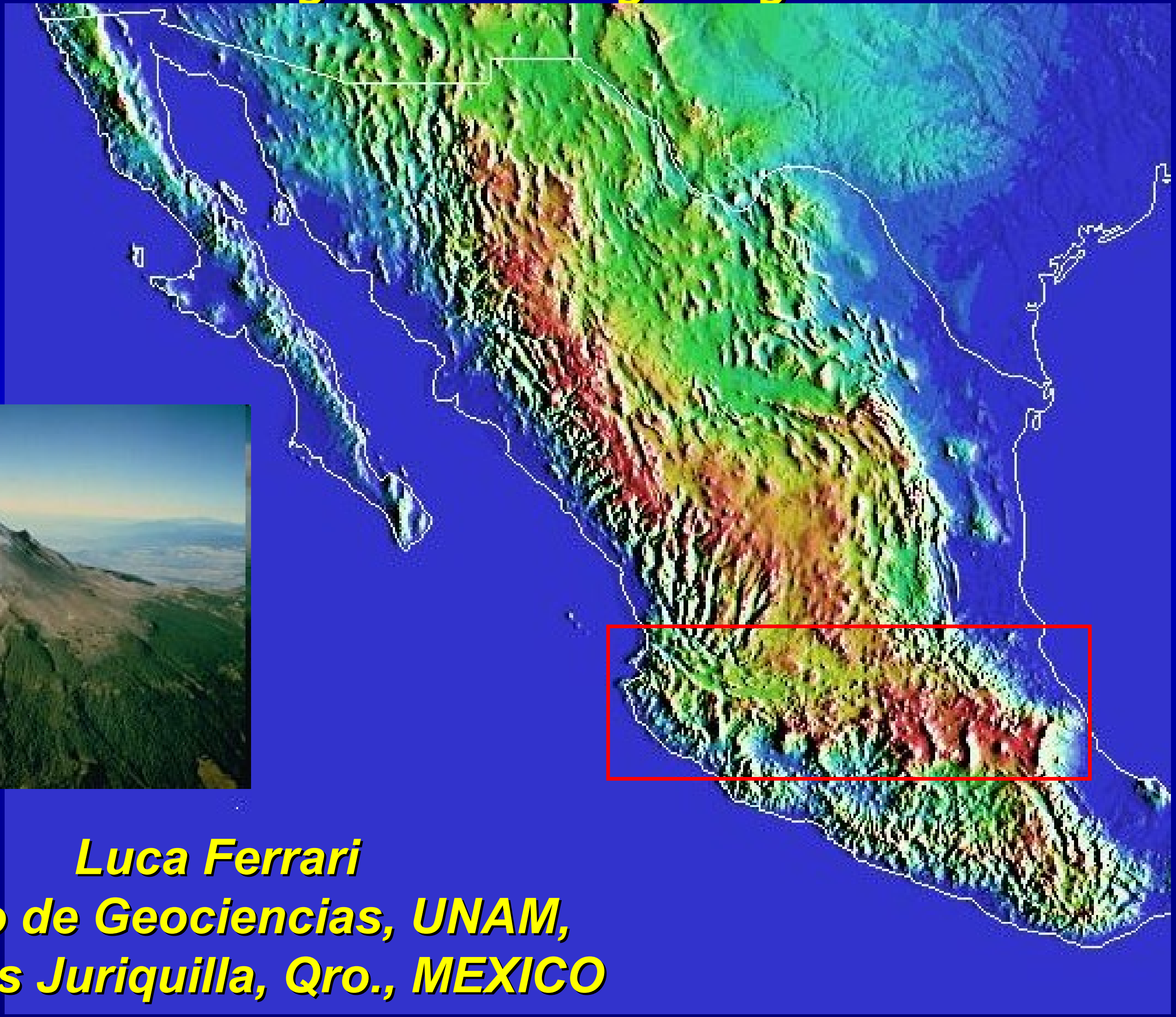
The Trans-Mexican Volcanic Belt

Tectonic background and geologic evolution



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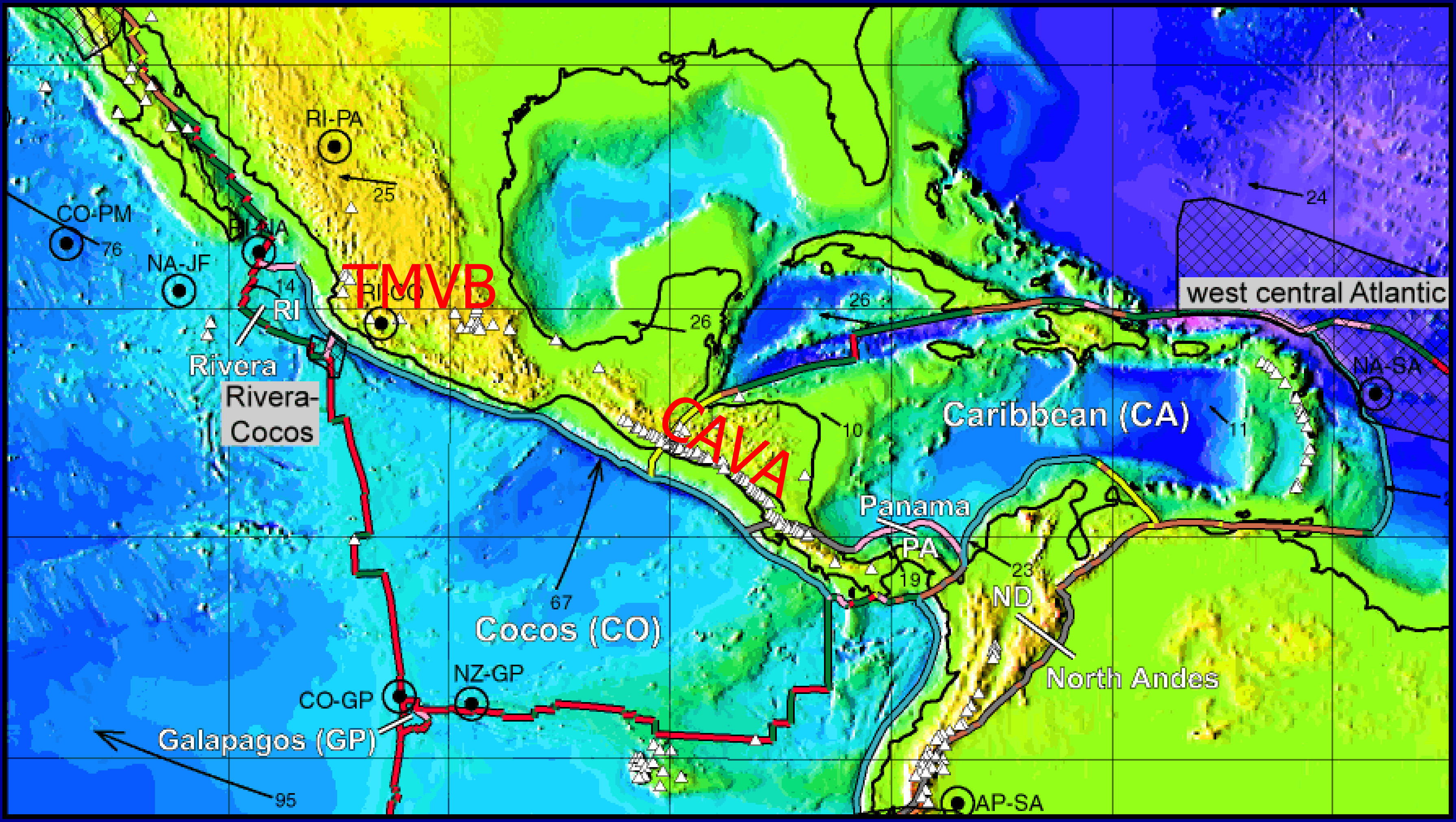
Index

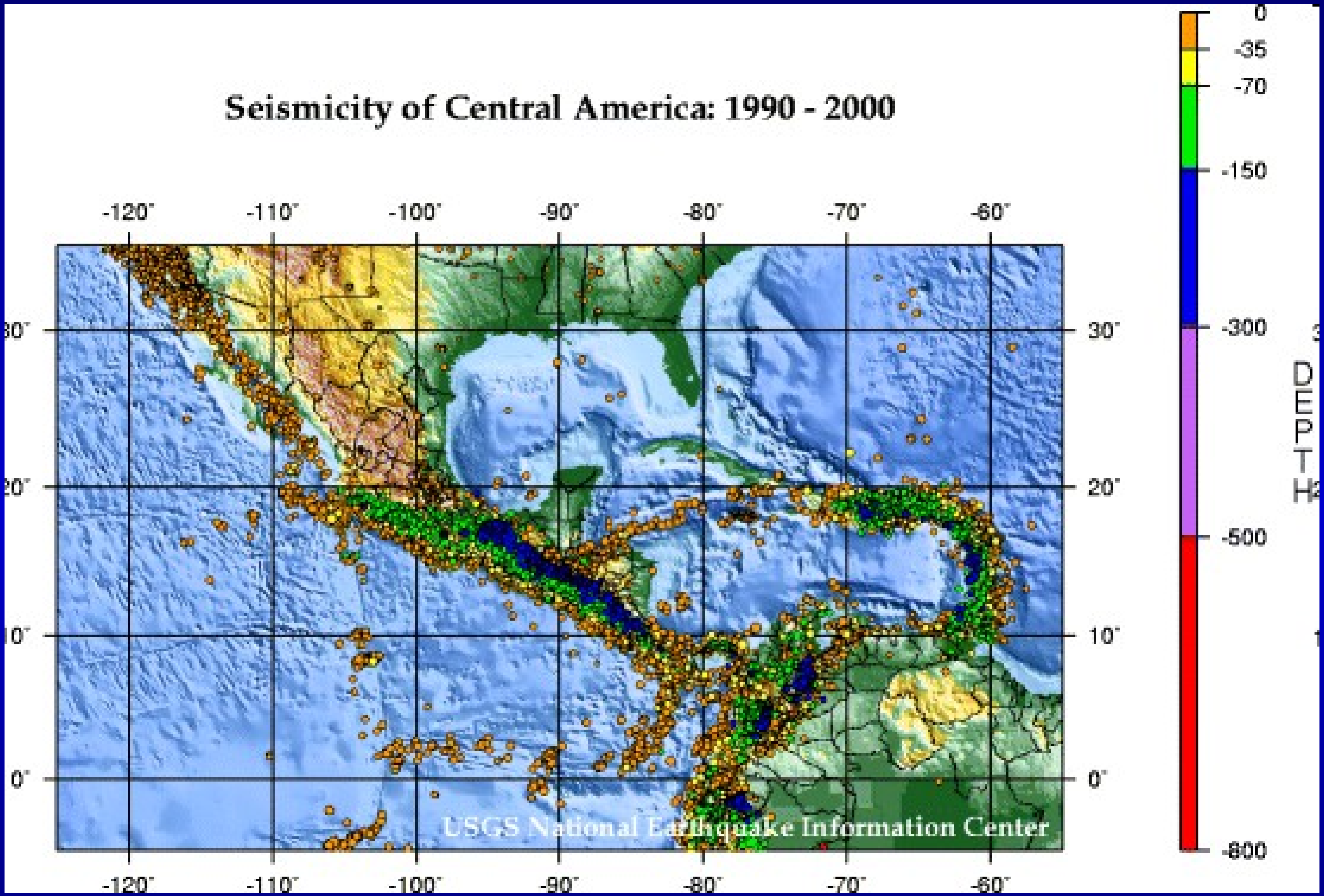
- Geodynamic framework and Cenozoic arc volcanism in Mexico
- The transition from the Sierra Madre Occidental (SMO) to the Trans-Mexican Volcanic Belt (TMVB)
- Geophysical data on the subducting plates and the upper mantle beneath the TMVB
- Intra-arc tectonics of the TMVB
- Geologic evolution of the TMVB
- Genetic models for the TMVB (subduction denial vs. subduction dynamics)
- Preliminary results from recent seismic experiments (MASE, MARS)

Geodynamic framework



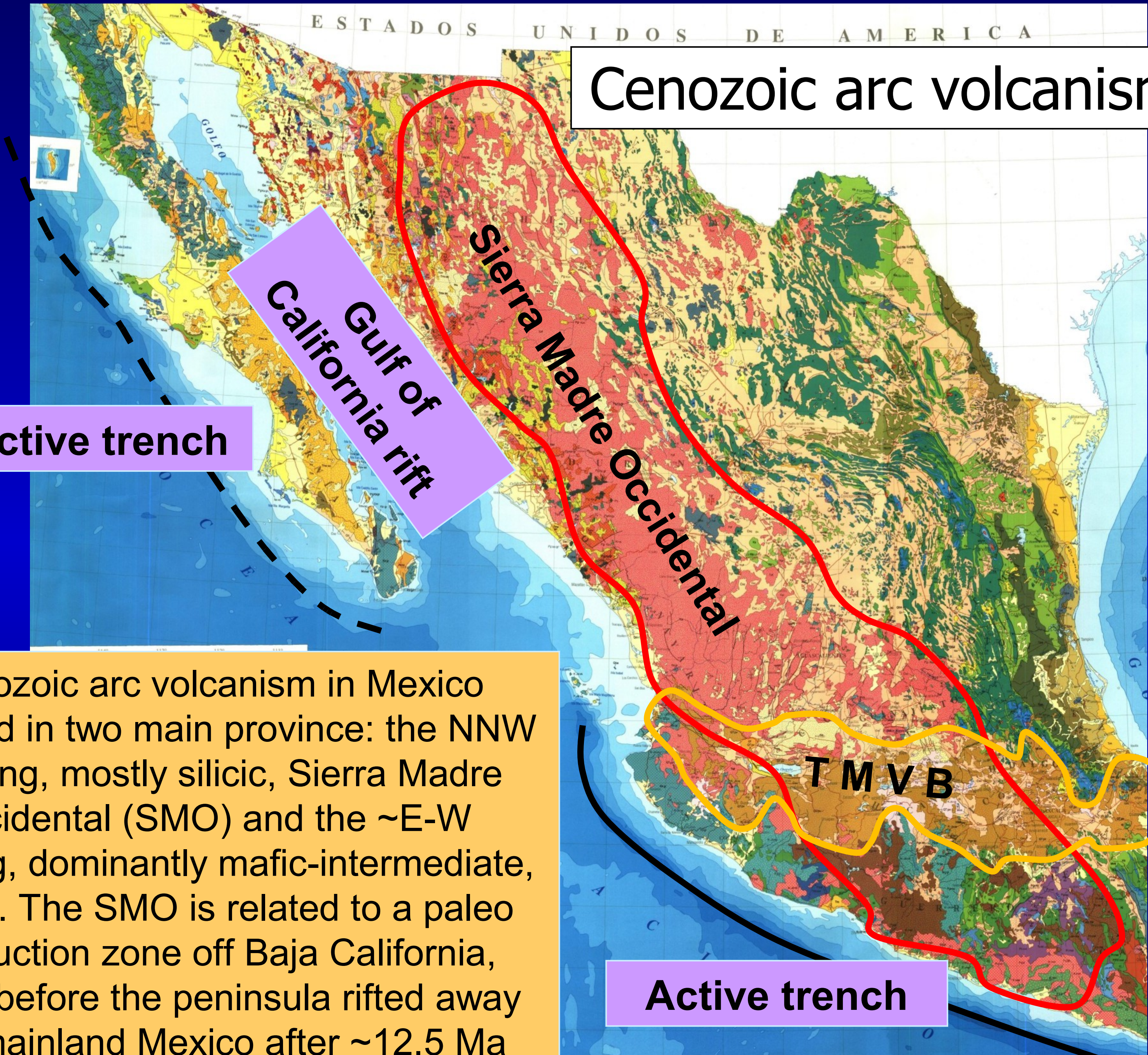
The TMVB is the largest Neogene volcanic arc built on the North America plate. It lays in front of the Middle America subduction zone, where the Rivera and Cocos plate subduct beneath the North America plate. Cocos also subducts beneath the Caribbean plate, forming the Central America Volcanic Arc (CAVA).

