Space-time patterns of Cenozoic arc volcanism in central Mexico: From the Sierra Madre Occidental to the Mexican Volcanic Belt

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ABSTRACT

A histogram of 778 isotopic ages of magmatic rocks younger than Eocene in central Mexico shows a multimodal distribution with peaks at about 30 Ma, 23 Ma, 10 Ma, and 5 Ma. The sample suite displays systematic spatial variations with age that likely reflect the protracted transition from the north-northwest–trending arc of the Sierra Madre Occidental to the east-west–trending Mexican Volcanic Belt. The reorientation of the arc is accompanied by a change in the dominant composition of the products from silicic ignimbrites and rhyolites to andesitic and basaltic lavas. The observed transition is related to the Miocene reorganization of the subduction system following the cessation of subduction off Baja California and the eastward motion of the Caribbean–Farallon–North America triple junction along the southeastern margin of Mexico. Our data support an early–middle Miocene age for the initiation of subhorizontal subduction in southern Mexico and confirm that the locus of arc volcanism was primarily controlled by the geometry of plate boundaries and the thermal structure of the subducting slab.

INTRODUCTION

Cenozoic subduction-related volcanism covers a large part of western and central Mexico and has been referred to as two major arcs: the north-northwest–trending Sierra Madre Occidental volcanic province and the roughly east-west–trending Mexican Volcanic Belt. The two volcanic belts overlap between the Pacific coast and the longitude of Mexico City (Fig. 1). The limit in space and time between these volcanic provinces has never been agreed upon, partly because there has never been a comprehensive presentation of the geographic evolution of the magmatic activity over the entire region. A view of the locus of volcanism through time in central Mexico is also useful to constrain models of the kinematic evolution of the subducting slab deduced from the tomographic images of the upper mantle (e.g., van der Lee and Nolet, 1997). A complete description of the geographic pattern of volcanism awaits a systematic geologic mapping, which is still to be undertaken in several areas of Mexico. Nevertheless, isotopic age determinations, which have nearly doubled in the past decade, can provide a first definition of the Neogene evolution of arc volcanism in central Mexico. In this work, we use the most updated compilation of isotopic ages for central Mexico to analyze the variation in time and space of the continental volcanism in relation with the evolution of the subduction system and to solve the long-debated problem of the age of the waning of the Sierra Madre Occidental volcanism and the inception of the Mexican Volcanic Belt.

CENTRAL MEXICO GEOCHRONOLOGIC DATABASE

We have compiled isotopic ages of subduction-related magmatic rocks ranging from the Oligocene to the present in the region between lat N16° and N24° and long W106° and W95°. Ages of subduction-related volcanic rocks ranging from 30 to 12 Ma in southern Baja California were also included, as this part of the Peninsula was within those coordinates during this time span. The database is an update of that used by Ferrari et al. (1994a), and includes information about location, rock type, method of dating, material dated, and source of the reported age. All dates are calculated or recalculated using the International Union for Geoscience conventional decay constants (Steiger and Jäger, 1977). New unpublished dates obtained during an ongoing project for the first geologic map of the entire Mexican Volcanic Belt are also used. The database currently contains 825 entries; ~15% of them are unpublished. These data are available through the GSA data repository[1].

As any compilation of this type, one may be concerned that data could be biased by oversampling of a particular unit or by low-quality data. Duplicate sampling of a specific unit occurred only in a few cases, in which we have used only the age obtained by the most reliable method (Ar/Ar rather than K/Ar) or published more recently. In addition, to eliminate low-quality data, entries with 2σ error in excess of 15% of the age were discarded, unless the error was less than 1 m.y. Based on this criteria, a subset of 784 dates was left for analysis.

To analyze the space-time variation of the volcanism, the data were plotted in a frequency histogram (Fig. 2) and in geographic maps. The frequency distribution of our data shows peaks with high age at about 30 Ma, 23 Ma, 10 Ma, and 4 Ma (Fig. 2), which, in agreement with other authors (e.g., Kennett et al., 1977), we consider to reflect the intensity of magmatic activity in a region where volumetric estimations are missing (see also below for discussion). To analyze the spatial evolution of magmatism, several geographic maps were produced using different time intervals. On the basis of magmatic minima and/or changes in a geographic pattern we found that the five periods of time shown in Figure 3 were the most significant for the purpose of this paper. The main features emerging from the present database are similar to those seen by Ferrari et al. (1994a) with only 60% of the present data, which confirms that our dataset is sufficiently representative of the Neogene volcanism of central Mexico.

