it can be inferred that sites n15 and n16 correspond to the Amealco II or Amealco III, which have a normal polarity, and sites n17 and n18 correspond to the Amealco I, which is the only of the three ignimbrites with a reverse polarity.

Other Pliocene-Quaternary volcanism

Between the Pliocene Amealco tuff ignimbrites and the Quaternary volcanism described here, there is a sequence of undated andesitic flows. Their age is difficult to estimate from the field relationships. Sampling sites n1 and n2 yielded a reverse magnetic polarity; therefore, these lavas may be within the Matuyama chron.

Basalto Los Metates

This unit forms an irregular volcanic structure located close to the Pastores fault in the eastern part of the Acambay graben. Sánchez-Rubio (1984) first identified it and tentatively assigned it a Pliocene age. The lavas are massive with rare plagioclase and olivine, and commonly have vesicles. The magnetic polarity in the two sites studied (i3 and i4, Fig. 2) is reverse; therefore, they may be correlated with the Matuyama chron.

Andesita Atlacomulco

Named by Sánchez-Rubio (1984), this unit consists of lavas of intermediate composition with a hyalophitic texture, containing plagioclase, orthopyroxene, and a brown glass groundmass. According to Sánchez-Rubio (1984) it may be Pleistocene, which agrees with the reverse polarity (site i5; Fig. 2) this unit yielded, and thus it may also correspond to the Matuyama chron.

Quaternary rhyolitic volcanism

A Quaternary rhyolite sequence is exposed within the central-eastern sector of the graben, in the vicinity of Temascalcingo (sites i6, i7, n3, and n7; Fig. 2). This sequence is mainly formed by lavas and thick, massive pumice deposits, presumably related to the San Pedro El Alto volcano (3100 m asl, Fig. 2). Obsidian is common. The glassy lavas contain plagioclase, sanidine, quartz, biotite, Fe-Ti oxides, and rare orthopyroxene or green hornblende. The sequence and the San Pedro El Alto volcano are displaced by normal faults of a central fault system within the Acambay graben (Fig. 2). An obsidian K-Ar age yielded 1.57 ± 0.15 Ma (Demant et al., 1975). Three samples for paleomagnetism yielded reverse polarities (sites i6, n3, and n7), thus corresponding to the Matuyama chron, but sample i7, to the west of Temascalcingo, yielded a normal polarity, and is uncertain to which normal polarity period it could belong.

Quaternary lake deposits and mafic lava flows

Lake deposits overlie the Amealco tuff and older mafic and intermediate lavas 6–14 km to south of the Pastores fault (site NT-26, Fig. 2). These deposits apparently accumulated in tectonically controlled basins, or sag ponds, that formed along the Venta de Bravo and Pastores faults (Suter et al., 1991), and may

be correlated to the Quaternary Ixtapantongo Formation of Sánchez-Rubio (1984). Mafic lava flows associated with Quaternary cinder lava cones are younger than these lake deposits (Suter et al., 1995). The cinder cones generally occur within, and close to the southern wall of, the Acambay graben (site n4, Fig. 2). One of these lavas yielded an $^{39}\text{Ar}/^{40}\text{Ar}$ age of 0.4 Ma (sample NT-26, Suter et al., 1995).