Geodynamic framework



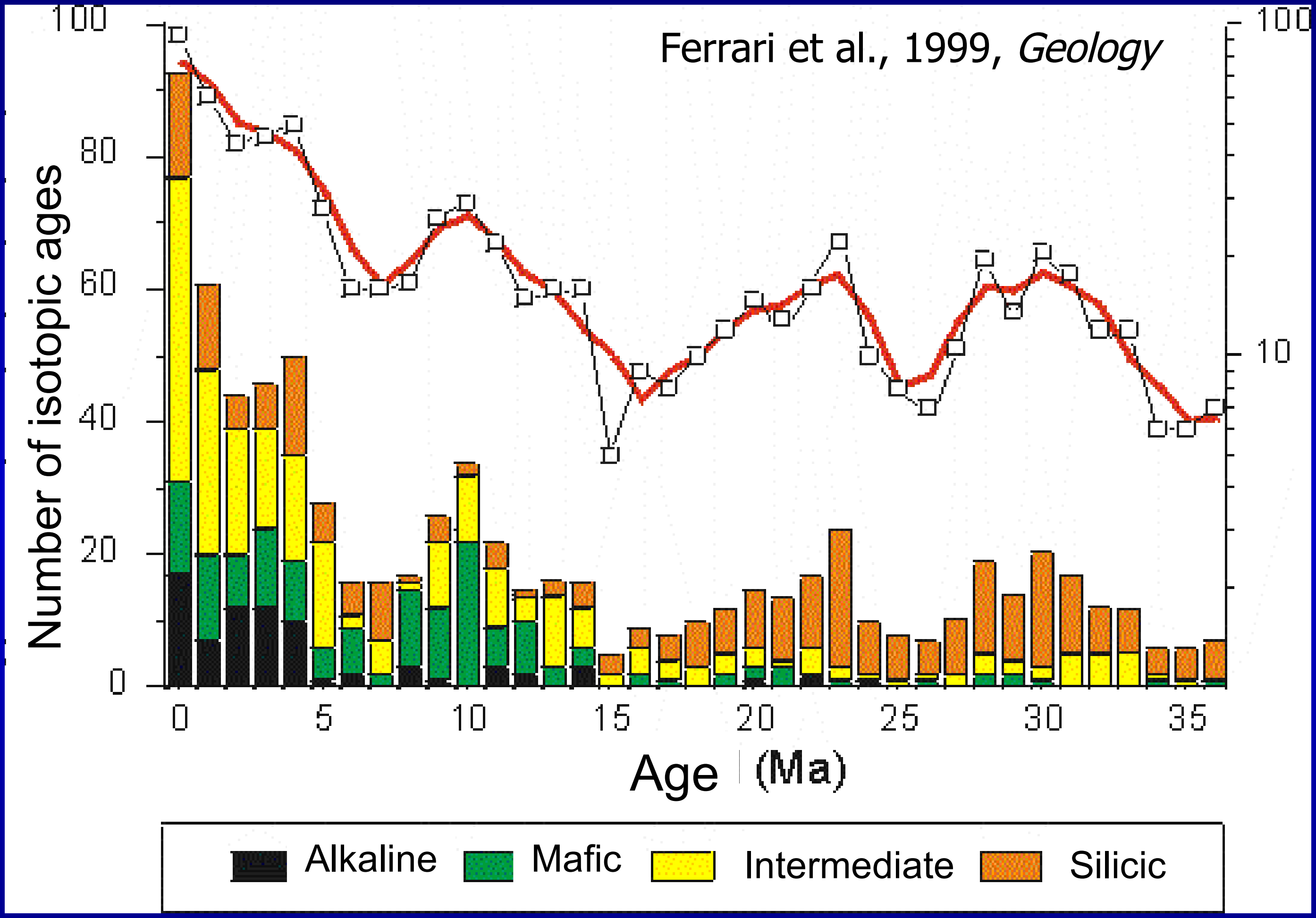
Seismicity associated with the subduction of the Cocos plate is shallower in central Mexico than in Central America

Cenozoic arc volcanism



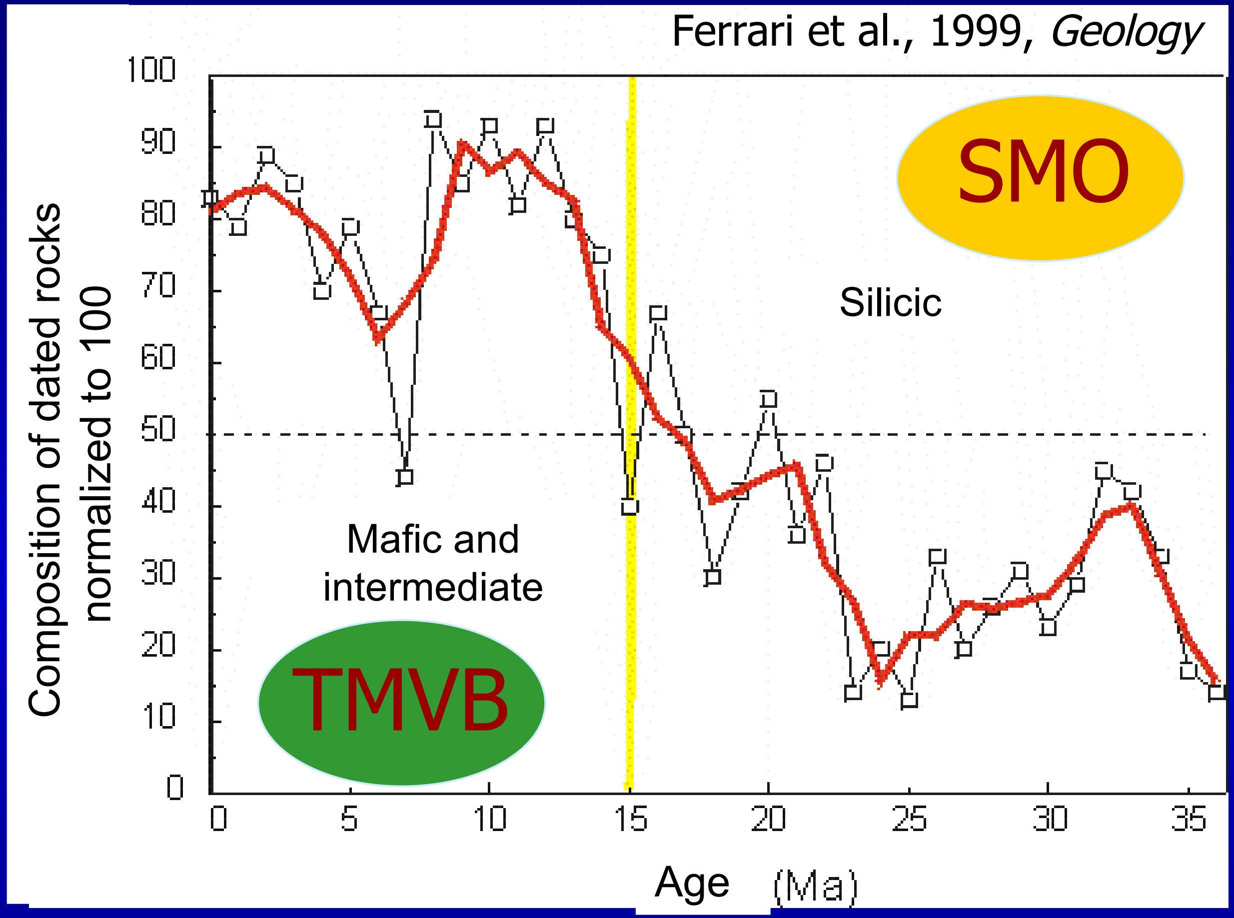
Cenozoic arc volcanism in Mexico occurred in two main province: the NNW trending, mostly silicic, Sierra Madre Occidental (SMO) and the ~E-W trending, dominantly mafic-intermediate, TMVB. The SMO is related to a paleo subduction zone off Baja California, active before the peninsula rifted away from mainland Mexico after ~12.5 Ma

How and when was the transition between SMO and TMVB?



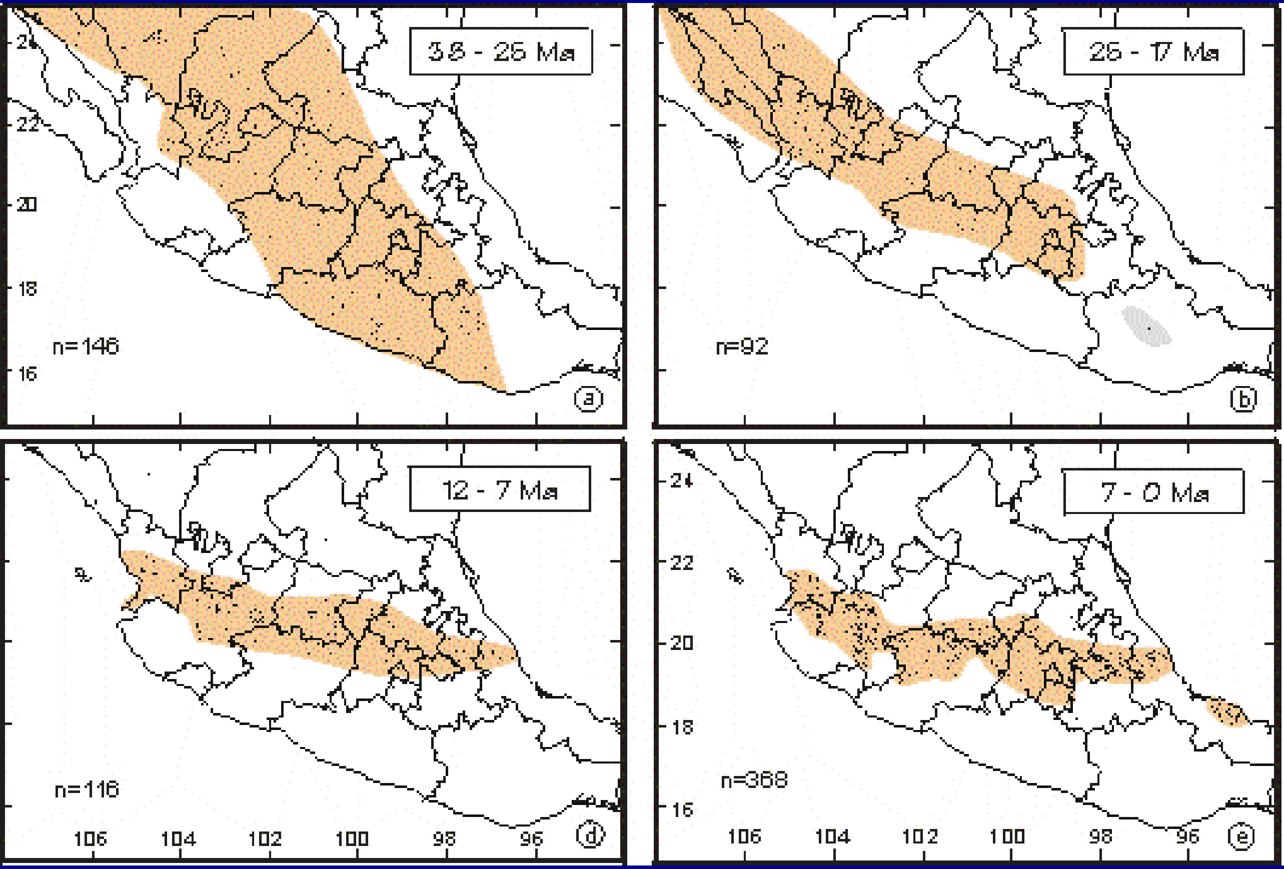
Distribution of dated rocks shows several volcanic pulses since 38 Ma and a minimum in middle Miocene.

The transition between SMO and TMVB



The same data normalized at 100 clearly show the transition from silicic to more mafic composition in Middle Miocene, with a turning point at ~15 ma. Given that the SMO is dominated by silicic products Middle Miocene is taken as the time when TMVB started

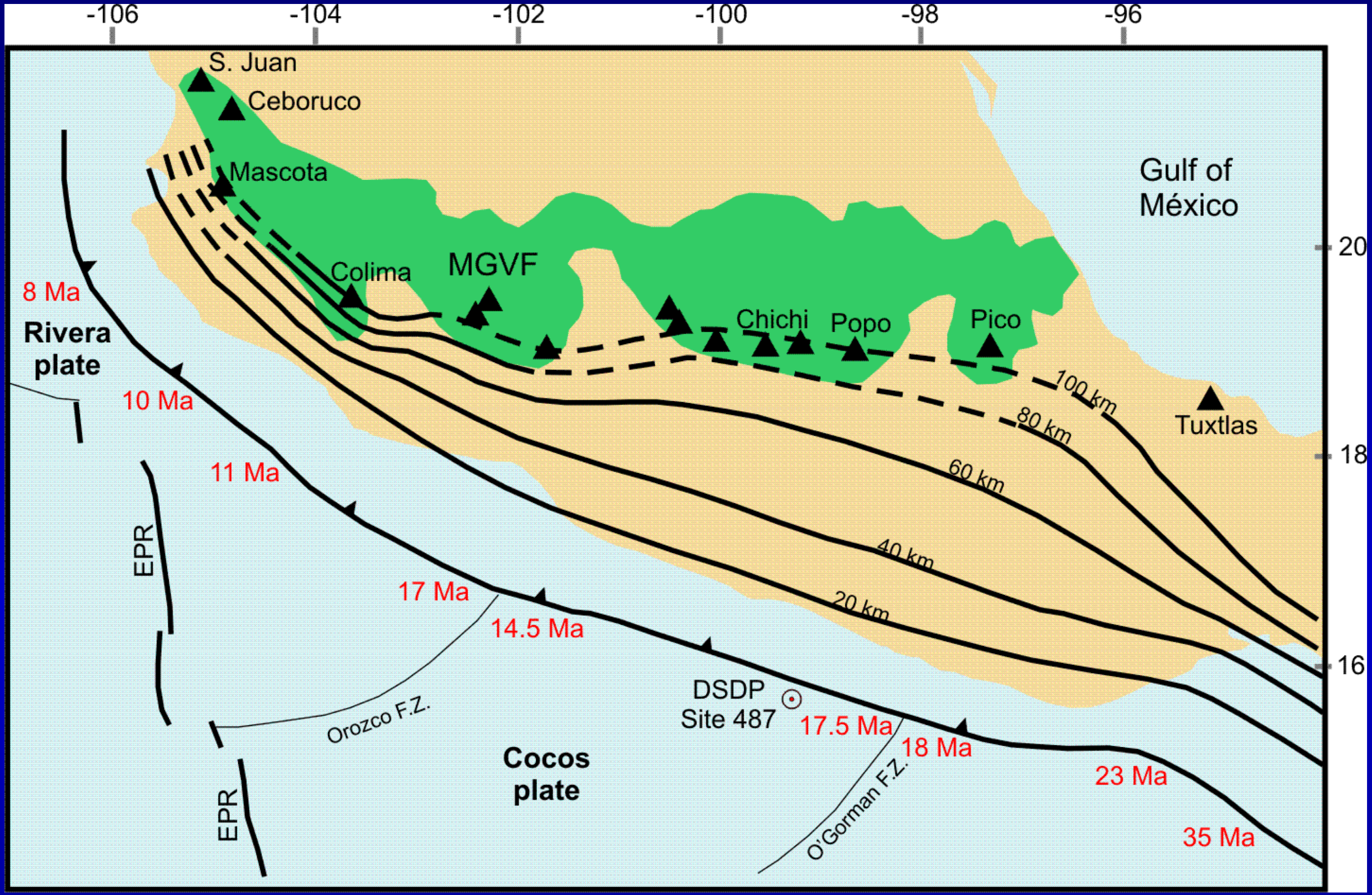
The transition between SMO and TMVB



Ferrari et al. 1999, *Geology*

Geographic distribution of dated rocks in central Mexico show the progressive counterclockwise rotation of volcanic arc from the SMO to the TMVB. An arc with the orientation of the TMVB was already in place by Middle Miocene

