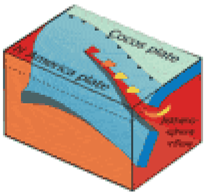

The Geochemical Puzzle of the Trans-Mexican Volcanic Belt: Mantle Plume, Continental Rifting, or Mantle Perturbation Induced by Subduction?

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Introduction

The Trans-Mexican Volcanic Belt (TMVB) is the Neogene volcanic arc built on the southern edge of the North American plate (*Ferrari et al.*, 1999) (Figure 1). TMVB volcanism presents a wide range of chemical compositions. The geochemical signature of fluids from the subducting plate varies strongly and lavas with a slab melting fingerprint have been reported from several locations. Small amounts of lavas with an intraplate (or OIB) signature are found side by side with those with a subduction signature and with similar ages. In addition, seismicity associated with the subducting Cocos plate is abundant in the forearc region but ends rather abruptly just to the south of the TMVB at around 100 km depth (Figure 1) where the upper mantle has a relatively low density and high temperature. The geochemical diversity and absence of seismicity beneath the TMVB prompted several workers to develop genetic models at variance with a classic subduction scenario.

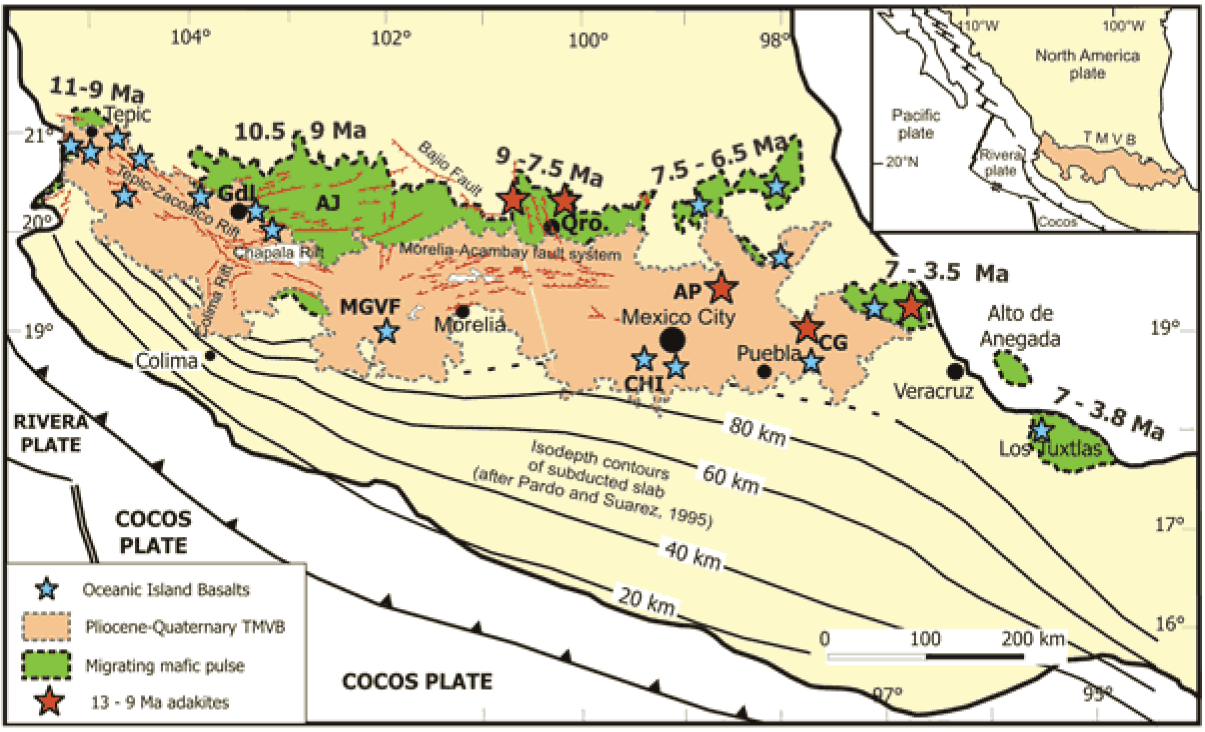

Figure 1. Simplified geologic map of Neogene volcanism and faults in central Mexico (modified after Ferrari, 2004). Note the eastward migrating pulse of mafic volcanism to the north of the Plio-Quaternary TMVB and its possible continuation to the southeast along the gulf of Mexico. GDL=Guadalajara; AJ=Altos de Jalisco; QRO=Queretaro; CIII=Sierra Chichinautzin; AP=Apan volcanic field; CG=Cerro Grande volcanic complex; MGVF=Michoacan-Guanajuato volcanic field. Click on image to enlarge.

The plume model