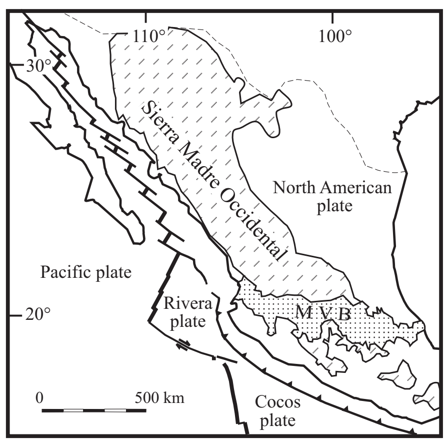

Figure 1. Geodynamic setting of Mexico showing main Cenozoic volcanic provinces. MVB—Mexican Volcanic Belt.

[1]Data Repository item 9928, Compilation of ages of rocks in Central Mexico, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

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Data Repository item 9928 contains additional material related to this article.

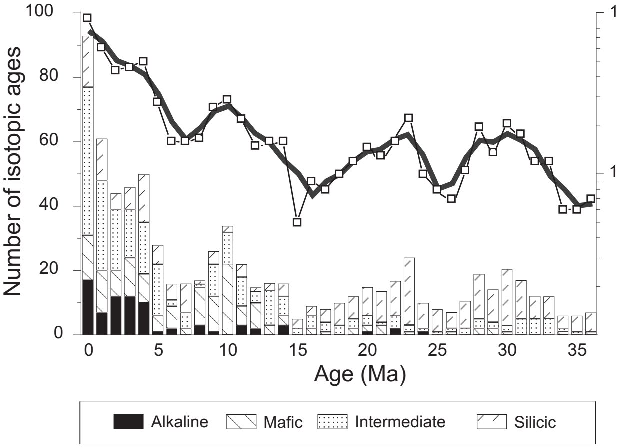

Figure 2. Frequency distribution (right side scale) and log-normal plot (left side scale) of data per 1 m.y. interval. Multimodal distribution suggests that volcanism occurs in pulses (see text for discussion). Smoothing (bold line) was obtained by averaging two adjacent values.

EVOLVING GEOGRAPHIC PATTERNS OF OLIGOCENE TO PRESENT MAGMATISM IN CENTRAL MEXICO

The first snapshot, between 38 and 25 Ma, was chosen because it encompasses the major episode of ignimbritic volcanism in the Sierra Madre Occidental, the so-called ignimbrite flare-up (McDowell and Clabaugh, 1979). Recent works demonstrated that silicic to intermediate volcanism with these ages is also widespread south of the Mexican Volcanic Belt (e.g., in Pasquarè et al., 1991; Alba-Aldarve et al., 1996; Morán Zenteno et al., 1999). Rocks of these ages appear distributed in an ~300-km-wide and N150°-trending arc, which extends continuously from Zacatecas and San Luis Potosí to eastern Michoacán, Guerrero, and western Oaxaca, where it is now truncated by the present trench (Fig. 3a). The apparent exceptional width of the volcanic arc during this period is probably due to the abundant ages of ignimbrites, which can travel as much as 100 km from the source.

By the early Miocene (Fig. 3b), the arc had rotated counterclockwise by ~30° and has approached the paleo-trench off Baja California. Voluminous silicic ignimbrites of these age are exposed in southern Baja California (Hausback, 1984), Nayarit-northern Jalisco (Scheubel et al., 1988; Moore et al., 1994; Nieto-Samaniego et al., 1999), and Guanajuato (Cerca-Martínez, 1998). Less-differentiated rocks are also present in northern Michoacán in the Morelia and Zitacuaro areas (Pasquarè et al., 1991; Capra et al., 1997). East of long W98°30′ and between lat 18°30′ and 17°, the volcanism almost ceased but persisted in northwestern Oaxaca (Ferrusquía-Villafranca et al., 1988).