Complexities of TMVB and Mexican subduction zone



- Varying slab dip, no seismicity beneath the arc
- Young subducting plates (< 15 Ma) nevertheless volcanism occurs
- Large variation of volcanic style, variation in arc width
- Large compositional variation: intraplate-like (OIB) and adakitic lavas coexist in space and time with typical subduction volcanism

Geometry of subducting plates

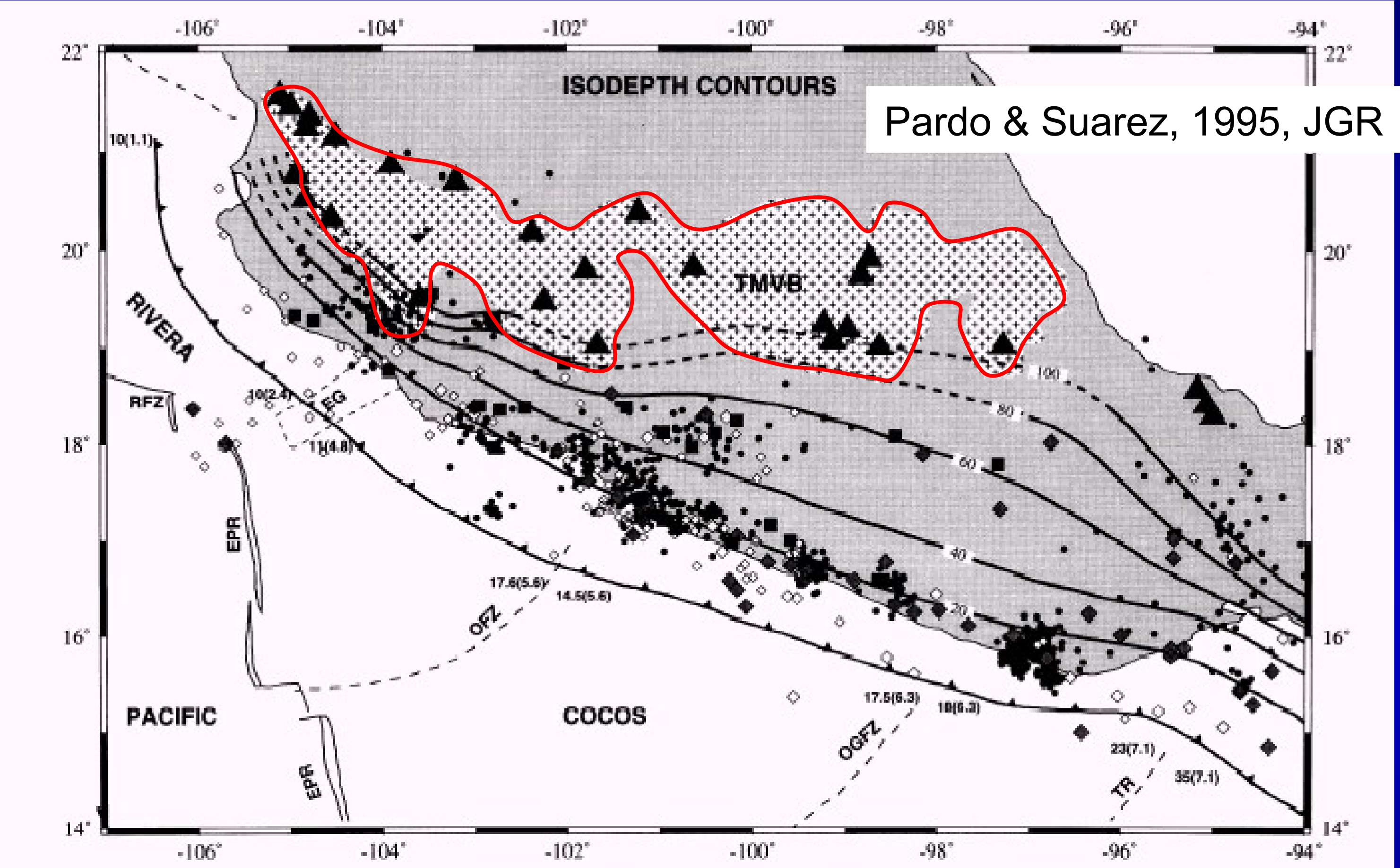
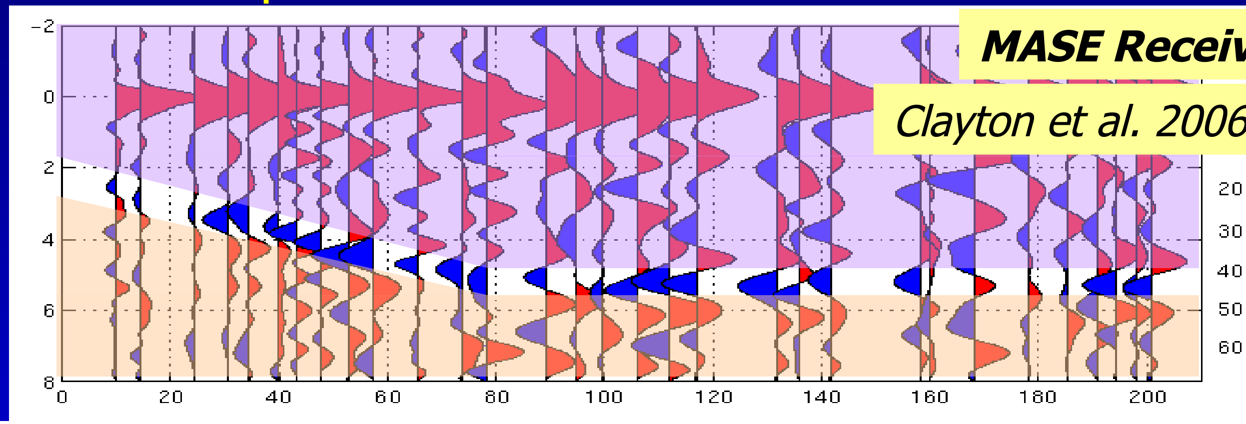


Figure 6. Isodepth contours of the subducted oceanic slab beneath the North American plate in southern Mexico drawn using a spline interpolation. Dashed lines indicate where the contours were extrapolated because no hypocentral data are available. Other symbols as on Figure 1. The age (Ma) of the oceanic slab and the convergence rate in parentheses (cm/yr) are shown along the Middle American Trench.

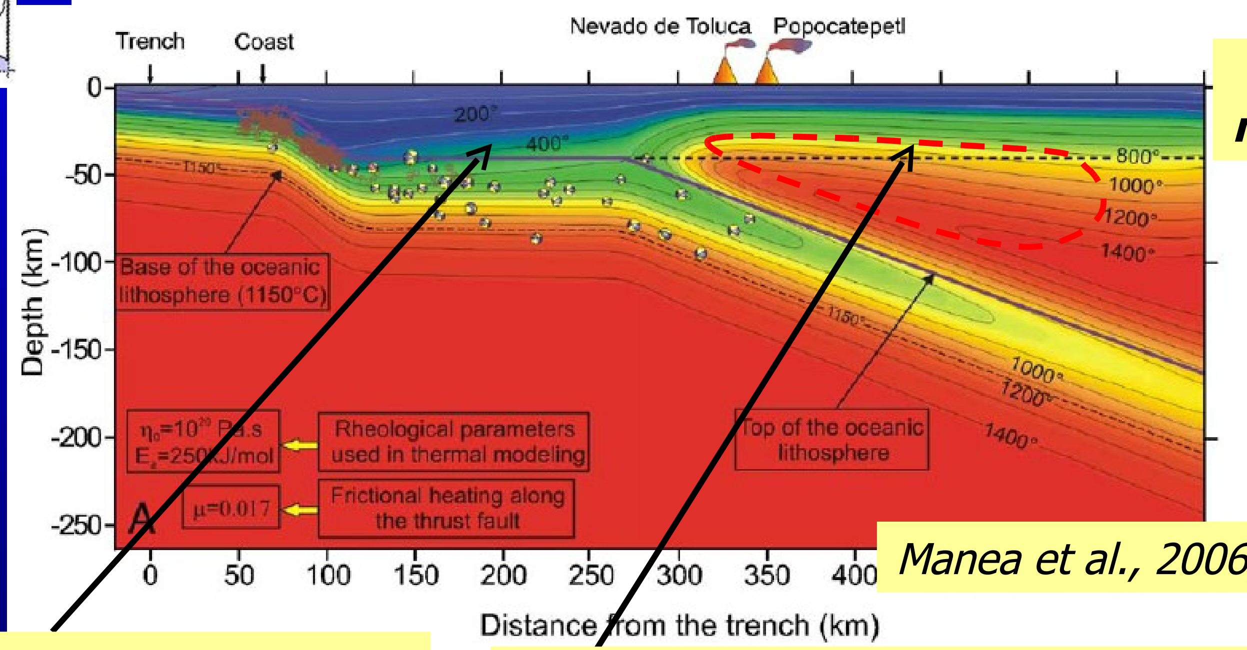
Rivera dips steeper than western Cocos. Cocos dips steeply to the east of Tehuantepec isthmus. Variation in slab dip may explain why the arc is not parallel to the trench. But what happen beneath the arc?

At the longitude of Mexico city the subducting Cocos plate is flat and lays just below the Moho. Slab geometry is poorly defined beneath the TMVB but thermal modelling and gravimetry indicate the presence of asthenosphere. There is no mantle lithosphere beneath southern Mexico



MASE Receiver Functions

Clayton et al. 2006, BOA Meeting



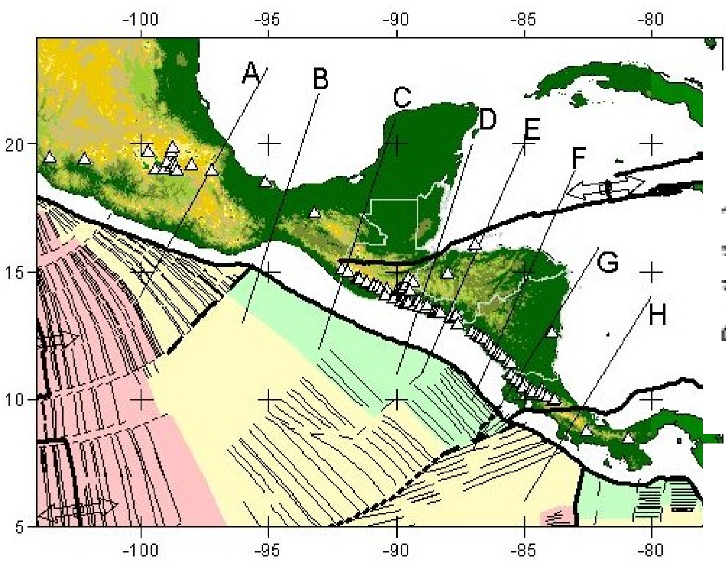
Thermal modelling

Manea et al., 2006, Tectonophysics

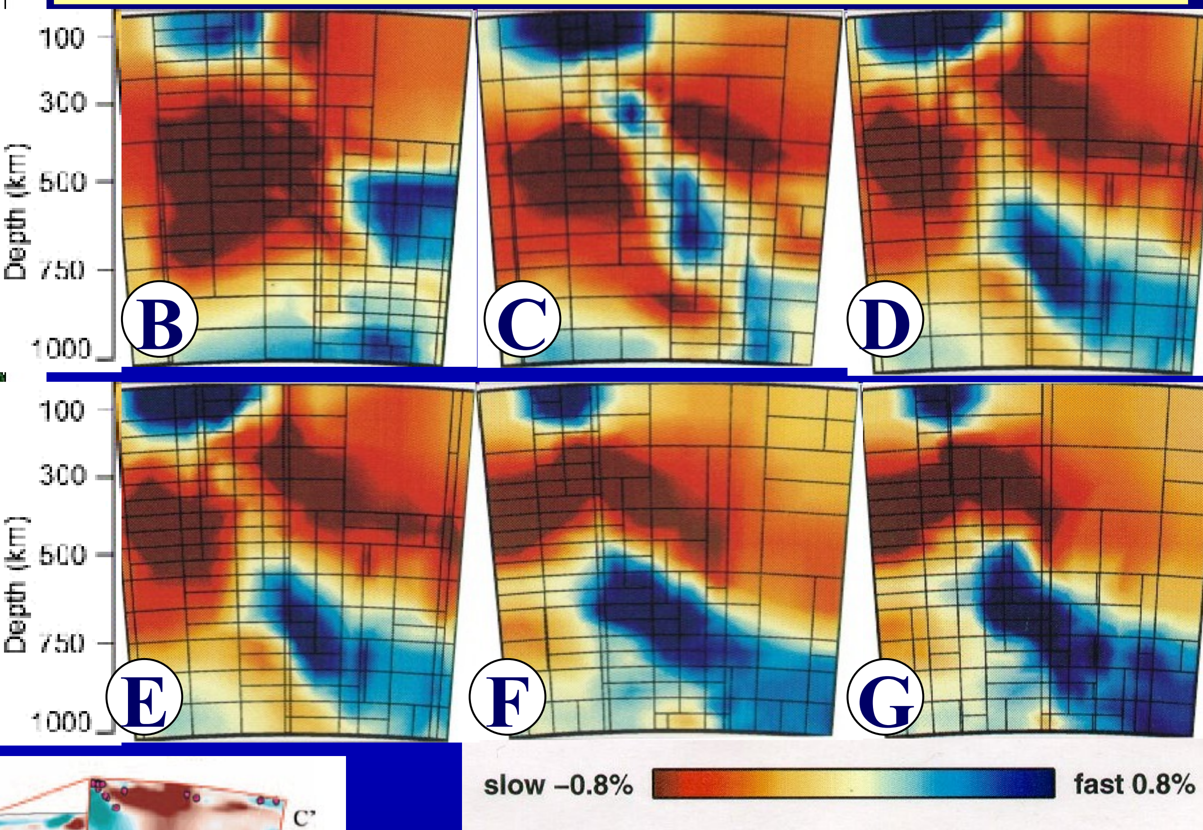
Slab in contact with the upper plate: no space for lid

Low Vp, low density, high T: convective mantle

Seismic tomography



(Rogers, Karason & Van der Hilst, 2002, Geology)



Regional tomography studies show a broken slab beneath Central America but the situation is unclear under TMVB

parallel to the trench (Pardo & Suárez 1995). Fig. 1 also locates the three northeast–southwest profiles and one east–west profile, which will be referred to in Figs 2 and 3.

