Slab detachment control on mafic volcanic pulse and mantle heterogeneity in central Mexico

Luca Ferrari* Centro de Geociencias, Universidad Nacional Autónoma de México, Campus Juriquilla, Queretaro 76230, Mexico

ABSTRACT

Seismic tomography studies and plate reconstructions suggest that the Farallon slab broke off shortly before subduction ended off southern Baja California. However, the progress of detachment in time and space and its consequences on the volcanism of central Mexico have not so far been considered. Here I use the Neogene geologic record of central Mexico to propose a lateral propagation of slab detachment beneath the Trans-Mexican volcanic belt during the late Miocene. I suggest that the trace of the detachment is expressed by a short (2–3 m.y.), eastward-migrating pulse of mafic volcanism that took place from ca. 11.5 to ca. 6 Ma to the north of the Pliocene–Quaternary volcanic arc, as hot, subslab material flowing into the slab gap produced a transitory thermal anomaly in the mantle wedge. Slab detachment of the deeper and denser part of the plate was initiated in the southern Gulf of California area by the incoming 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, paralleling the southern Mexico trench system. The decrease in the Rivera–North America convergence rate between ca. 9 and 7 Ma appears to be related to the loss of slab pull after the detachment. Sparse oceanic-island–type basalts emplaced since the end of the Miocene in the Trans-Mexican volcanic belt are located above a trench-parallel slab window between the inferred detachment trace and the leading edge of the present slab, which has been detected seismically. In this context, the occurrence of these unusual intraplate magmas is easily explained by the infiltration of enriched asthenosphere into the subarc mantle.

Keywords: slab detachment, volcanic pulse, Miocene, Trans-Mexican volcanic belt, oceanic-island basalts.

INTRODUCTION

Detachment of the lower part of a subducted slab has been increasingly recognized in many subduction systems worldwide. In the classic case of the Mediterranean area, detachment is caused by the arrival of buoyant continental lithosphere at some point in the subduction zone and by the initiation of collisional tectonics (Wortel and Spakman, 2000). Detachment in an ocean-continent subduction setting without intervening continental fragments has rarely been described. However, regional seismic tomography studies of western North America imaged upper-mantle high-velocity anomalies unconnected to those related to the still-subducting slab, implying that detachment must have occurred in the late Tertiary. Several plate reconstructions also suggested that the Farallon slab broke off when the East Pacific Rise arrived near the trench off Baja California (Dickinson, 1997; Atwater and Stock, 1998; Borgois and Michaud, 2002), but the only consequence considered in these papers was the formation of a slab window or a slab gap in front of the inactive trench. The migration of the detachment in time and space and its consequences on the volcanism east of the Gulf of California were not contemplated. In this paper I propose that after the detachment began in the Gulf of California area, the tear in the slab propagated laterally parallel to the southern Mexico trench system, where subduction was still active. I argue that this process should have produced a transitory thermal anomaly along the propagating tear and a major pulse of volcanism in the upper plate. The latter is a prominent feature in the late Miocene volcanic record of central Mexico and thus allows the location of the detachment in time and space to be inferred. The occurrence of lavas with an intraplate affinity in the Trans-Mexican volcanic belt is also easily explained once slab detachment is taken into account.

DETACHED SLAB BENEATH CENTRAL MEXICO

Evidence for a detached slab beneath central Mexico comes primarily from seismology. Seismicity associated with the subducting Cocos plate is abundant in the forearc region but ends abruptly just to the south of the Trans-Mexican volcanic belt at ~100 km depth (Fig. 1) (Pardo and Suarez, 1995), where the upper mantle shows a relatively low density and high temperatures (Goes and van der Lee, 2002). Seismic tomography studies, however, identify slab-like material at greater depth in the upper mantle. The S-wave traveltime tomography of Van der Lee and Nolet (1997) shows two subparallel slab anomalies 300–600 km beneath northern and central Mexico. The P-wave tomography of Van der Hilst and Karason for the Central America region (Rogers et al., 2002) clearly shows a gap in the Cocos slab beneath northern Central America and southeastern Mexico. Rogers et al. (2002) also provided several pieces of geologic evidence for the occurrence of slab detachment beneath Guatemala some time between 9 and 3.5 Ma.