In the middle Miocene (17–12 Ma), the arc extended eastward and reached the coast of the modern Gulf of Mexico (Fig. 3c). This “discontinuous” arc included a north-west–trending segment located on the southern margins of the Gulf of California (Gastil et al., 1979; Hausback, 1984), an east-southeast–trending segment mainly represented by andesitic successions between northern Michoacán and Mexico city area (e.g., Pasquarè et al., 1991), and a roughly east-west–trending segment in Puebla and Veracruz (López-Infanzon, 1990). A last and isolated locus of volcanism is also observed in eastern Oaxaca (Ferrusquía-Villafranca, 1996) as a remnant of the previous configuration.

By the late Miocene, the arc had reached a stable orientation (Fig. 3d) with a west-northwest–east-southeast trend west of lat W102° and a roughly east-west orientation in the remaining part. The dominant products were basaltic lavas emplaced from the Pacific coast to the longitude of Mexico City in the form of extensive plateaus (Ferrari et al., 1994b [and references therein]). Andesitic complexes are also present in southern Queretaro (Carrasco-Núñez et al., 1989; Perez-Venzor et al., 1997) and more to the east, in northern Puebla (Carrasco-Núñez et al., 1997).

Since 7 Ma, the arc has remained in its orientation, but the volcanic front migrated toward the trench. This is especially evident in the western Mexican Volcanic Belt, where the volcanic front was at 180 km from the trench in the late Miocene and is now at only 110 km. The dominant volcanic products are andesites. However, a widespread episode of silicic volcanism is observed between 7 and 3.5 Ma either in the western (Gilbert et al., 1985; Rossotti et al., 1997) or in the central part of the Mexican Volcanic Belt (Aguirre-Díaz, 1997).

LIMIT BETWEEN THE SIERRA MADRE OCCIDENTAL AND THE MEXICAN VOLCANIC BELT

In the past, no agreement has been reached about the onset of Mexican Volcanic Belt activity, which has been suggested to be Quaternary (Demant, 1978), late Pliocene (Cantagrel and Robin, 1979), early Pliocene (Nixon et al., 1987), or late Oligocene (Mooser, 1972). In a certain way this may be a semantic problem. Like plate boundaries, volcanic arcs are moving objects on the earth surface, and any spatial definition of a given arc may be viewed as a snapshot in a continuously changing scenario.

However, the Sierra Madre Occidental and the Mexican Volcanic Belt have at least two characteristic features: the broad orientation of the arc and the dominant composition of the rocks. Figure 3 shows that the volcanic arc had almost the orientation of the modern Mexican Volcanic Belt already since middle Miocene times. The variation in the dominant composition of dated rocks is shown in Figure 4, where a threshold was chosen at 63% of SiO_2, corresponding to the lower limit of rhyolitic composition. The figure illustrates clearly that the dominant composition of dated rocks changed rapidly from silicic to intermediate-mafic during the middle Miocene, with a turning point at about 15 Ma.

We believe that the observed variations of spatial distribution and composition of volcanism allow a conclusive assessment of the temporal definition of the two arcs. Although no volcanic lull can be observed at the continental scale of our study area, it can be seen that the transition from the Sierra Madre Occidental to the Mexican Volcanic Belt occurred in early to middle Miocene times, and that an arc with the characteristics of the Mexican Volcanic Belt already existed by the late Miocene, as proposed by Ferrari et al. (1994a).

RELATION TO THE EVOLUTION OF THE SUBDUCTION SYSTEM

When compared with the geographic evolution of volcanism in western North America, the Mexican case seems relatively simple. The data indicate a progressive reorientation of the volcanic arc that can be related to the change in the thermal structure of the subducting slab and to changes in the plate boundary geometry. North of lat N22°, volcanism terminated ca. 17 Ma, about 5 m.y. earlier than the end of Farallon subduction off Baja California (Lonsdale, 1991). At that time, the slab subducting at the trench was less than 5 Ma (Lonsdale, 1991). As pointed out by Severinghaus and Atwater (1989), very young and hot oceanic crust in the subduction zone releases fluids before arriving in contact with the mantle wedge, thus inhibiting partial melting and arc volcanism.