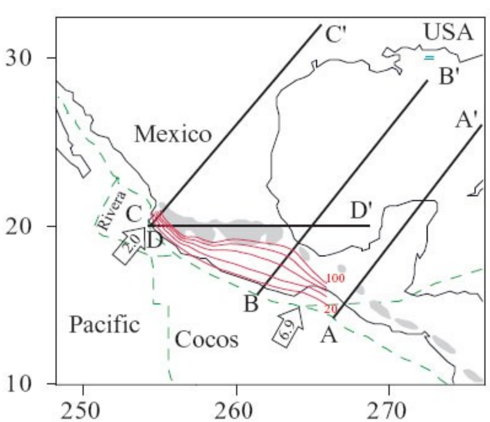


Figure 1. Tectonic framework of the study area. The dashed curve shows

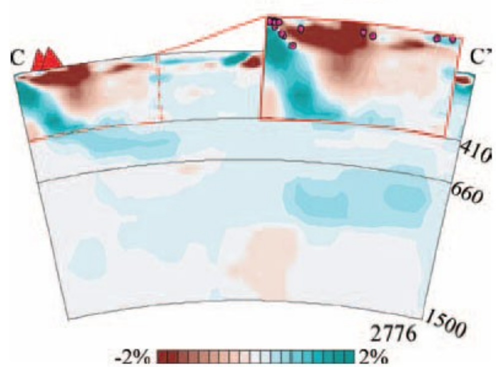
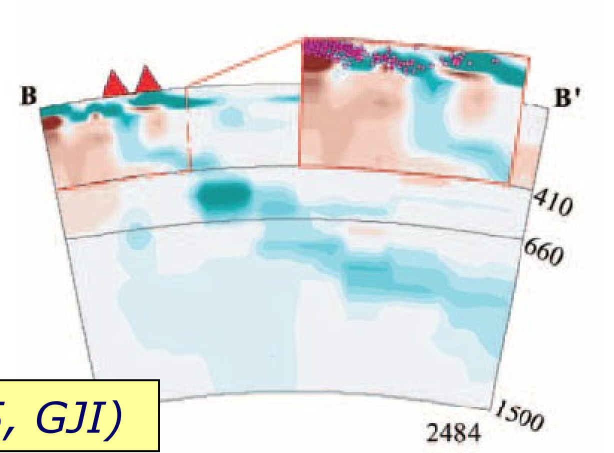


Figure 2. Cross-sections of the *P*-wave tomographic model along profiles AA′ to CC′ whose locations are given in Fig. 1. Positive and negative velocity anomalies (in per cent) relative to the reference earth model AK135 (Kennett *et al.* 1995) are indicated in blue and brown, respectively. Red triangles are

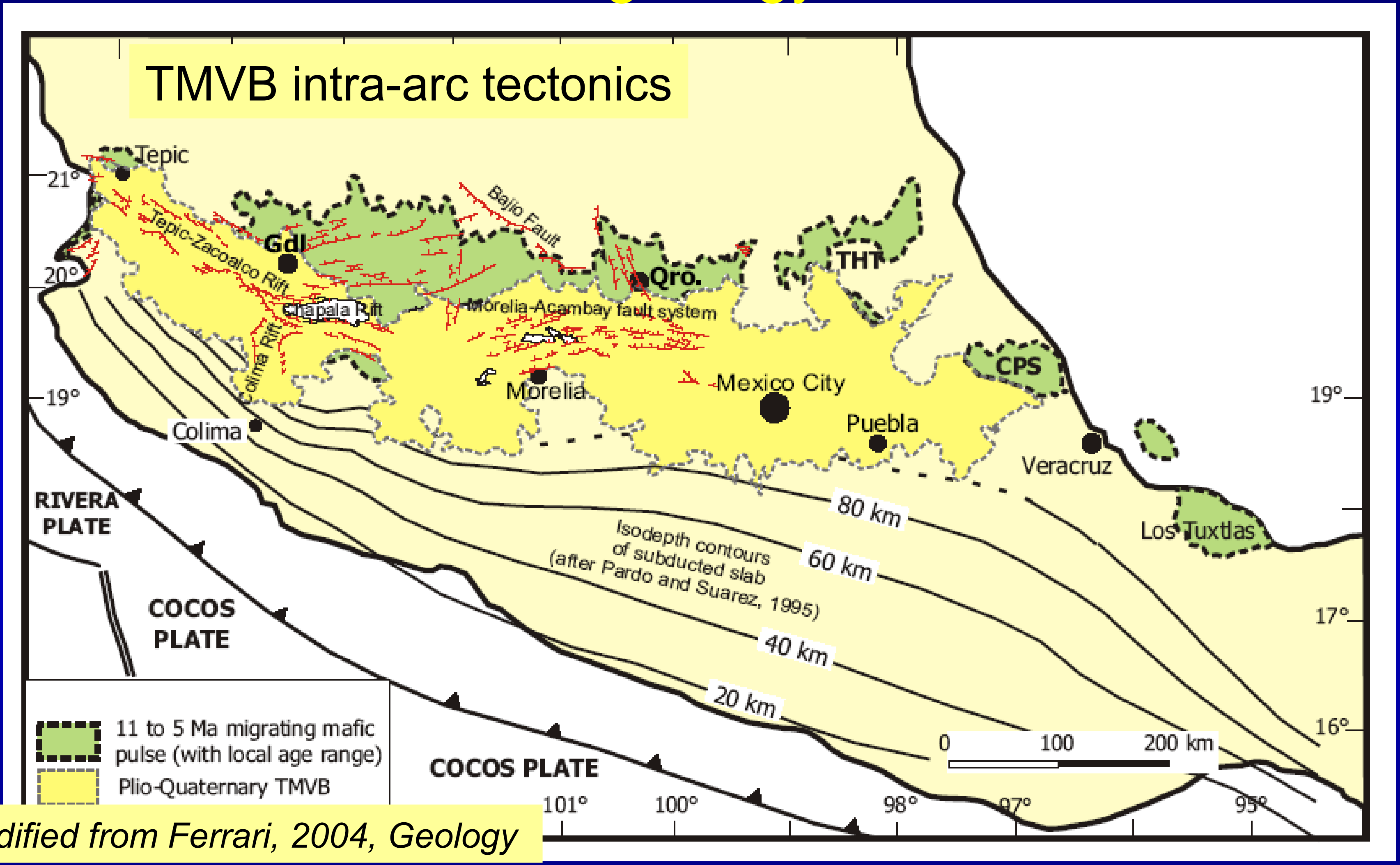


(Gorbatov & Fukao, 2005, GJI)

Summary of geophysical data

- Young subducting plates
- Varying slab geometry (steep in the W flat to the E)
- No seismicity beneath the TMVB
- No mantle lithosphere in central TMVB
- Slab geometry unknown under TMVB. Is there a slab?

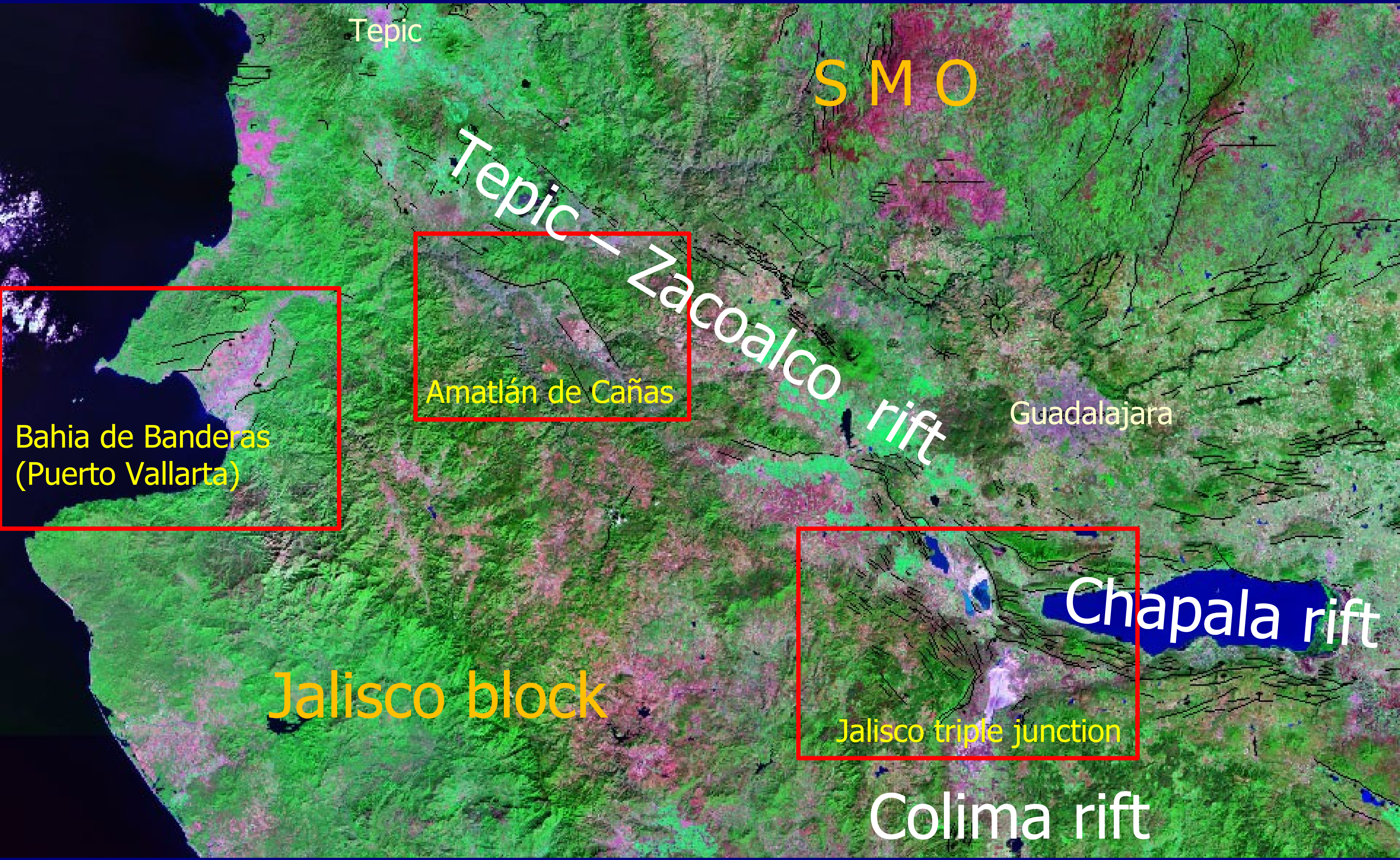
Tectonics and geology of the TMVB



Modified from Ferrari, 2004, Geology

Neogene extensional faulting occurs within the arc (in contrast to back-arc extension in some arcs). This intra-arc extension occurs in the western and central part of the TMVB and wane eastward, where the slab become flat.

Recent and active tectonics in the western TMVB



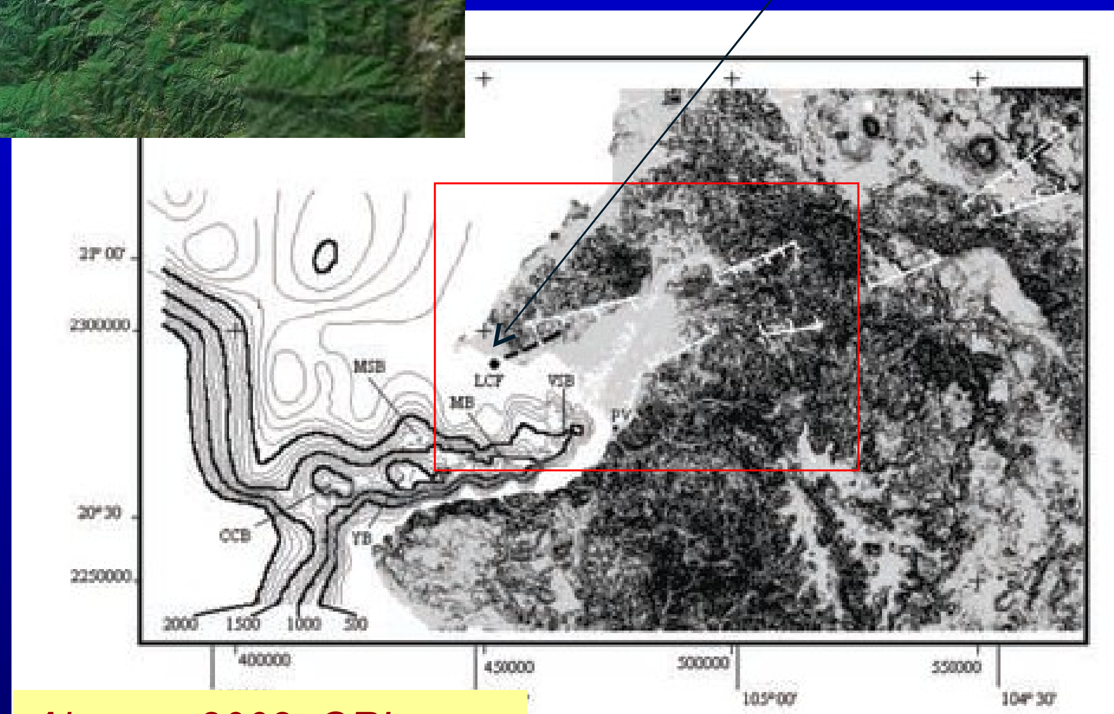
Three extensional fault system called “rift”: Tepic-Zacoalco (WNW-ESE), Chapala (E-W) and Colima (~N-S). Faulting active since the end of Miocene. Presently active systems boxed in red and illustrated in the next slides

Active faults in Bahía de Banderas and Puerto Vallarta graben

Filling of the Puerto Vallarta graben is cut by this fault (Ferrari et al., 1994, Geof. Int.)