CAUSE OF SLAB DETACHMENT

The slab pull of a subducting plate is basically related to the density contrast between the bulk density of the oceanic lithosphere and the underlying asthenospheric mantle. The bulk density of oceanic lithosphere is a function of its age, and a normal, 10-m.y.-old oceanic lithosphere has the same density as that of the asthenosphere (Cloos, 1993). A plate younger than 10 Ma would be therefore increasingly difficult to subduct and the pull exerted on it by its deeper and denser part may lead to a stretching of the plate. The Tertiary history of subduction of the Farallon plate beneath North America indicates a progressive approach of the East Pacific Rise to the trench that led to increasing young oceanic lithosphere at the subduction zone (Atwater and Stock, 1998). Seafloor age and marine geology studies show that the ridge did not subduct along most of the paleotrench and that spreading and microplates subduction ended when the oceanic lithosphere reaching the trench was 1–3 m.y. old (Lonsdale, 1991). As the ridge approached the trench, increased coupling to the overriding North American plate caused the younger, upper part of the partially subducted microplate to detach from the older, colder, sinking slab. Once this occurred, the slab pull of the microplate was essentially removed, and both subduction beneath North America and spreading, relative to the Pacific plate, ceased.

SLAB DETACHMENT INITIATION AND PROPAGATION

The mechanism envisaged herein suggests that the slab detached some time before the end of subduction off Baja California. In southern Baja California the subduction of the Magdalena microplate ended ca.

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*E-mail: luca@geociencias.unam.mx.

Geology; January 2004; v. 32; no. 1; p. 77–80; DOI 10.1130/G19887.1; 3 figures; Data Repository item 2004012.