The reorientation of the central and eastern part of the arc during early and middle Miocene time appears related to the change in the geometry of the North America–Farallon–Caribbean plate boundaries. Morán-Zenteno et al. (1996) demonstrated that the eastward motion of the Chortis block (Caribbean plate) during the Neogene progressively modified the subducting boundary between the North America and Farallon plates, forming a new trench in an inland position. On the other hand, Pardo and Suarez (1995) related the oblique orientation of the Quaternary Mexican Volcanic Belt with respect to the trench with an along-trench variation in the slab dip, observing that the Cocos plate has a very shallow dip beneath the central and eastern part of the volcanic arc. The initiation of subhorizontal subduction in central Mexico is unknown. However, the

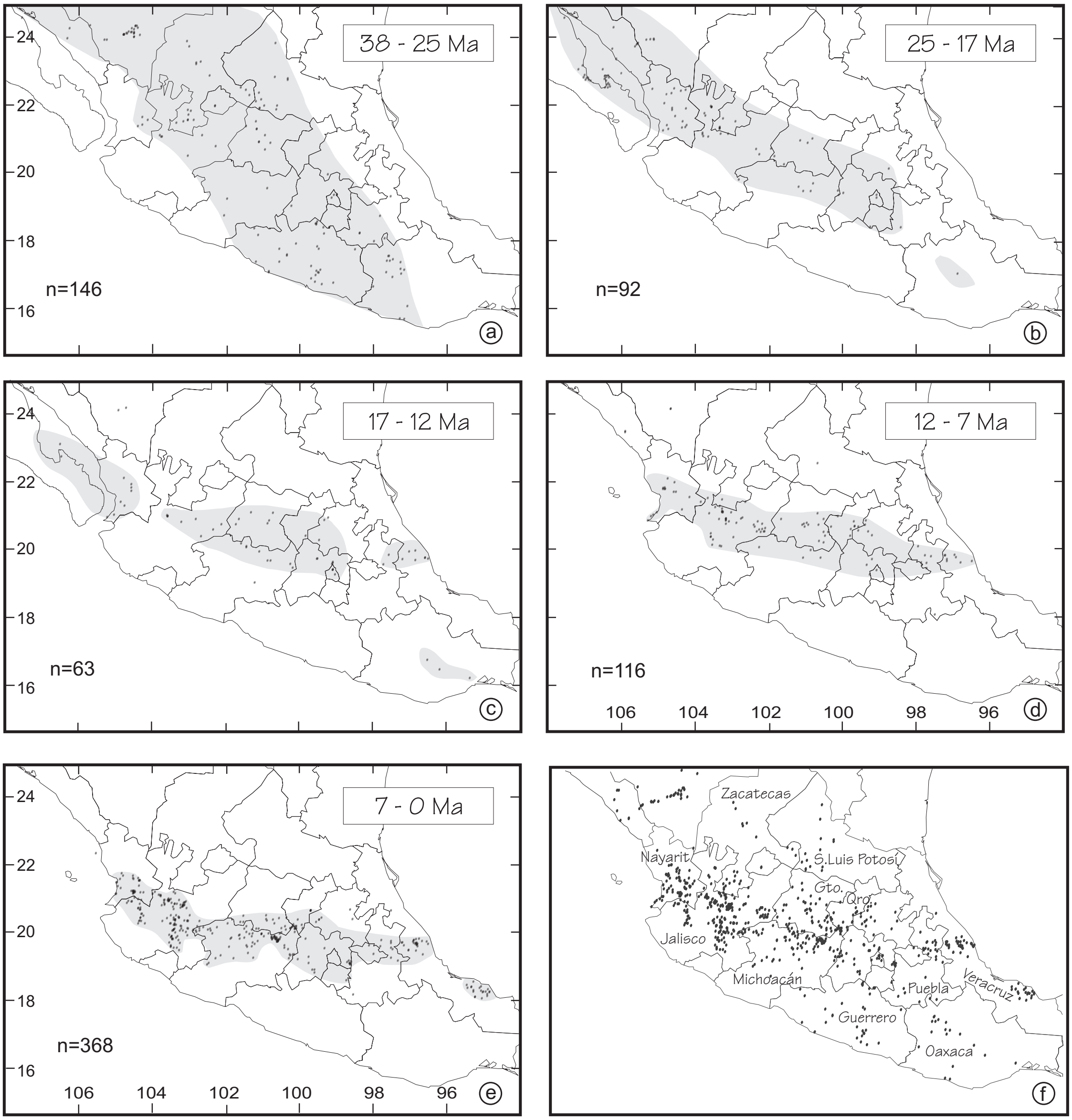

Figure 3. Geographic distribution of dated rocks in central Mexico since 38 Ma. Universe transverse mercator projection. Gray pattern depicts probable extent of volcanic arc based on envelope of known outcrops. Part f shows location of entire data set and names of Mexican states mentioned in text. Gto.—Guanajuato, Qro.—Queretaro.

data presented here show an abrupt cessation of volcanism south of lat 18° and a landward jump of the volcanic front during the early Miocene (Fig. 3b); they also show a volcanic front close to the present position by the middle Miocene (Fig. 3c). Based on these observations, we propose that the shallowing of the subducting slab occurred during early to middle Miocene.

IS VOLCANISM REALLY EPISODIC?

Although we lack systematic volumetric estimations of volcanic rocks per time interval, several observations indicate that most of the peaks of isotopic ages shown on Figure 2 reflect real pulses of intense volcanic activity. First of all, the geographic coverage of the database (Fig. 3f) is very good, at least for the central part of the study area. Other geologic observations can support the episodicity of volcanism. A pulse at ca. 30 Ma is well known in the Sierra Madre Occidental to the north of the study area (McDowell and Clabaugh, 1979), and has