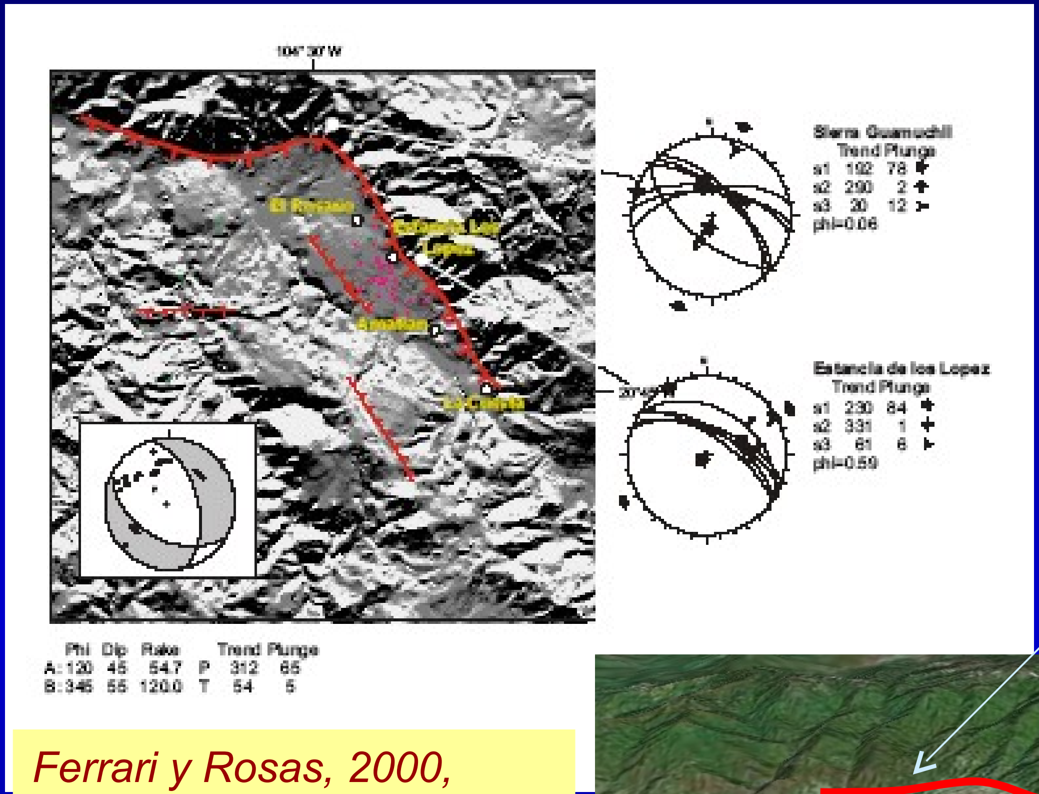
Submarine hydrothermal activity is occurring here (Prol et al., 2003, Econ. Geol.)

Large ~WSW-ENE submarine scarps over 1.5 km high define an offshore continuation of the Puerto Vallarta graben in the Bahia de Banderas (Alvarez, 2002).



Alvarez, 2002; GRL

Amatlán de Cañas half graben

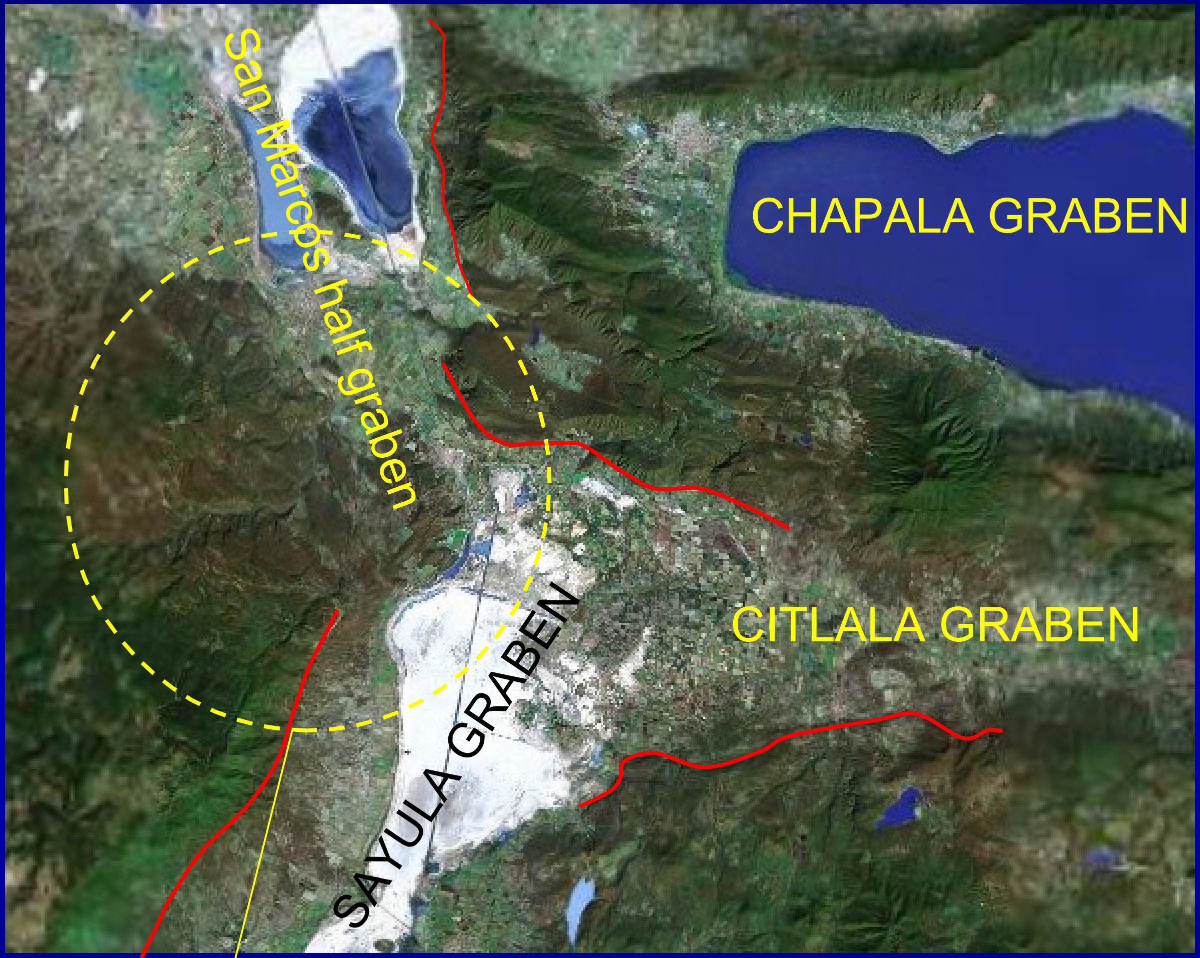


Main listric extensional fault with E-W to NW-SE orientation. Striations on the fault plane indicate ~NE-SW extension (Ferrari and Rosas, 2000, GSA Spec. Paper).
A seismic swarm occurred in 1995 with max M = 2.5-3.6 and depth = 6 to 10 km.
Composite focal mechanism solution agrees with paleostress orientation from fault kinematics.

Ferrari y Rosas, 2000, (GSA Sp. Paper 334) and unpublished data

Conjugate fault cutting 0.65 Ma small basaltic shield volcano

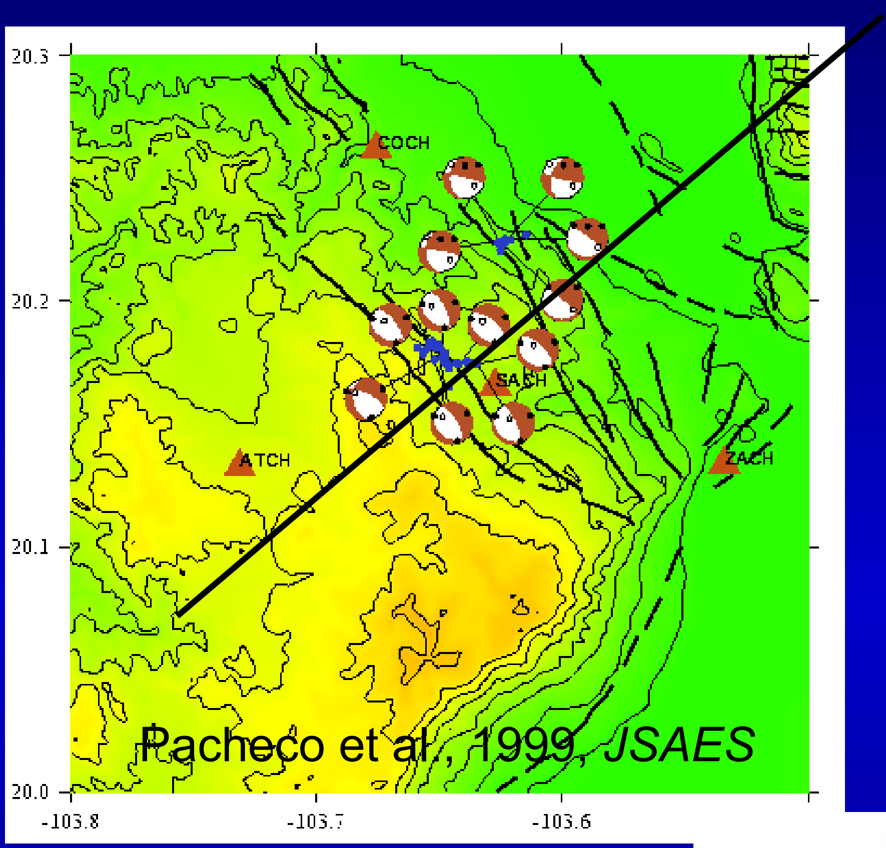
The Jalisco triple junction



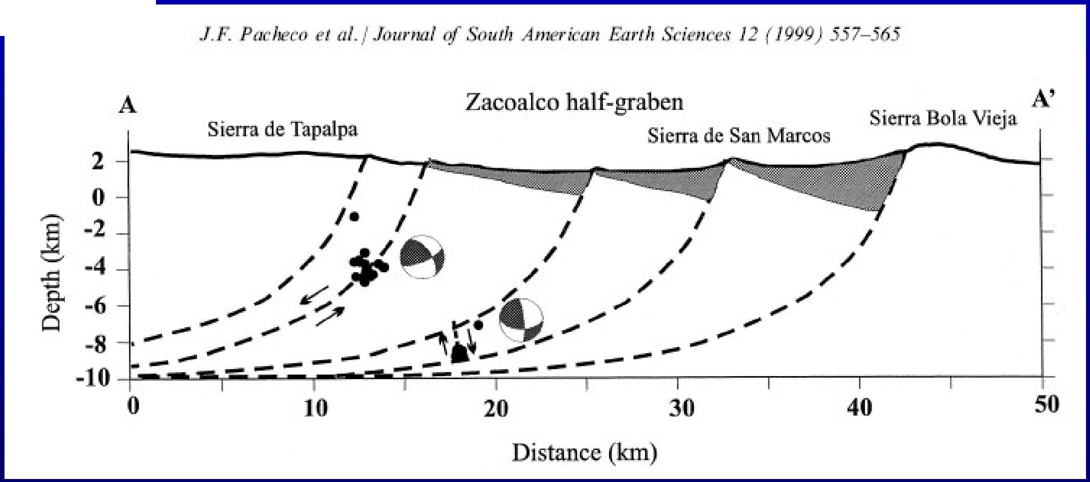
In the so-called "Jalisco triple junction" the SE end of the Tepic-Zacoalco rift (San Marcos half-graben) joins with the northern end of the Colima rift (Sayula graben) and the E-W Citlala graben. The Chapala lake occupies an older graben active mostly in the Pliocene. Faulting initiated at the end of Miocene (Ferrari and Rosas, 2000). The Sayula graben filling may be as thick as 1.5 km (Allan, 1986) and the fault scarp is ~1 km high.

1568 Sayula earthquake
Mw > 7 (Suárez et al., 1994, *Tectonophysics)*

San Marcos detachment fault and Sierra de Tapalpa conjugate faulting

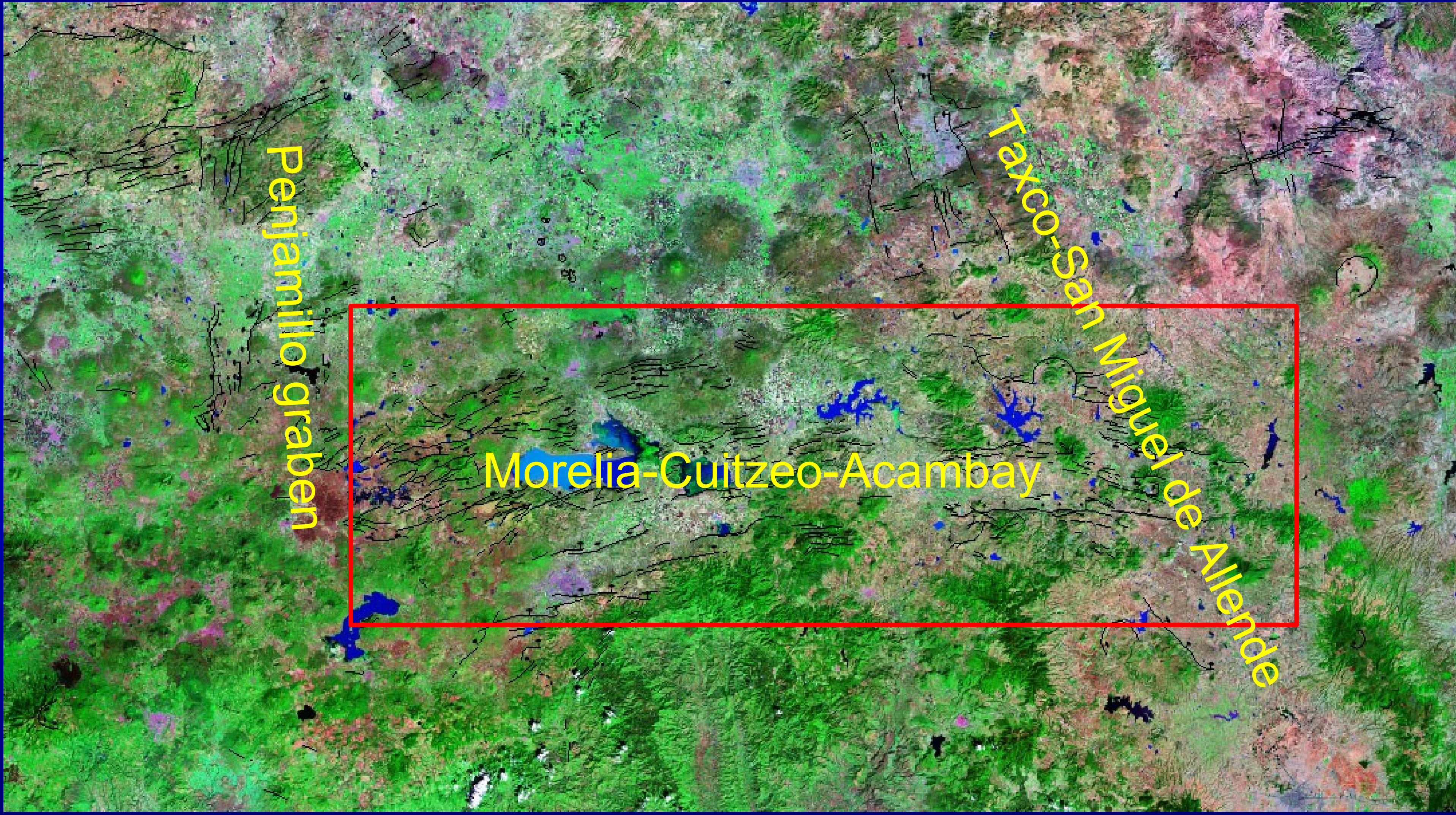


A seismic swarm occurred in 1997 in Sierra de Tapalpa with M = 1.5 - 3.5 and depth = 4 to 10 km. It confirmed a previous geologic model (Rosas et al., 1997) proposing a system of listric detachment faults that sole at ~10 km of depth.