Moore et al. (1994) first suggested the presence of a mantle plume beneath Guadalajara. This model was later expanded by *Marquez et al.* (1999), who proposed that the entire TMVB is related to a mantle plume that impacted western Mexico in the late Miocene. In the model of *Marquez et al.* (1999) the plume first broke the subducting plate but the plate will eventually take revenge by cutting off the plume head (Figure 2).

Both models were based mostly on geochemistry and are inconsistent with the geology and tectonics of the TMVB. In their comment to the paper of *Marquez et al.* (1999) *Ferrari & Rosas* (1999) showed that:

1. neither the rifting nor the OIBs present the age progression required by the plume model;
2. in western Mexico, where the plume should have impacted, there is no evidence of regional uplift;
3. the volume of OIB lava in the TMVB is only a fraction that of the subduction-related volcanism and much lower than typical continental flood basalts.

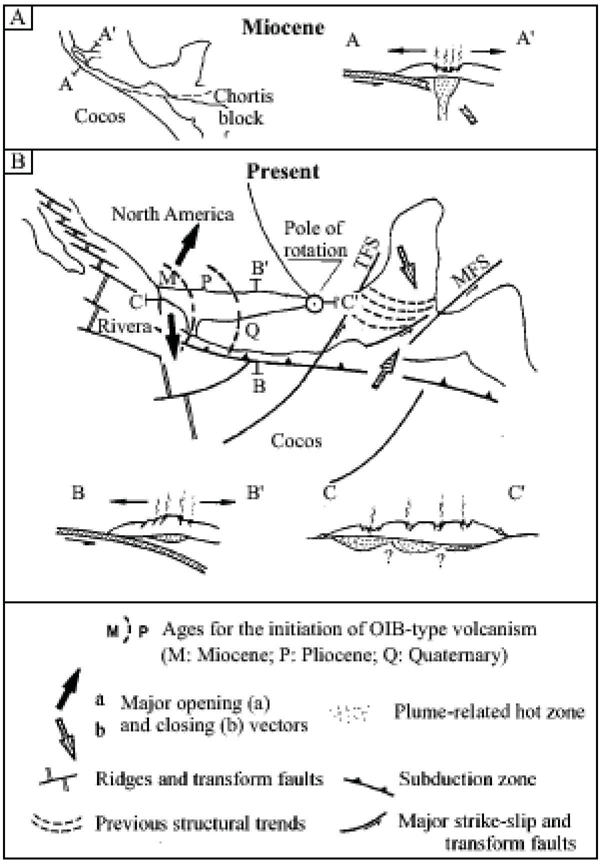

Figure 2. The plume model for the TMVB as originally proposed by Marquez et al. (1999). Original caption reads: Proposed tectonic model for evolution of Mexican volcanic belt. A: Disruption and foundering of subducted slab at subduction zone, rising of plume beneath western Mexico, and development of graben triple junction during Miocene. B: Propagating rift (see vectors), volcanism, and position of currently unrooted upper plume under Mexican volcanic belt. OIB – oceanic-island basalt, TFS – Tehuantepec fault system, MFS – Motagua fault system.

An additional problem is posed by the fact that nowhere else in world is a plume (supposing that they exist) claimed to have punched through a subducting plate and, even worse, in this model a plate is considered capable of cutting off the plume head. Proposed plumes have usually been sited away from subduction zones because these are regions of cold downwelling.