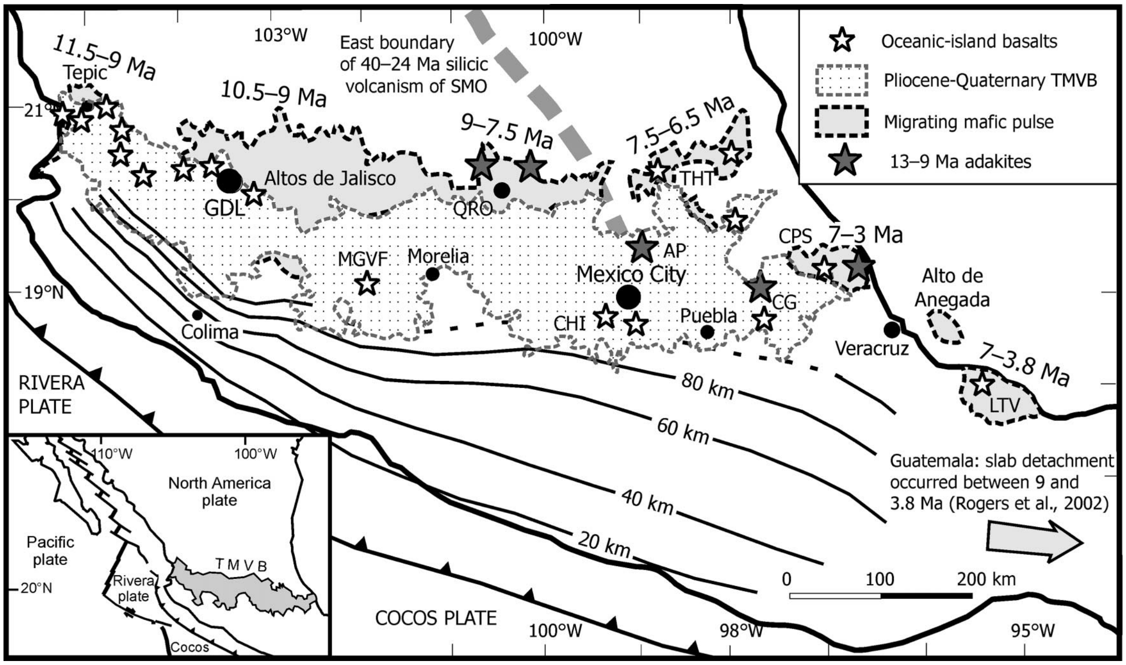

Figure 1. Geologic map and selected geochemical features of Neogene volcanism in central Mexico (simplified from Fig. DR1; see text footnote 1) with depth contours of subducting slabs in kilometers (from Pardo and Suarez, 1995). Note eastward-migrating pulse of mafic volcanism to north of Pliocene–Quaternary Trans-Mexican volcanic belt (TMVB) and its possible continuation southeastward along Gulf of Mexico. GDL—Guadalajara; SMO—Sierra Madre Occidental. QRO—Queretaro; MGVF—Michoacán-Guanajuato volcanic field; CHI—Sierra Chichinautzin; AP—Apan volcanic field; CG—Cerro Grande volcanic complex; THT—Tlanchinol-Huejutla-Tantima basaltic flows; CPS—Chiconquiaco–Palma Sola mafic plateau; LTV—Los Tuxtlas volcanic field. Inset shows location of TMVB and its present geodynamic setting

12.5 Ma (Fig. 2A) (Lonsdale, 1991). A seafloor anomaly on the Pacific plate at the latitude of the southernmost part of the Magdalena microplate indicates that the half-spreading rate decreased from ~43 mm/yr between 14.8 and 14.1 Ma to ~25 mm/yr from 14.1 to 12.9 Ma (measured from Plate 3C of Atwater and Severighaus, 1989). Thus it seems fair to consider that the initiation of detachment occurred within ~1 m.y. before the end of spreading and subduction. Several authors considered that the end of subduction produced a slab gap or slab window directly in front of the inactive trench (e.g., Dickinson, 1997; Borgois and Michaud, 2002). However, numerical models and case studies (Yoshioka and Wortel, 1995; Wortel and Spakman, 2000) have shown that, once a slab starts to detach, a tear will tend to propagate laterally, even along the zone where subduction is still active, because of the increased slab pull exerted on the still-attached part of the slab. I propose that detachment began beneath the present southern Gulf of California, because farther west the slab was in contact with the Baja California lithosphere. Location of a slab tear in this area was also proposed by Calmus et al. (2003), who suggested that the late Miocene