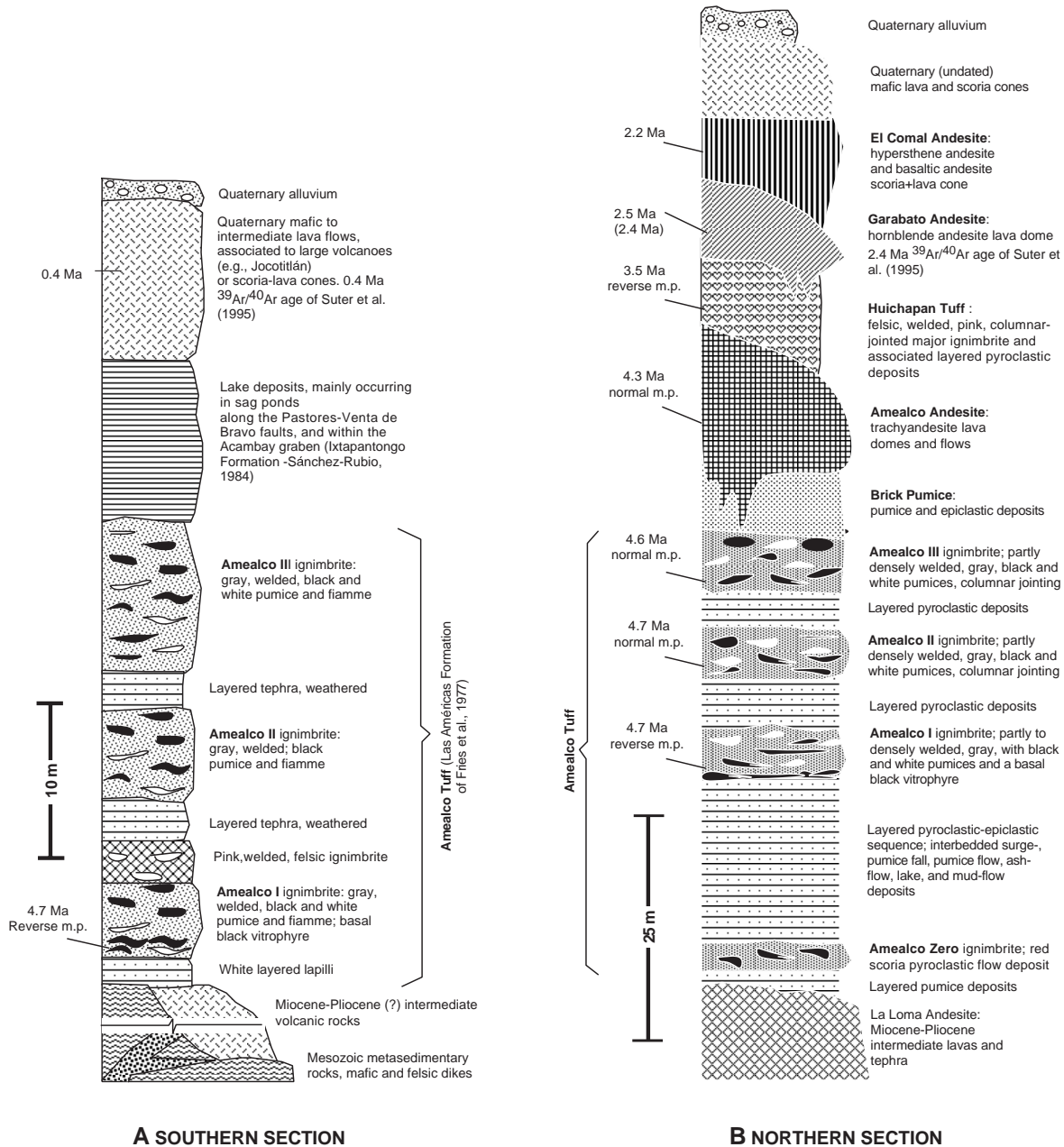


Figure 5. Composite stratigraphic sections indicating paleomagnetic polarities and K-Ar and $^{39}\text{Ar}/^{40}\text{Ar}$ ages. $^{39}\text{Ar}/^{40}\text{Ar}$ ages are from Suter et al. (1995). A: Composite stratigraphic section of the southern sector of the Acambay graben, in the vicinity of Venta de Bravo and Tlalpujahua villages. B: Composite stratigraphic section representative of the northern uplifted block of the Acambay graben. m.b. is magnetic polarity.

STRATIGRAPHY OF THE NORTHERN SECTOR OF THE ACAMBAY GRABEN

Figure 5B is a composite section of the northern wall of the graben in the vicinity of the Amealco caldera (for detailed single sections, see Aguirre-Díaz and McDowell, this volume). The age range of the dated volcanic rocks exposed in this shoulder of the graben is 5.7–2.2 Ma. The age of 5.7 Ma was obtained from a basaltic andesite about 28 km to the north of the Epitacio fault cropping out in the bottom of Zúñigas river (Fig. 1). The oldest units exposed along the northern graben wall remain undated (La Loma Andesite), except for a 5 Ma K-Ar age obtained from a scoria cone that may be a satellite cone of the Ñado volcano.