Shortly after these papers, the plume model for the TMVB was criticized by *Sheth et al.* (2000). Since that paper no-one has argued in favour of a TMVB plume, which thus died, decapitated, after a very brief life.

The "subduction-phobic" model

Provocatively, some workers have recently argued against any role for subduction in the genesis of the TMVB and proposed that continental rifting above a heterogeneous mantle may be the cause of its formation (*Sheth et al.*, 2000; *Verma*, 2002 and reference therein). Again, the rejection of subduction influence in the genesis of the TMVB has been essentially based on petrologic and geochemical-statistical grounds, aided by a simple interpretation of the lack of seismicity beneath the arc. However, the mechanism by which the mantle is melted to produce TMVB volcanism was never clearly described. *Sheth et al.* (2000, p. 1127) comment only that "*under the present extensional conditions the [mantle] enriched sources have undergone melting*" whereas *Verma* (2002, p. 1098) mentions "*partial melting of an upwelling heterogeneous mantle source ... facilitated by ongoing rifting process*".

These generic statements, that seem to suggest extensional tectonics as the cause for TMVB magmatism, are contradicted by the geology of the arc.

In reality, Plio-Quaternary extensional faulting is missing in about 70% of the region where rifting is predicted to occur by *Verma* (2002), i.e. east of longitude W102° (see Figure 1). Extensional faulting is < 5 Ma west of Mexico City (*Ferrari & Rosas-Elguera*, 2000; *Suter et al.*, 2001) but much older to the east. A large extensional basin is buried beneath Mexico City and Puebla but almost all the faulting is older than middle Miocene (*Ferrari et al.*, 2003). It is therefore unrelated to the TMVB. Paradoxically Nicaragua, predicted to have the strongest slab signature (*Verma*, 2002) is characterized by a major transtensional system with prominent grabens (also known as the Central America graben). Even west of Mexico City, Quaternary extensional faults show a very low average strain rate of less than 0.1 mm/yr (*Ferrari & Rosas-Elguera*, 2000; *Suter et al.*, 2001). This is several order of magnitudes lower than typical continental rifts.

In addition, several studies provide strong evidence for the presence of fluids from the subducting plate beneath the TMVB volcanic front. In the central TMVB *Blatter & Carmichael* (1998) found mantle xenoliths with hydrous minerals and high O fugacity, indicating metasomatism by slab fluids in this part of the sub-arc mantle. More recently, *Cervantes & Wallace* (2003) analyzed major and trace elements in melt inclusions in several cinder cones of the Sierra Chichinautzin (Figure 1) and found that the lavas with the highest water contents also have the highest LILE and LREE concentrations. These are strong indications that subduction fluids impart their signature to the mantle beneath the TMVB.

Geologic history of the TMVB and mantle evolution in central Mexico

The establishment of a consistent tectonic and petrogenetic model for the TMVB requires careful geologic study of the whole arc. In the past 6 years I have led a project aimed at developing the first digital geologic information system of the whole TMVB (visit GSA Data Repository). The Geographic Information System (GIS) of the TMVB, which incorporates over 1,000 ages and 2,700 geochemical data, is now complete. The data show that the TMVB is a composite arc made by the superposition of 4 episodes that correlate with slab loss and changes in slab geometry and subduction rate. Below, I summarize the geologic evolution of the TMVB and discuss the implications for the mantle and related petrogenesis.

1. The initial TMVB consisted of a broad arc of andesitic to dacitic polygenetic volcanoes that extends from western Michoacán (longitude 102°) to the Palma Sola area (longitude 96°30') and formed between 17 and 10 Ma. During this period volcanism migrated far from the trench toward the NE. The youngest (12-10 Ma), and most inland centers (Palma Sola, Cerro Grande, Apan area, Zamorano, Palo Huerfano), form a WNW-ESE belt with an adakitic signature (*Gomez-Tuena et al.*, 2003). The progressively more inland position of the arc and the slab melt signature of the youngest products within this period suggest that the dip of the subducting slab changed from moderate to flat. As a consequence part of the mantle lithosphere beneath the TMVB may have been removed at this time.