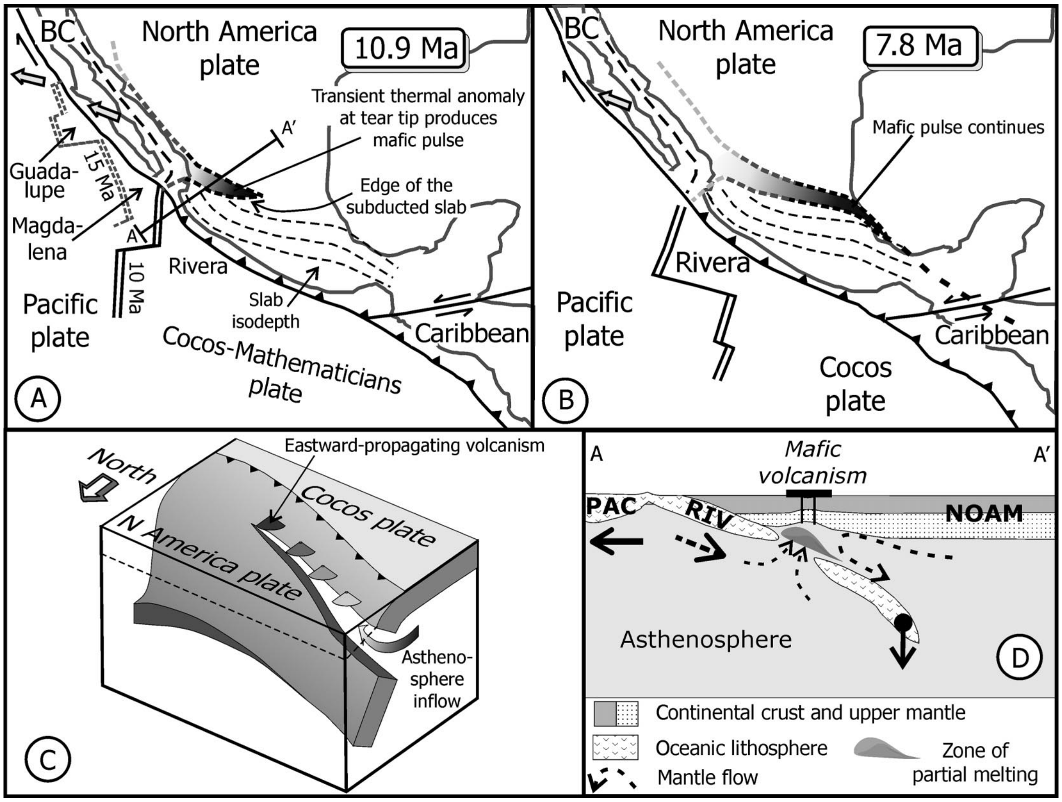

Figure 2. A and B: Late Miocene tectonic setting of Mexican subduction zone at 10.9 and 7.8 Ma with proposed location of slab detachment. Line A–A′ in A indicates location of cross section in D. C: Three-dimensional block diagram showing proposed lateral propagation of detachment and resulting migrating volcanism induced by upwelling, hot, subslab asthenosphere (modified after Wortel and Spakman, 2000). D: Schematic cross section of detachment mechanism and consequences in western Mexico. Mafic volcanism on North America plate (NOAM) resulted from thermal melting of mantle wedge previously modified by subduction. RIV—Rivera plate; PAC—Pacific plate; BC—Baja California.

magnesian andesites exposed in Baja California Sur were the result of a hotter thermal regime associated with the tear. Once initiated, the tear must have propagated to the east-southeast, parallel to the southern Mexico subduction system (Figs. 2A and 2B), possibly aided by the presence of an east-west–striking fracture zone in the subducted oceanic lithosphere. One way to test the lateral propagation of detachment is to look at the behavior of the subducting plate. The Rivera plate, which was already moving independently by 10 Ma, decreased its convergence rate with respect to the North America plate from ~50 mm/yr to ~12 mm/yr between 9 and 7 Ma (DeMets and Traylen, 2000). Slowdown in subduction velocity is likely to have occurred because of the loss of slab pull after the detachment. A more precise account of the propagation of the detachment in space and time, however, can be inferred from the geologic record of central Mexico.

TRACE OF SLAB DETACHMENT IN THE NEOGENE VOLCANIC EVOLUTION OF CENTRAL MEXICO

The breaking of a subducted plate has a profound impact on the thermal structure of the mantle wedge. A major consequence of the detachment that is likely to produce a visible effect on the upper plate is a transitory increase of upper-mantle temperature. Numerical models of the thermal structure of a plate deduced from the Cenozoic plate tectonic history (Schmid et al., 2002) indicate that even after tens of millions of years of subduction, the detached Farallon slab remained 200–400 °C cooler than the upper mantle. The subducting plate is also a sort of cold shield for the underlying hot oceanic asthenosphere. If the slab breaks off, this hot asthenosphere will well up into the gap. Forward numerical models (Van de Zedde and Wortel, 2001) indicate that a 35-km-deep detachment of a 100-km-thick lithosphere may result in a temperature increase of up to 500 °C at the top of the trailing edge of the broken plate. The slab beneath western Mexico was thinner and detached at greater depth, so the temperature increase was lower. However, any increase of temperature is likely to enhance melting in a mantle wedge with zones already near or above the solidus (Fig. 2D). This increasing melting, in turn, should result in a notable augmenttation of volcanism in the upper plate that should migrate in time with the progression of the detachment at depth.