La Loma Andesite

The oldest rocks in the northern shoulder of the graben are lava flows and tephra of intermediate compositions. Some of these intermediate products were named La Loma Andesite by Sánchez-Rubio (1984). The La Loma Andesite was mainly erupted by the largest volcano in the Acambay graben area, Ñado volcano, with an elevation of 3320 m asl and a base diameter of about 15 km. Together with other volcanoes that are just to the south of Ñado, such as Boti (3300 m asl) and El Gallo (3080 m asl), this complex is 20 km in diameter. The La Loma Andesite has not been dated, but is inferred to be late Miocene or early Pliocene. The western outcrops are overlain by the Amealco tuff, and the northern and northeastern outcrops are covered by the Huichapan tuff (described in the following paragraphs).

Sánchez-Rubio (1984) reported a K-Ar age of 5 Ma in products of a scoria cone on the northern flank of Ñado volcano, which could have been a satellite cone to Ñado. The cone was almost completely buried by Huichapan tuff (described in the following paragraphs). The corresponding magnetic polarity is reverse (site i1, fig. 2).

Amealco Tuff

This pyroclastic sequence is widely exposed on the northern shoulder of the graben. It is a widespread deposit that formed an intermontane plateau as it filled and leveled a preexisting rough volcanic terrain. The type section of this unit is along a road just south of Epitacio Huerta (Figs. 1 and 2). In this section, and in several others, the three ignimbrites Amealco I, Amealco II, and Amealco III are interlayered with surge, pumice, mud-flow, and fallout deposits. In some parts, the sequence is as thick as about 100 m (Aguirre-Díaz and McDowell, this volume). At Epitacio Huerta, it is 50 m thick, about the average thickness. The ignimbrites show a distinctive glass mingling with a predominance of black pumice and fiamme. The ignimbrites are dark gray to light gray, low-aspect ratio deposits, commonly 4–10 m thick, with well-developed columnar jointing. The minerals in the igni-

mbrites and interlayered tephra are plagioclase, hypersthene, augite, and Fe-Ti oxides, accessory ilmenite, and occasionally olivine. The three main ignimbrites, Amealco I, Amealco II, and Amealco III, are equally extensive for at least 25 km around the Amealco caldera.

Amealco I in the Epitacio Huerta site yielded a feldspar K-Ar age of 4.5 ± 0.3 Ma, and a glass K-Ar age of 4.7 ± 0.2 Ma (sample Am-1, Table 1); the average is 4.6 Ma. The magnetic polarity is reverse (site am5, Table 2, Fig. 2). In the same section at Epitacio Huerta, the Amealco II ignimbrite yielded a glass K-Ar age of 4.7 ± 0.1 Ma (sample Am-22, Table 1). The magnetic polarity is reverse (site am4, Fig. 2). Farther north, the Amealco III ignimbrite yielded a feldspar K-Ar Age of 4.6 ± 0.4 Ma (sample Am-12, Table 1, Fig. 1). The magnetic polarity on the same flow unit but closer to Amealco is normal (site am3, Table 2, Fig. 2).

Brick Pumice

This unit was first described by Sánchez-Rubio (1984). It consists of a succession of pumice lapilli and epiclastic deposits; surge deposits are intercalated at some sites. This sequence was also derived from the Amealco caldera, and is found mainly to the east of the caldera (Aguirre-Díaz and McDowell, this volume). It overlies the Amealco Tuff and La Loma Andesite. The Brick Pumice is cut by the Acambay-Tixmadejé fault (Suter et al., 1991) in the proximity of Mexquiti-lán (Fig. 1). Abundant slickenside surfaces can be found along these faulted outcrops.

Amealco Andesite

The Amealco Andesite forms the rim of the Amealco caldera, which was constructed as several lava domes were emplaced at ring-fracture vents. Localized lava flows were also derived from some of these vents. A K-Ar age of 4.3 ± 0.1 Ma was obtained for this unit (Table 1). The rock is trachyandesite (Aguirre-Díaz and McDowell, this volume), but it has the textural appearance of an andesite. Only with aid of the chemical analysis is possible to recognize it as a trachyandesite (according to the classification of Le Bas et al., 1986). A variety of lithofacies is evident in this unit, including massive lava, platy jointed lava, crumbled breccia, and vesiculated lava. Textures are also variable, from porphyritic to glassy. Most commonly, the rock is porphyritic, and as the Amealco ignimbrites, it includes plagioclase, hypersthene, augite, Fe-Ti oxides, and rare olivine. Groundmass is generally glassy.