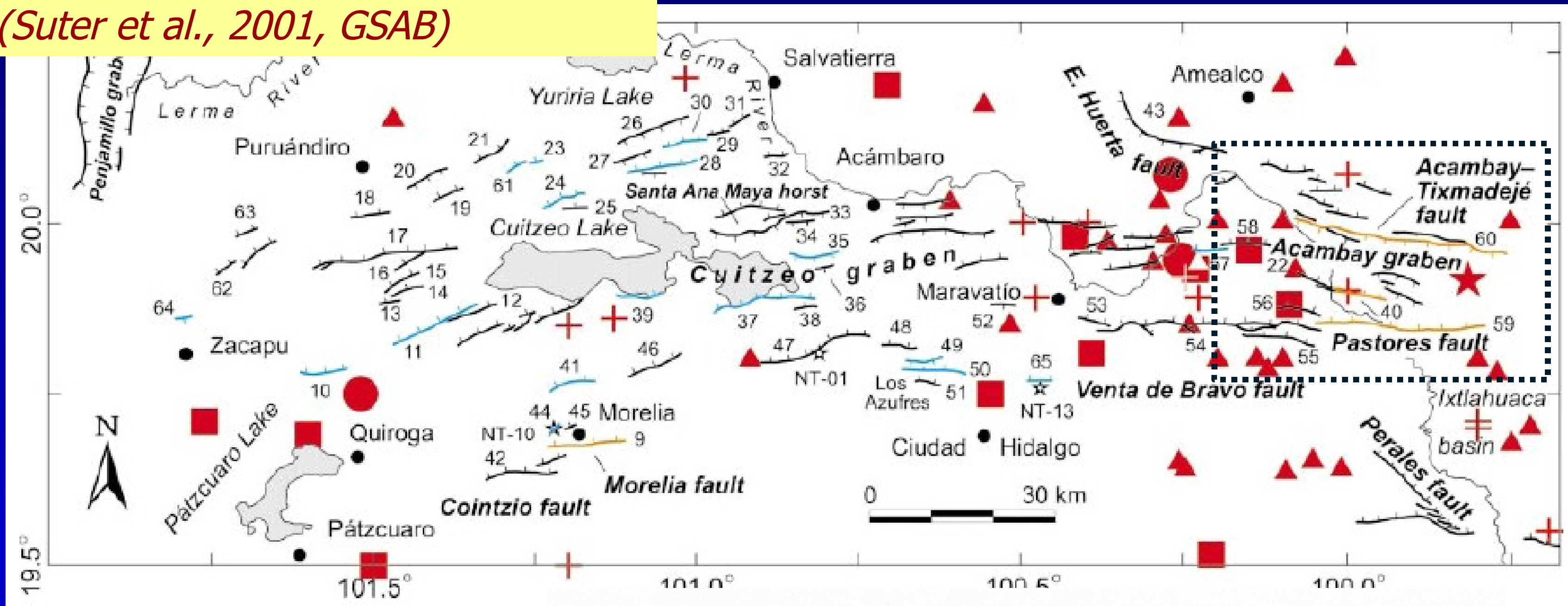
Intra arc extension in the central TMVB

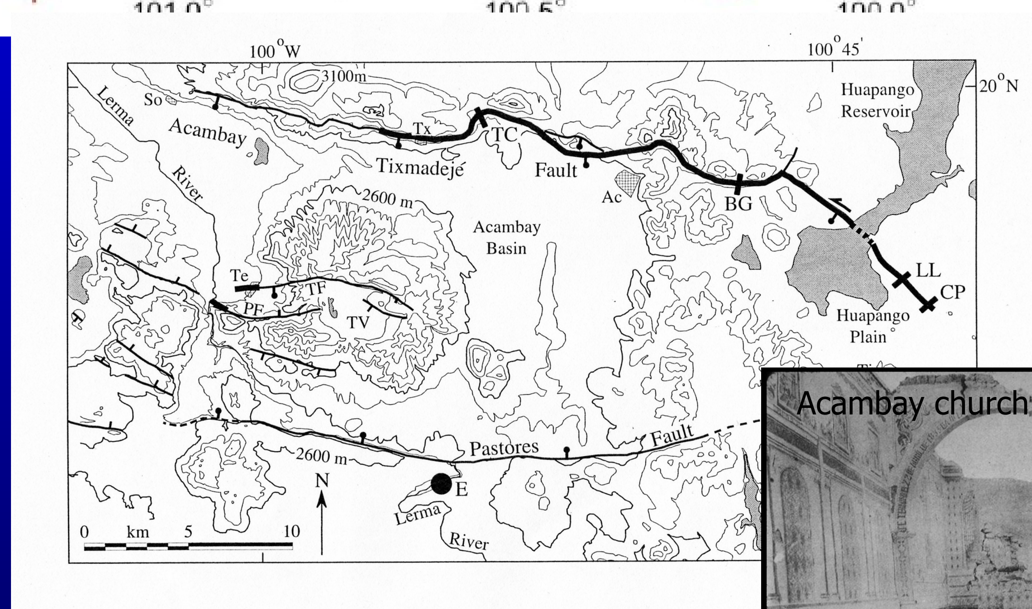
Morelia- Cuitzeo-Acambay and Taxco-San Miguel de Allende systems



Seismicity and Quaternary faulting in the central FVTM

(Suter et al., 2001, GSAB)





Several tens of normal faults with Plio-Quaternary activity make up the Morelia-Acambay system. The eastern part of the system is still active (Suter et al., 2001).

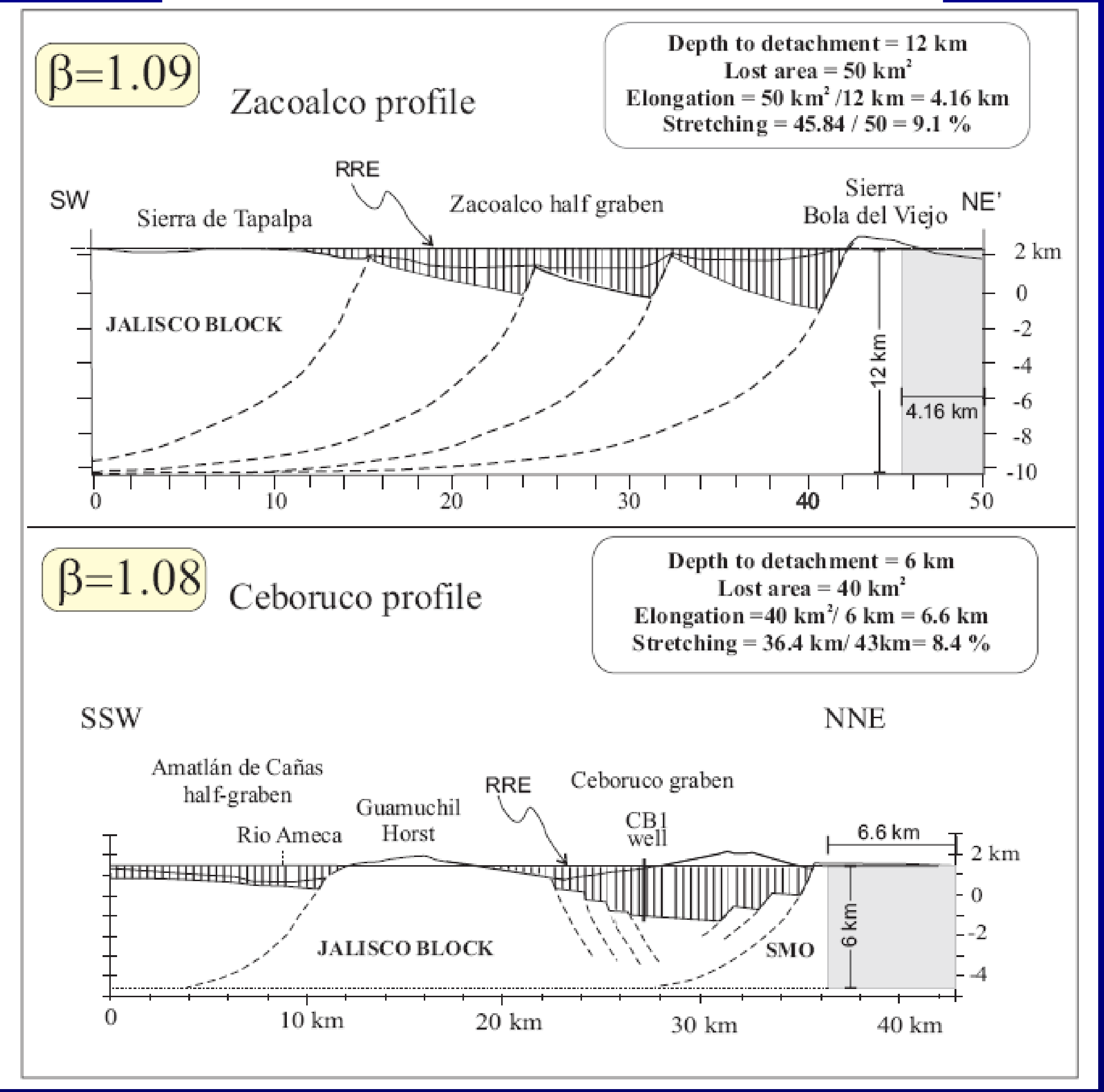
A M=6.1 earthquake occurred along the Acambay fault in 1912. Paleoseismic study estimate a recurrence time of 3,600 yr and a slip rate of 0.17 mm/yr (Langridge et al., 2000, JGR).

Intra-arc extension and intraplate volcanism in the western TMVB: Is the Jalisco block really rifting away?

Several arguments argue against a true continental rifting:

1) Low strain rate. In the Tepic-Zacoalco and Colima rifts extensional faulting took place for over 5 Ma but only produced less than 10% extension (Ferrari et al., 2001). Quaternary fault slip is <0.1 mm/yr (Ferrari and Rosas, 2000), similar to what happen in the central TMVB (Suter et al., 2001). These values are orders of magnitude less than in a typical continental rifting

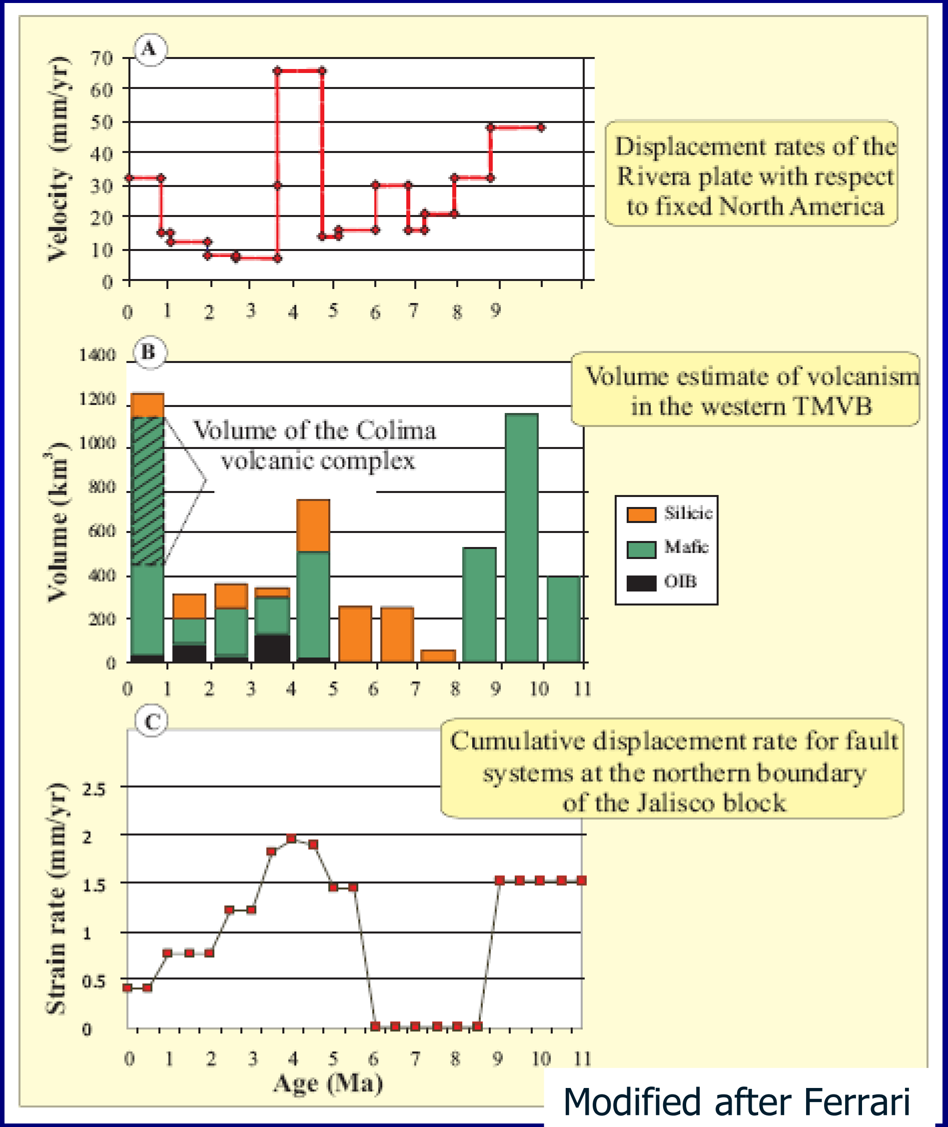
Ferrari et al., 2001, Geology (Data Repository)



Intra-arc extension and intraplate volcanism in the western TMVB: Is the Jalisco block really rifting away?

2) Alkaline volcanism (sometimes referred to as OIB) account for less than 5% of the volume of magmatism in the WTMVB (Ferrari et al., 2001).

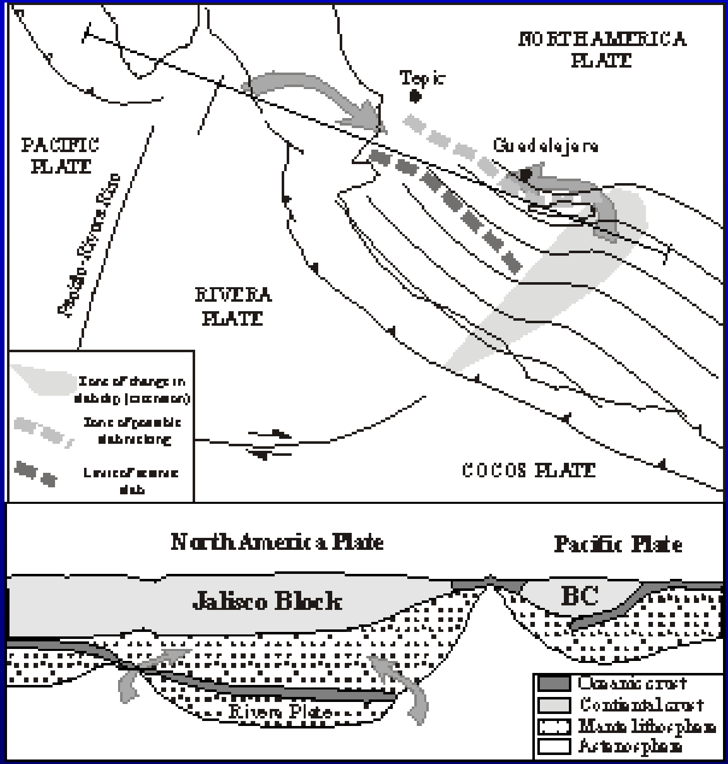
3) Period of high volcanic activity and faulting match periods of high convergence rate between Rivera and North America plates. This suggest that subduction (trench retreat?) ultimately control both processes.