A migrating pulse of mafic volcanism is now clearly identifiable in central Mexico. The compilation of the geology of the entire Trans-Mexican volcanic belt, incorporating more than 1100 ages and 2600 geochemical data (Fig. DR1[1]), shows that mafic lavas were emplaced in the late Miocene along an approximately east-trending belt from the mouth of the Gulf of California to the Gulf of Mexico (Fig. 1). These rocks, west of the longitude of Mexico City, were studied by Ferrari et al. (2000), who found that they have ages progressively younger to the east, from 11.5 to 7.5 Ma. Toward the east, this mafic belt continues to the Gulf of Mexico (Fig. 1), where other volcanic fields have been identified and dated as 7.5–6.5 Ma (Orozco-Esquivel et al., 2003) (Fig. 1). Other mafic volcanic fields located to the southeast along the Gulf of Mexico coast suggest a prolongation of this mafic pulse (Fig. 1): the Chiconquiaco–Palma Sola plateau, with most ages ranging from 7.0 to 3.0 Ma (Orozco-Esquivel et al., 2003), the Alto de Anegada mafic volcanism offshore Veracruz Port (Orozco-Esquivel et al., 2003), and the Los Tuxtlas volcanic field, with a first mafic alkaline volcanic episode between 7 and 3.4 Ma (Nelson and Gonzalez-Caver, 1992).

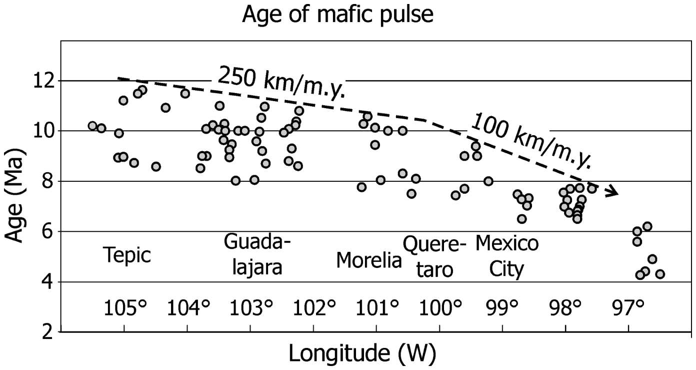

Figure 3. Plot of available ages of late Miocene mafic volcanism vs. longitude with indication of migration rate. Time of detachment may precede initiation of volcanism by ~2 m.y. Ages are listed in Table DR1 (see text footnote 1). Locations are shown in Figure 1.

This eastward-migrating pulse of mafic volcanism is difficult to explain in a steady-state subduction scenario. The timing of along-arc migration of mafic volcanism (Fig. 3) supports the idea that this volcanic pulse is related to the propagation of the slab detachment from the southern Gulf of California into central Mexico. Taking into account the first occurrence of mafic volcanism, I infer that the detachment propagated to the east at a rate of ~250 km/m.y. between Tepic and Queretaro and ~100 km/m.y. farther to the east (Fig. 3). The trace of detachment east of Queretaro was located immediately to the north of a belt of previous adakitic volcanism (Fig. 1) that has been related to flat subduction during the middle Miocene (Gómez-Tuena et al., 2003). This geographic link strongly suggests that the detachment propagated at 14–11 Ma along a zone of weakness where the slab was melting.

The geochemical fingerprint of the mafic pulse is uneven. West of Mexico City, the lavas have a subalkaline to transitional geochemistry (Ferrari et al., 2000), whereas to the east they show an oceanic-island–type affinity (Orozco-Esquivel et al., 2003). A possible explanation for this discrepancy is intrinsic in the detachment scenario. The region to the west of Mexico City was affected by Cretaceous and Tertiary volcanism (Fig. 1), whereas to the east, the mantle was unaffected by any subduction input, at least since 250 Ma. After detachment, the influx of anhydrous asthenosphere promoted a thermal (advective) melting. The geochemical signature of the mafic pulse, therefore, simply reflects the chemical structure of the preexisting mantle.