The Amealco Andesite overlies the Amealco tuff. The Brick Pumice unit either underlies, is interbedded with, or overlies the Amealco Andesite. In this way, the Brick Pumice can be regarded as evidence of explosive activity contemporaneous with the emplacement of the rim lava domes of the Amealco caldera (Amealco Andesite), possibly related to further collapse of the Amealco caldera (Aguirre-Díaz and McDowell, this vol-

ume). The Amealco Andesite is cut by the Epitacio fault, as the southern portion of the Amealco caldera was displaced by this fault (Fig. 1).

Santa Rosa Andesite

Five lava domes with a trachyandesitic composition (Aguirre-Díaz and McDowell, this volume) were emplaced within the Amealco caldera. This group of lava domes was redefined by Aguirre-Díaz (1993) as the Santa Rosa Andesite after the original definition of Sánchez-Rubio (1984). The rock is a porphyritic dark gray lava, which texturally has the aspect of an andesite. It includes plagioclase, hypersthene, augite, Fe-Ti oxides, and a glassy groundmass. A K-Ar age of 3.8 ± 0.3 Ma was obtained for this unit (Table 1). The southernmost lava dome of that group was displaced by the Epitacio fault.

Las Hormigas Andesite

Lava flows from Las Hormigas volcano (located to the northwest of Amealco caldera, Fig. 1) overlie the Amealco tuff. The cone and lava cover an area of about 26 km² and are as much as 5.5 km north of the vent. Hormigas lavas are olivine bearing with a microcrystalline groundmass of plagioclase laths, orthopyroxene, and glass. Las Hormigas andesite yielded a whole-rock K-Ar age of 3.7 ± 0.4 Ma (sample Am-78, Table 1) and is characterized by reverse polarity (site am7, Table 2). This supports a post-Amealco ignimbrite age, as is the case.

Huichapan Tuff

This unit can be divided into two members. The lower member consists of layered pyroclastic deposits that include surge, ash-flow, mud-flow, and pumice-fallout deposits. The upper member is a major ignimbrite, light pink to yellow, welded, and with prominent columnar jointing. The thickness of the major ignimbrite ranges from 2 m at the distal western facies, to more than 50 m closer to its probable source, the Huichapan caldera, in the State of Hidalgo, ~66 km to the east of the Amealco caldera. The ignimbrite is essentially a vitric tuff, mainly composed of glass shards and white pumice lumps. It has a crystal content ranging between 2 and 10 vol%, with low-K sanidine, quartz, and a lithic content to 5 vol%. The Huichapan tuff ponded against the northern flank of the Ñado volcano (La Loma Andesite). It also overlies the Brick Pumice and buried the eastern front of the Amealco tuff about 20 km to the east of the Amealco caldera.

The Huichapan tuff was sampled and dated at a site in the bridge over the Piedras Grandes stream along the Amealco-Aculco highway (Fig. 1), about 25 km to the east of the Amealco caldera (see Aguirre-Díaz and McDowell, this volume). The K-Ar age on a feldspar separate was 3.4 ± 0.2 Ma, and a glass separate from the same sample yielded an age of 3.6 ± 0.1 Ma (Table 1). The weighted mean of these ages is taken as

the representative age of this unit, 3.5 ± 0.2 Ma (Table 1). The magnetic polarity of the Huichapan tuff is reverse (site am8, Table 2).

It is unclear if the Huichapan tuff was displaced by the Acambay-Tixmadejé master fault. The southeasternmost outcrops of it are found proximal (3 km) to this fault. It is possible that secondary faults associated with the Acambay-Tixmadejé fault affect the Huichapan tuff.

Garabato Andesite

This is a local unit on the southern portion of the Amealco caldera (Fig. 1). Sánchez-Rubio (1984) named it the Garabato Andesite. The rock can be classified as hornblende andesite. It is a light gray, massive or platy jointed, mesa-forming lava. The rock is porphyritic, containing phenocrysts of hornblende, plagioclase, and sparse biotite, and a groundmass mostly composed of plagioclase laths and dark glass. A K-Ar age of the Garabato Andesite was 2.5 ± 0.3 Ma (Table 1). Suter et al. (1995) provided a ³⁹Ar/⁴⁰Ar age of 2.4 ± 0.2 Ma of the same unit (sample NT25, Fig. 2), which agrees with the K-Ar age. The Garabato Andesite is cut by the Epitacio Huerta fault, with a displacement of ~25 m (Sánchez-Rubio, 1984).