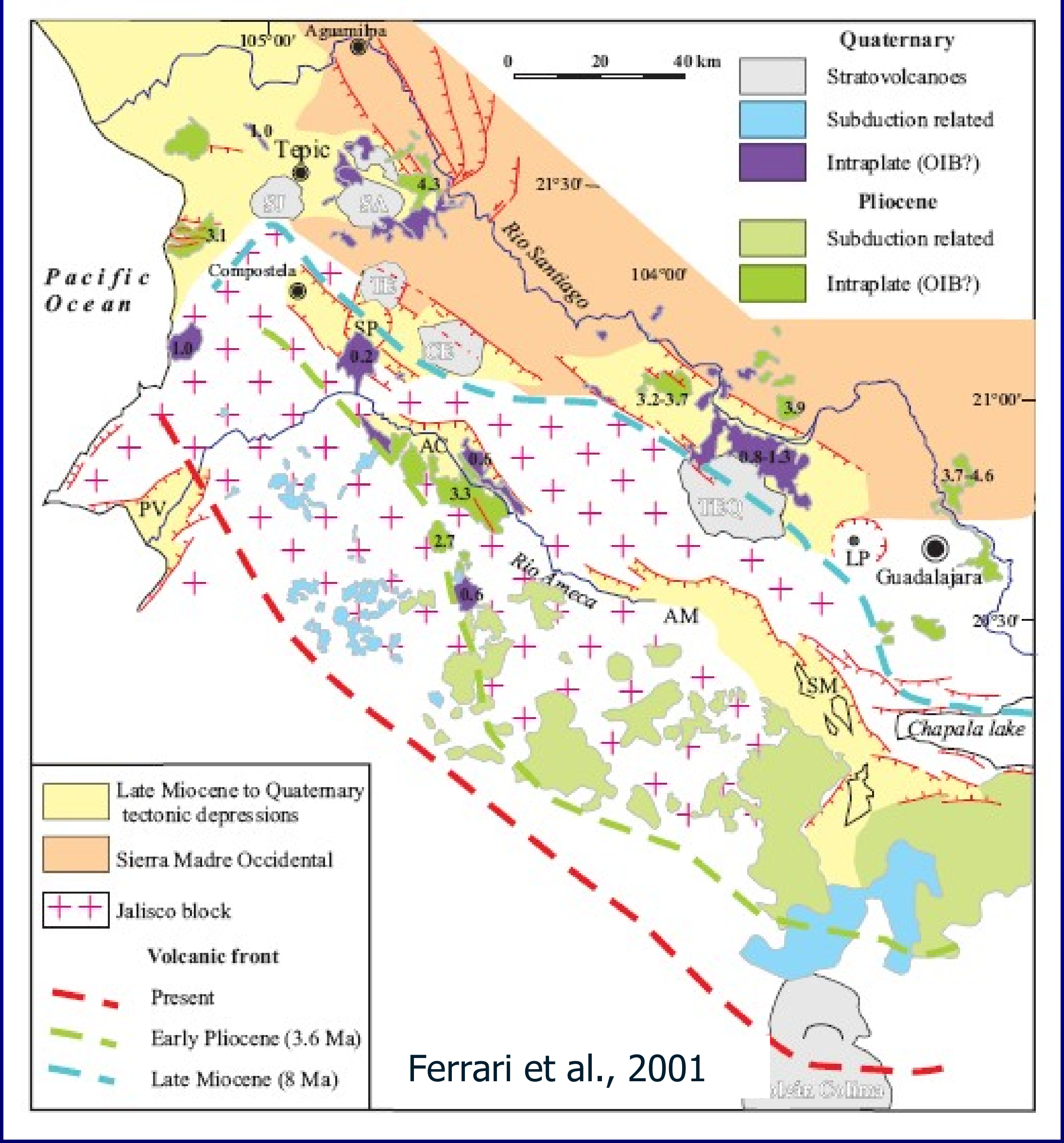


Modified after Ferrari et al., 2001, Geology

The southward migration of the volcanic front since ~8 Ma suggest that the Rivera microplate rolled back since then in response to decreasing convergence (DeMets and Traylen, 2000).

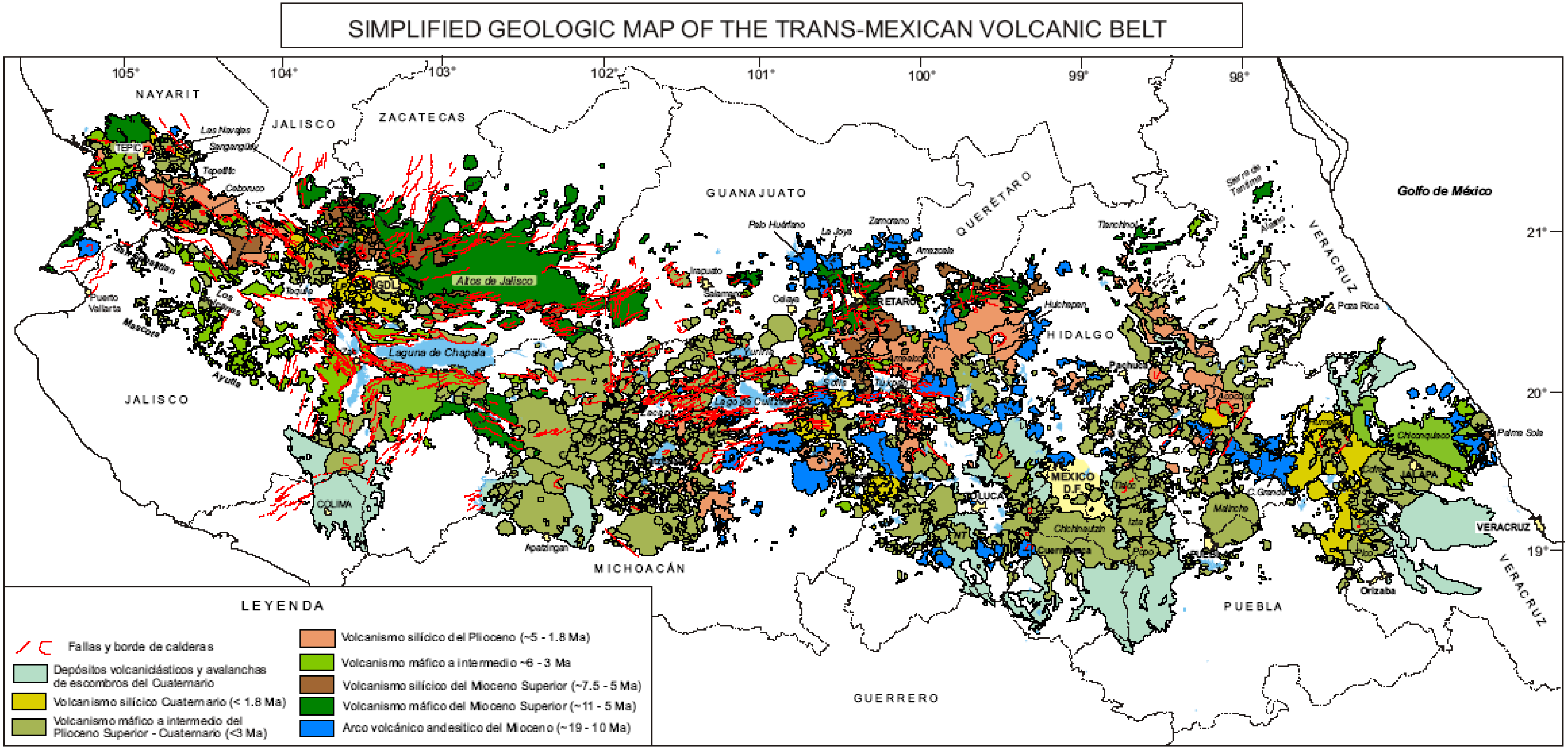
Ferrari et al. (2001) proposed that this process produced lateral infiltration of enriched sub-slab asthenosphere, resulting in intraplate (OIB?) volcanism emplaced in the rear part of the arc