SLAB DETACHMENT AND GEOCHEMICAL EVOLUTION OF THE TRANS-MEXICAN VOLCANIC BELT

A predictable consequence of a slab detachment is the appearance of volcanism with an unusual geochemical affinity for a subduction setting. Several papers have documented the passage from calk-alkaline to alkaline volcanism after slab breakoff in a collisional setting (e.g., Coulon et al., 2002, and references therein). More rarely, the influence of slab detachment on the geochemistry of volcanism has been considered where subduction continues. This is the case for the Pliocene–Quaternary Trans-Mexican volcanic belt, where intraplate lavas with the composition of oceanic-island basalts (OIBs) have erupted since 5 Ma in different parts of the arc (Fig. 1) together with the dominant calc-alkaline volcanism. Geochemists have tried to explain the occurrence of this OIB-type volcanism as a result of a mantle plume (Marquez et al., 1999) or an active continental rift (Verma, 2002). These explanations have poor confirmation in the geologic record of the arc, but are not required once slab detachment is taken into account. In fact, after the slab breakoff, chemically enriched subslab asthenosphere will flow into the slab gap and the mantle wedge. The resulting subarc mantle may thus consist of enriched domains (the source of OIB) embedded in a matrix of depleted mantle (the source of subduction-related magmas), and melting of both domains may occur simultaneously (Fer-

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[1] GSA Data Repository item 2004012, Table DR1 (age data and references) and Figures DR1 (simplified geologic map of Trans-Mexican volcanic belt) and DR2 (plot of ages versus distance from the trench along three transects), is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

rari et al., 2001; Goméz-Tuena et al., 2003; Cervantes and Wallace, 2003). The location and timing of intraplate volcanism in the Pliocene–Quaternary support this hypothesis. Lavas akin to OIB started to appear 5–3 m.y. after the inferred age of detachment in the western and central part of the arc. Infiltration of asthenosphere will likely take a few million years to occur because the enriched material needs to be convectively transported into the mantle wedge. The geographic location of OIB also agrees with the model. As shown in Figure 1, these lavas are located between the inferred trace of the detachment and the present edge of the seismic slab: in the region between, the slab must have retreated (rolled back) and/or thermally eroded after the detachment, as suggested by the trenchward migration of the volcanic front (Fig. DR2; see footnote 1). Here the upper plate would have been exposed to the upwelling asthenosphere along an east-west, trench-parallel slab window.

CONCLUDING REMARK

The lateral propagation of slab detachment depicted in this work provides a good explanation for several volcanic and geochemical features of central Mexico. Other consequences stem from the model presented here. The region underlain by the slab-free area could have undergone uplift as buoyant mantle flowed to a shallow depth; the subduction velocity of the Cocos plate should have also slowed down after the detachment. These aspects were not considered in this paper, but may be tested by further studies. In addition, combined petrologic and thermo-chemical modeling may lead to a better understanding of the evolution of detachment depth in time.

The detachment model also plays a part in the controversy about the role of subduction in the petrogenesis of the Trans-Mexican volcanic belt. Although the geochemical signature of subduction in some lavas may be very low (e.g., Verma, 2002), I have shown here that subduction dynamics ultimately controlled the volcanic pulse and the generation of OIB-type volcanism.

ACKNOWLEDGMENTS

I am indebted to José Rosas, Gerardo Carrasco, Maria Teresa Orozco, Angel Nieto, Susana Alaniz, Tania Norato, and Norma Gonzalez, whose collaboration was essential for the construction of the Geographic Information System of the Trans-Mexican volcanic belt. Work was supported by grants IN108196 and IN102801. Reviews by Joann Stock and Rinus Wortel greatly improved the original manuscript. Arturo Gómez-Tuena provided a manuscript in advance of publication.

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Manuscript received 3 June 2003
Revised manuscript received 18 September 2003
Manuscript accepted 22 September 2003

Printed in USA