2. From 11 to 5 Ma an eastward-migrating pulse of mafic volcanism occurred across the whole of central Mexico (*Ferrari et al.*, 2000; *Orozco-Esquivel et al.*, 2003). This episode is thought to indicate the lateral propagation of a slab detachment episode, as hot sub-slab material flowing into the slab gap produced a transient thermal anomaly in the mantle wedge (*Ferrari*, 2004) (Figure 3). Slab detachment of the deeper and denser part of the plate was initiated in the southern Gulf of California area by the influx of progressively younger oceanic lithosphere at the paleotrench that produced an increasing coupling between the Magdalena microplate and the overriding North American plate. The tear in the slab

propagated eastward from the Gulf of California to the Gulf of Mexico, parallel to the southern Mexico trench system, and it may have continued to the SSE up to Guatemala.

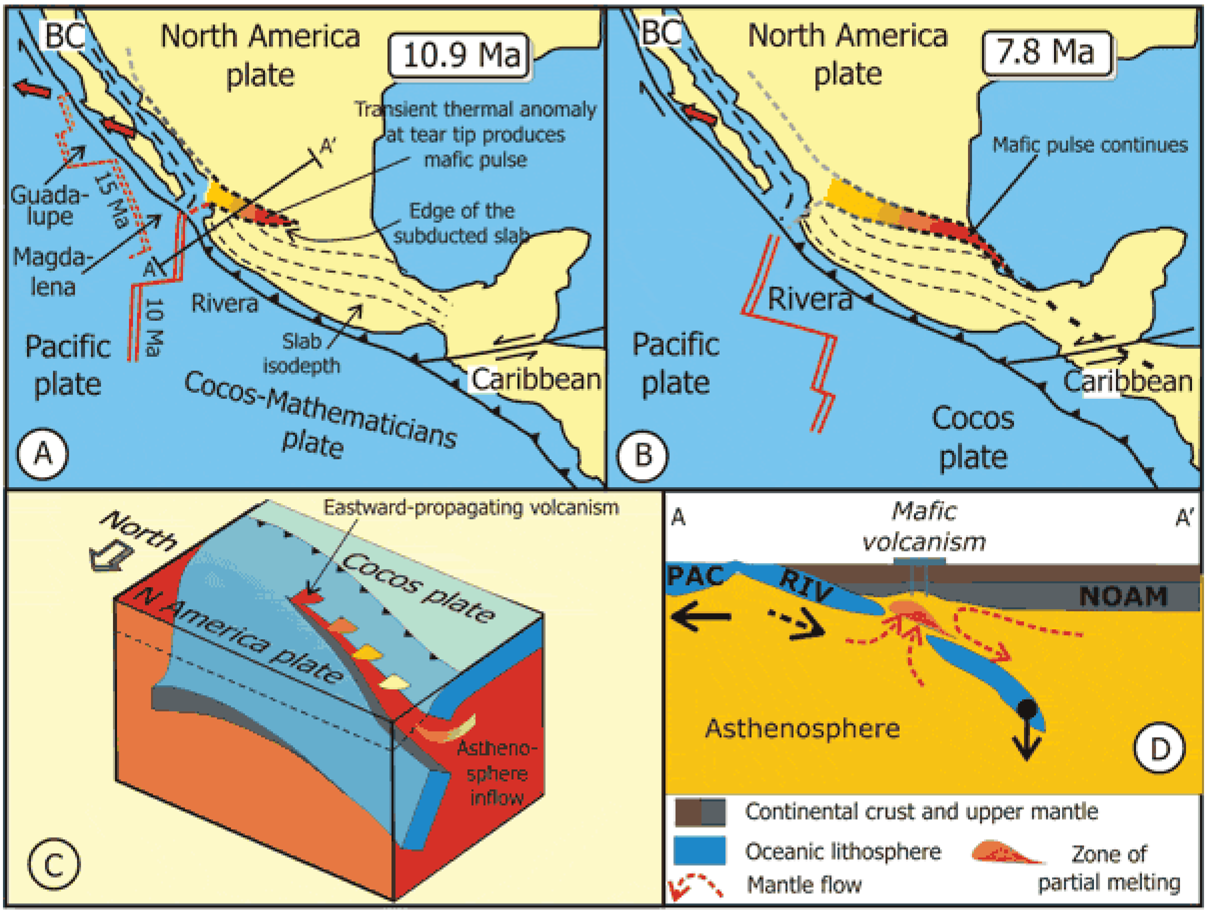

Figure 3. A and B: Late Miocene tectonic setting of the Mexican subduction zone at 10.9 and 7.8 Ma with proposed location of slab detachment. Line AA' in A indicates location of cross section in D. C: Three-dimensional block diagram showing proposed lateral propagation of detachment and resulting migrating volcanism induced by upwelling, hot, sub-slab asthenosphere (modified after Worrel & Spakman, 2000). D: Schematic cross section of detachment mechanism and consequences in western Mexico. Mafic volcanism on North American plate (NOAM) resulted from thermal melting of mantle wedge previously modified by subduction. RIV=Rivera plate; PAC=Pacific plate. After Ferrari (2004).

3. Large calderas and silicic dome complexes developed from 7.5 to 3.5 Ma between Tepic and Mexico City and at the eastern border of the altiplano (Hidalgo State). Volcanism in the age range ~9 to 3.5 Ma is absent in the region between Mexico City and Pico de Orizaba. Mafic lavas with OIB affinity were emplaced shortly after the silicic pulse together with calcalkaline lavas. This episode marks the reorganization of subduction after detachment. Silicic volcanism in the western TMVB reflects the decline in subduction rate following the decrease in slab pull after the detachment of the deep slab. On the other hand, the loss of the flat slab may have exposed an already thinned mantle lithosphere to higher temperature mantle, thus causing it to partially melt. The volcanic gap occurs where the crust is thicker and may indicate that there the subducted slab was still flat and in contact with the base of the crust.