been recently documented that most of the silicic volcanism in Guanajuato, San Luis Potosí, and Zacatecas also occurred between 31 and 28 Ma (Nieto-Samaniego et al., 1999). The second peak at ca. 23 Ma is corroborated by over 1000 m of silicic ignimbrite with this age found in southern Durango (El Salto sequence, McDowell and Keizer, 1977), northern Jalisco (Bolaños area, Scheubel et al., 1988), and northeastern Nayarit (Ferrari, unpublished data), which account for about 80% of the volcanism in these areas. In the Mexican Volcanic Belt, a late Miocene mafic pulse is substantiated by 10.5 to 9 Ma basaltic successions, over 800 m thick in places, which cover ≈3500 km^3 in Nayarit and Jalisco (Ferrari et al., 1997) and for which we estimate a volume 2 to 3 times larger than the volcanic rocks emplaced from 8 to 5 Ma. A volcanic pulse in the last 5 m.y. is more difficult to evaluate because the database is clearly biased by the large number of dates obtained for

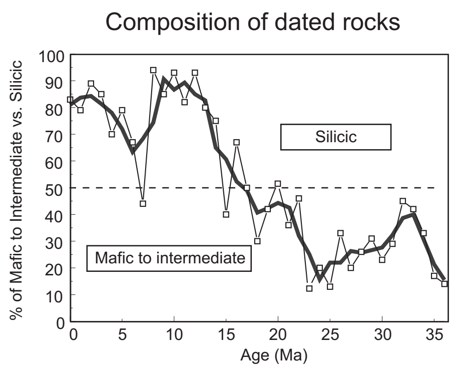

Figure 4. Variation of composition of dated rocks, expressed as percentage of rocks having mafic to intermediate versus silicic composition per 1 m.y. intervals. Mafic to intermediate—basaltic to dacite, silicic—rhyolite (SiO_2 > 63%). Note rapid change from silicic to intermediate-mafic varieties during middle Miocene. Smoothing (bold line) obtained by averaging two adjacent values. Same data subset as in Figures 2 and 3.

recent and active volcanoes. One argument favoring the existence of a pulse in the Quaternary is that a single large stratovolcano of the Mexican Volcanic Belt has a volume of one order of magnitude greater than the entire Michoacán-Guanajuato volcanic field (Hasenaka and Carmichael, 1985), and that all the large stratovolcanoes in the Mexican Volcanic Belt are less than 1.6 Ma. We believe that the above examples are a strong suggestion that volcanism occurred in pulses over the entire central Mexico. More systematic estimates of volcanic rates and a careful comparison with the plate tectonic evolution may lead to a better understanding of the reasons governing this volcanic episodicity.

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