El Comal Andesite

The El Comal volcano is a scoria cone that was emplaced just on the southern portion of the Amealco caldera (Fig. 1). The products of this cone are named the El Comal Andesite (Aguirre-Díaz, 1993), and include scoria-fall deposits, which built the cone, and a single lava flow that breached the northern side of the cone. Both fall and flow deposits are basaltic andesite (according to the classification of Le Bas et al., 1986). In general, the rock is porphyritic, containing phenocrysts of plagioclase, orthopyroxene, clinopyroxene, and Fe-Ti oxides, and has a glassy matrix. A sample of the scoria deposits yielded a K-Ar age of 2.2 ± 0.1 Ma (Table 1). The El Comal cone was not displaced by faulting in spite of have been emplaced on the fault trace; thus, the faulting that displaced the southern portion of the Amealco caldera, the Epitacio fault, has to be older than 2.2 Ma, but younger than 2.5 Ma, because the Garabato Andesite was affected by this faulting.

DISCUSSION

Measured stratigraphic sections, K-Ar ages, and magnetostratigraphy, if combined, proved to be a useful approach to understand the stratigraphy in faulted volcanic terrains, such as in the Acambay graben area. Identification of marker units and correlation between them using several lines of evidence is essential to establish the basic stratigraphy based on two representative stratigraphic columns of the region. The units used as markers are the ignimbrites within the Amealco tuff, which are widespread enough to be on both sides of the Acambay graben,

and the Huichapan tuff, which extends to the east-northeast of the Acambay graben.

Fries et al. (1977) first recognized the Las Américas Formation, on the southern shoulder of the Acambay graben, but did not recognize its correlation with the Amealco tuff, and therefore that the source of these ignimbrites was the Amealco caldera, 35 km to the north of Tlalpujahua, across the Acambay graben. The main problem was (and still is) that the Amealco tuff does not crop out within the graben, and still today there are no borehole or geophysical data to confirm its occurrence beneath the lake and volcanic deposits that presumably cover it within the graben. However, the bulk of the Las Américas Formation corresponds to the southern distal facies of the Amealco tuff. This is based on the following evidence (Aguirre-Díaz, 1995): (1) both sequences include the ignimbrites Amealco I, Amealco II, and Amealco III, which correspond to the “Primer Derrame,” “Tercer Derrame,” and “Cuarto Derrame,” respectively, as defined by Fries et al. (1977); (2) the ignimbrites have the same physical and chemical nature, particularly a distinctive glass mingling; (3) the ignimbrites have the same mafic mineralogy, plagioclase + hypersthene + augite + ilmenite + titanomagnetite; (4) the ignimbrites have the same age of 4.7 Ma; (5) the magnetic polarity for the Amealco I and its equivalent member of the Las Américas Formation is reverse; and (6) Amealco ignimbrites are found as far as 45 km to the north of their source, the Amealco caldera. Similarly, the distal southern facies across the graben are 30–45 km from this caldera.

There is general good agreement between paleomagnetic data and K-Ar ages. For example, the Amealco I at the Epitacio Huerta site yielded 4.54 ± 0.28 Ma (sample Am-1 feldspar, Table 1) and 4.74 ± 0.15 Ma (sample Am-1 glass, Table 1). A reverse polarity was obtained at this site for the Amealco I, which corresponds to the reverse period between the normal polarity chrons C3n.2n and C3n.3n, with a range of 4.55 to 4.74 Ma (Baksi, 1993).

However, inconsistencies are observed in some results. The Amealco II ignimbrite in the same section at Epitacio Huerta yielded 4.71 ± 0.14 Ma (glass separate, sample Am 22, Table 1). However, the Amealco I should be older than the Amealco II, but the larger uncertainty of the ages of the Amealco I allows this. The Amealco II yielded a normal polarity at this site, which does not correspond to any normal polarity at that time (4.7 Ma); the nearest normal magnetic chrons to 4.7 Ma are C3n.2n and C3n.3n. Because the Amealco II should be younger than the age of the Amealco I, it is reasonable to assume it to have an age between 4.7 and 4.4 Ma, if the 0.3 m.y. uncertainty is considered. Thus, the normal polarity will correspond to the polarity chron C3n.2n, which has a range of 4.37 to 4.55 Ma (Baksi, 1993), well within the analytical age uncertainty.