4. The modern arc consists of a whole range of products emplaced from the Gulf of California to the Gulf of Mexico after 3.5 Ma. Many segments of the arc broaden to the south within the volcanic front but in some places volcanism remains active in the rear part. This episode indicates that the leading edge of the slab rolled back, re-creating a mantle wedge.

The geologic model described above of the evolution of the crust and mantle may explain the geophysical and geochemical characteristics of central Mexico and the TMVB. The absence of seismicity and the presence of low-density mantle beneath the arc are consistent with the detachment model that predicts the upwelling of hot, sub-slab material into the slab gap. Similarly the OIB-type lavas emplaced since 5 Ma are located above a trench-parallel slab window that formed between the inferred detachment trace (the 11-5 Ma mafic pulse) and the leading edge of the present slab as defined by seismicity (Figure 1). In this context, the occurrence of these unusual intra-plate magmas is easily explained by the infiltration of enriched asthenosphere in the sub-arc mantle. The hydrous volcanic front is located just above or immediately to the north of the end of the seismicity, whereas the slabs (and serpentinized mantle dragged along with the slab?) are expected to release most of the water produced by dehydration reactions. Finally, the region affected by intra-arc extension is in front of that part of the slab which increased in dip subsequent to the detachment event, suggesting that slab rollback may have a role in controlling extension.

Concluding remarks

Some of the elements included in my model I drew from previous work (referenced here), although an explanation consistent with the geodynamic evolution of the region has been lacking up until now. Specifically, the presence of a heterogeneous mantle beneath the TMVB was suggested long ago by the Berkeley group led by Ian Carmichael. The upwelling of an enriched mantle was proposed by *Marquez et al.* (1999) and *Verma* (2002), although they suggested that it had been generated by a plume and by lithospheric rifting, respectively. In my model the gross features of volcanism in the TMVB are controlled by the history and dynamics of plate convergence.

In my view, the failure of some geochemically-based tectonic models was caused by the lack of space-time control, i.e. by overlooking the geologic evolution of the TMVB. The bottom line is that geology needs to provide the framework for any geochemical study, and geophysical data are best interpreted by scientists with a strong geological background.

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