The Amealco III was sampled for paleomagnetism and K-Ar dating at a locality 10 km to the north of Amealco, along Highway 120. The sample, a plagioclase separate, yielded an age of 4.55 ± 0.40 Ma (sample Am-12, Table 1) and a normal polarity. This age corresponds to a reverse polarity (Fig. 5).

However, the uncertainty of ± 0.4 m.y. of this age allows it to be placed in the closest normal polarity chron, C3n.2n, as was the Amealco II.

The change in polarity between the Amealco I and Amealco II ignimbrites (from reverse to normal), and the K-Ar ages of them, implies that the Amealco II ignimbrite was emplaced about 200 k.y. after the Amealco I. This quiescence in the Amealco caldera is evident in the field in the form of an erosional unconformity between the Amealco I and Amealco II in the Epitacio Huerta section. The Amealco II and Amealco III are also separated by an unconformity (soil and lake deposits), thus implying that there was another quiescence after the Amealco II ignimbrite was emplaced, although there is no polarity change in this case.

The Amealco and Huichapan tuffs were erupted at considerably different times; the Amealco tuff at about 4.68 ± 10 Ma (weighted mean of five K-Ar ages), and the Huichapan tuff at about 3.52 ± 0.16 Ma (Table 1). In the field this is marked by an ~1-m-thick paleosoil horizon between the last explosive products of the Amealco caldera (Brick Pumice) and the base of the Huichapan tuff (see Aguirre-Díaz and McDowell, this volume). The paleomagnetic data from the Huichapan tuff indicates reverse polarity, which corresponds to the upper age limit of the reverse chron between normal chrons C2An.2n and C2An.n, with a range from 3.27 to 3.38 Ma (Baksi, 1993); thus, the upper limit of the reverse chron is within the analytical uncertainty of the age (3.4 Ma) coinciding with the start of the chron.

There are two widespread stratigraphic markers for the central sector of the Mexican Volcanic Belt, the Amealco tuff ignimbrites and the Huichapan tuff ignimbrite. Both are distinct, and have clear megascopic features to recognize either one in the field. The combined areal extent of these ignimbrites exceeds 5000 km² (at least 2880 km² of Amealco tuff, and at least 2300 km² of Huichapan tuff; Aguirre-Díaz, 1993). Once one of these ignimbrites in the field is identified, and in case of doubt, once its paleomagnetic polarity is determined, one will now be certain where in the stratigraphic column one is standing.

CONCLUSIONS

1. We concentrate on two sections corresponding to the northern and southern walls of the Acambay graben, Amealco caldera, and Tlalpujahua sections. The southern section includes metasedimentary rocks that could be Cretaceous (equivalent to the Trancas Formation), Miocene intermediate lava flows, 4.7 Ma Las Américas Formation (Amealco tuff), and a Pliocene-Quaternary volcanic succession with intercalated Quaternary lake deposits. The units exposed in the northern section include only volcanic units: undated, older than 4.7 Ma volcanic rocks, at the base of the sequence correspond mainly to the La Loma Andesite. The dated sequence ranges from 4.7 to 2.2 Ma, including widespread Amealco and Huichapan ignimbrites, and intermediate lava domes and flows from the Amealco caldera.

2. The southern section has 4.7 Ma Las Américas Formation ignimbrite series. This series is correlated with the Amealco Tuff of the northern section. This is the only map unit widespread enough to be exposed on either side of the Acambay graben, implying that the Amealco tuff should extend beneath the graben; it does not crop out within the graben because it is buried by lake deposits and younger volcanic rocks.

3. The K-Ar and paleomagnetic data are consistent within analytical uncertainties. The Amealco tuff sequence includes three major ignimbrites. The oldest ignimbrite, Amealco I, has a reverse polarity and a K-Ar age of 4.7 Ma; the Amealco II has a normal polarity and a K-Ar age of about 4.7 Ma; and the Amealco III has a normal polarity and a K-Ar age of about 4.6 Ma. The ignimbrite of the Huichapan tuff has a reverse polarity and a K-Ar age of 3.5 Ma.

4. The Amealco tuff ignimbrites and Huichapan tuff ignimbrite are here defined as stratigraphic markers of the central sector of the Mexican Volcanic Belt.

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