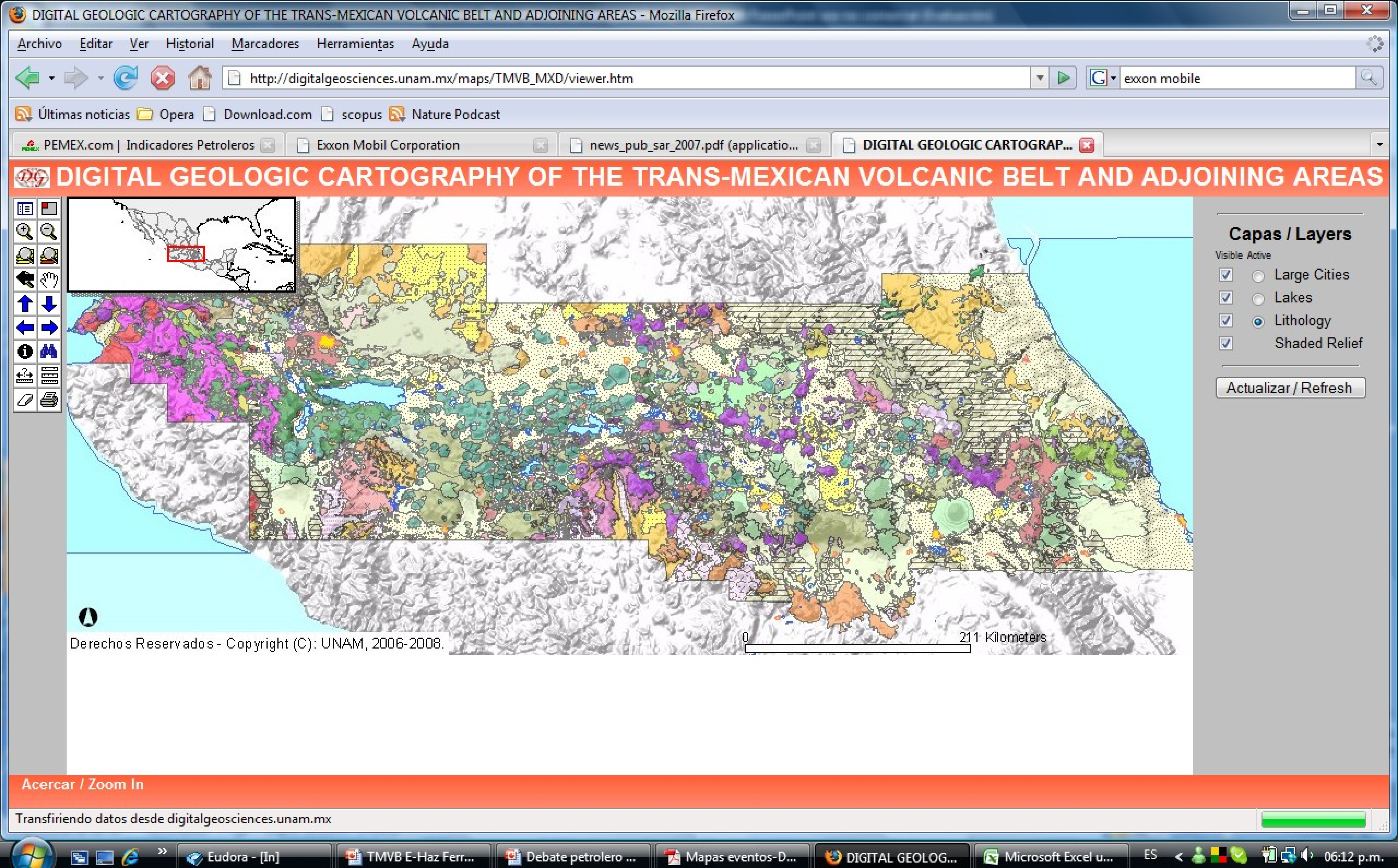


Ferrari et al., 2001

Geologic evolution of the TMVB

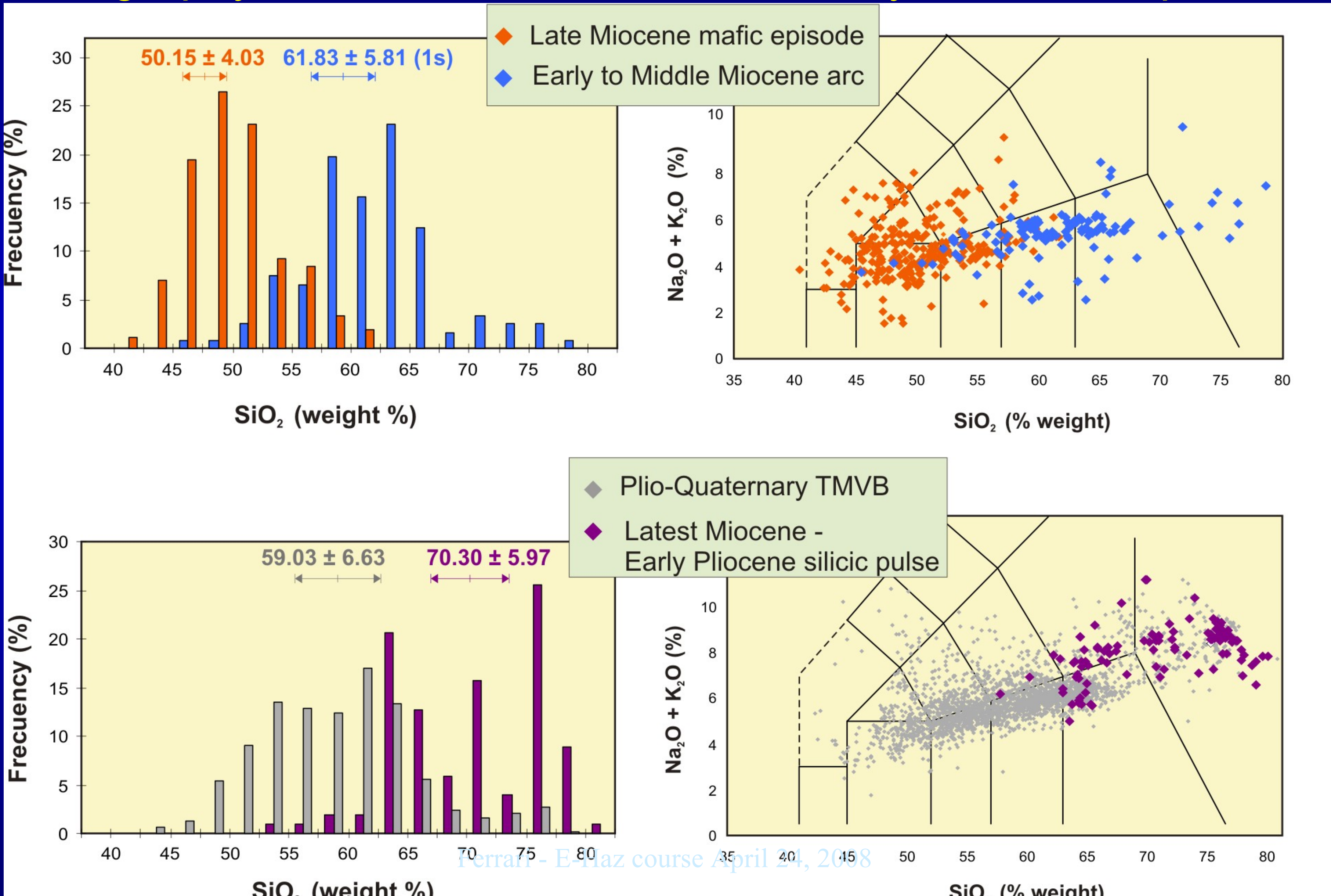


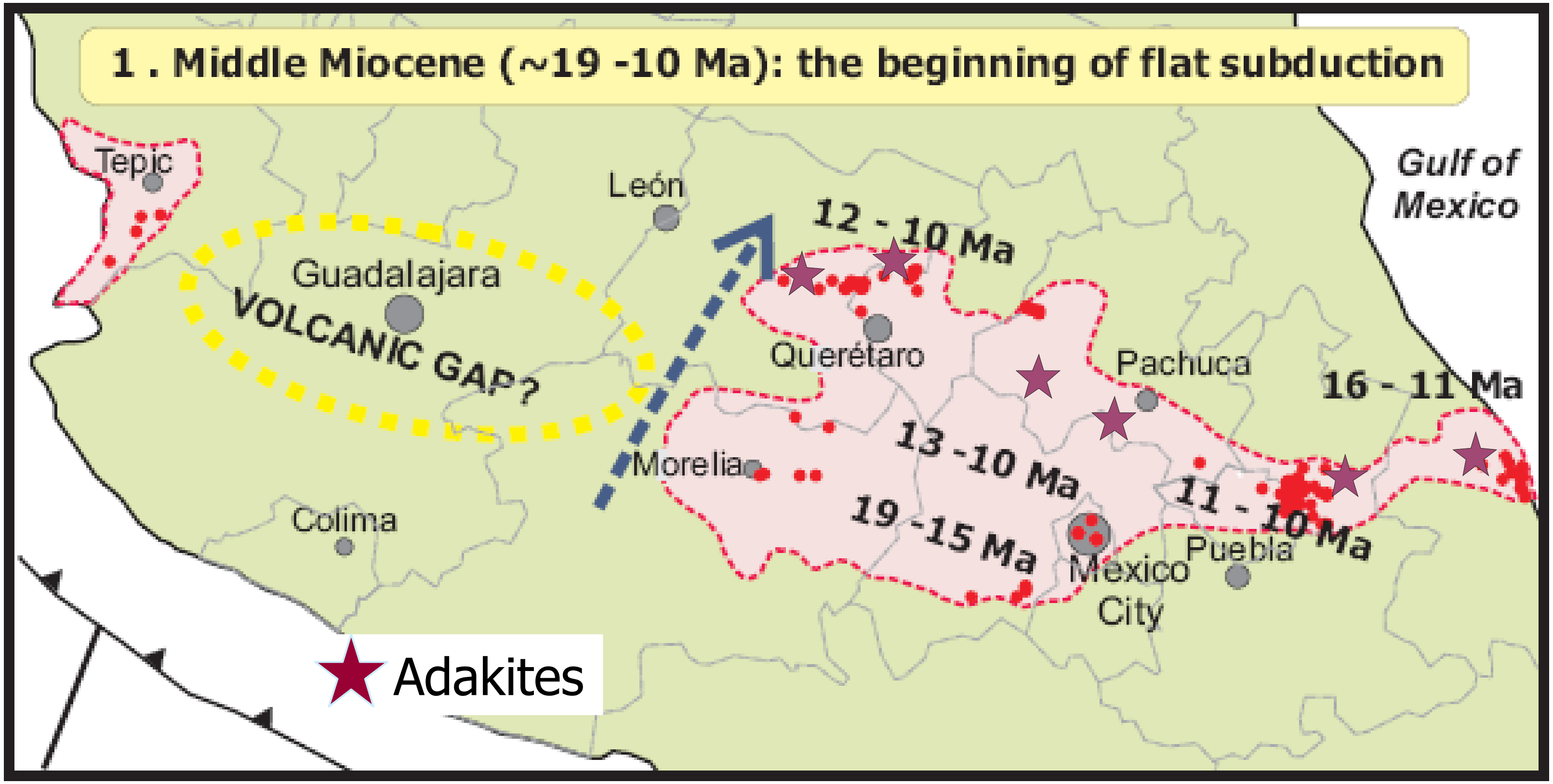
Gomez-Tuena, Orozco, Ferrari, (2007, GSA Special Paper)



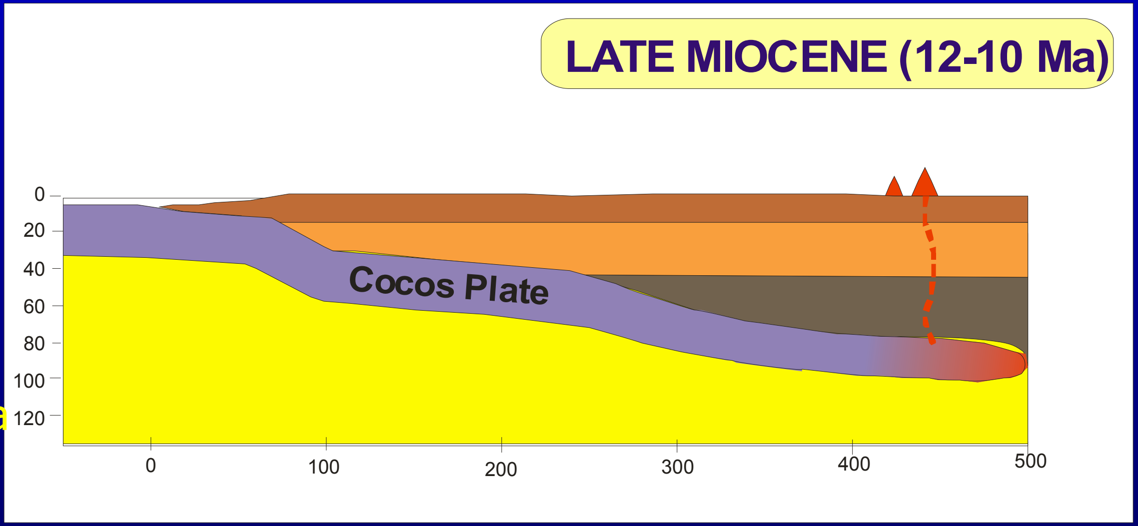
In the past seven years we compiled all the available geologic, geochronologic (~1,450 ages) and geochemical (~2,300 analyses) data for the TMVB into a Geographic Information System. The document is available online at: http://digitalgeosciences.unam.mx/toc.htm#ferrari_2005

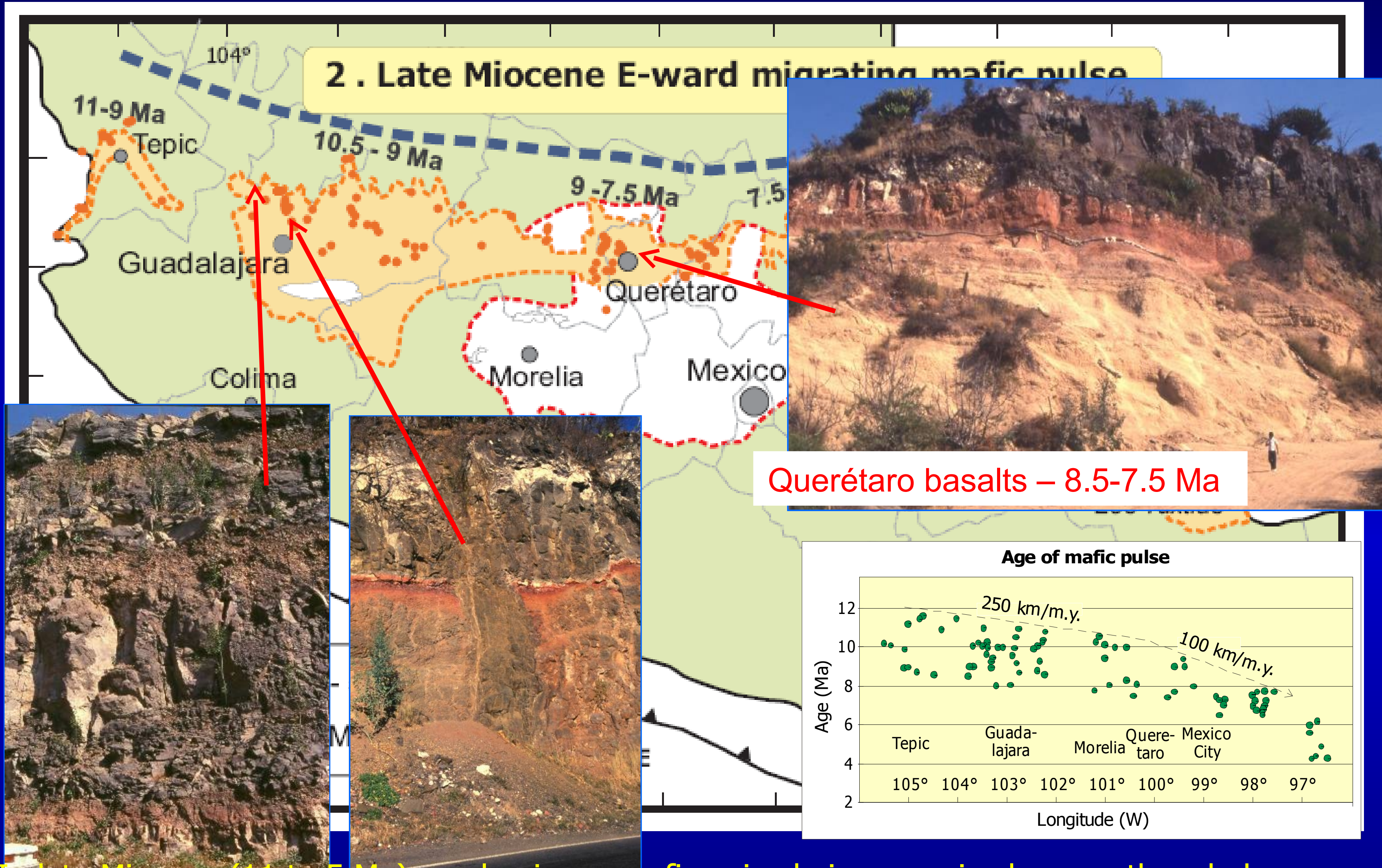
Combining geochemical and geochronologic data with geologic cartography the TMVB can be described by four main episodes





The initial TMVB consists of a broad arc of mafic to intermediate polygenetic volcanoes. From ~20 to ~10 Ma this volcanism migrated away from the trench, toward the NE. The youngest (13-10 Ma) and most inland centers form a WNW-ESE belt with an adakitic signature, which was interpreted as the result of a flat subduction (Gomez-Tuena et al., 2003) in agreement to the model of Gutscher et al. (2000).

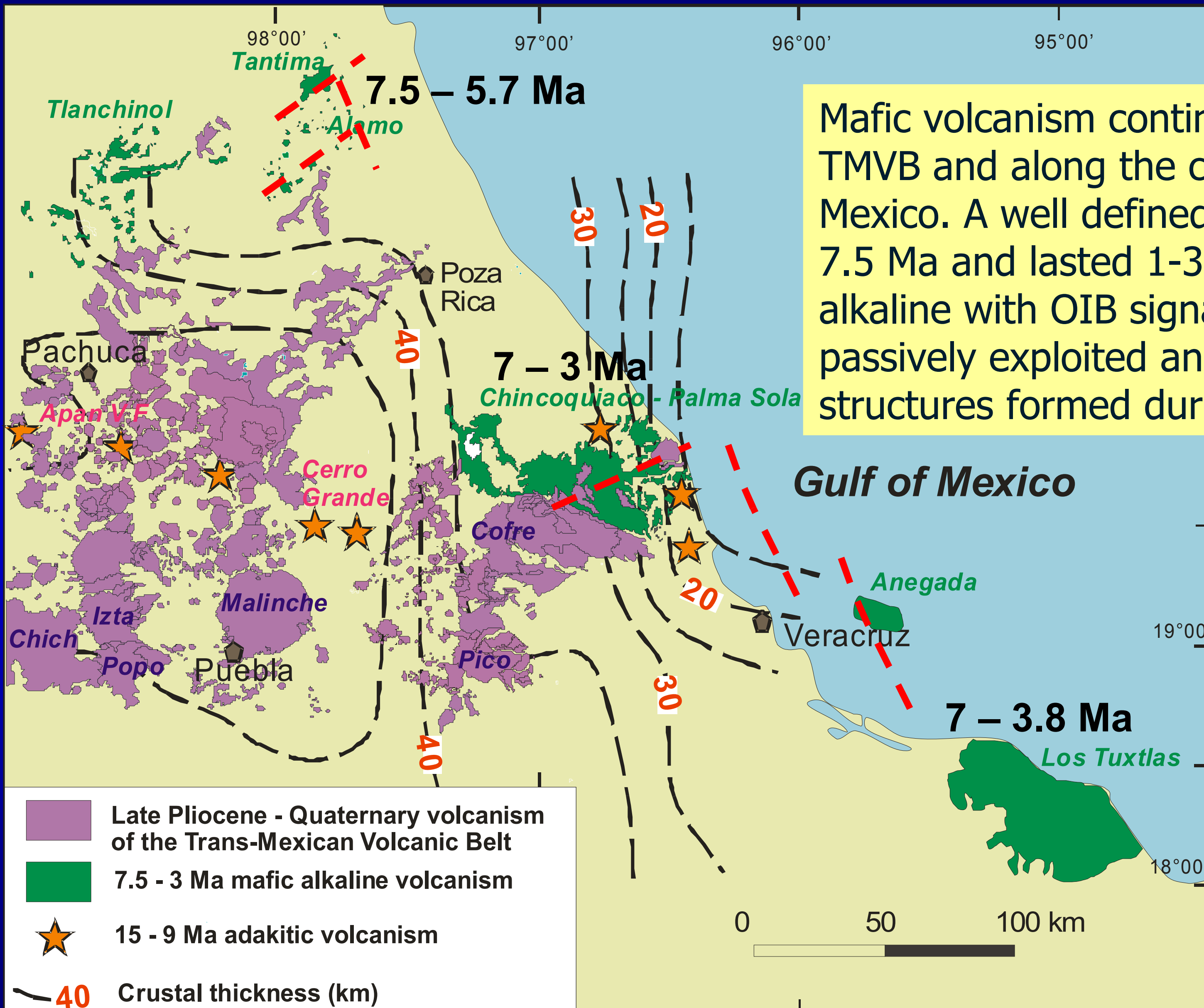




San Cristobal plateau, Gdl., 10.5 – 9.5 Ma

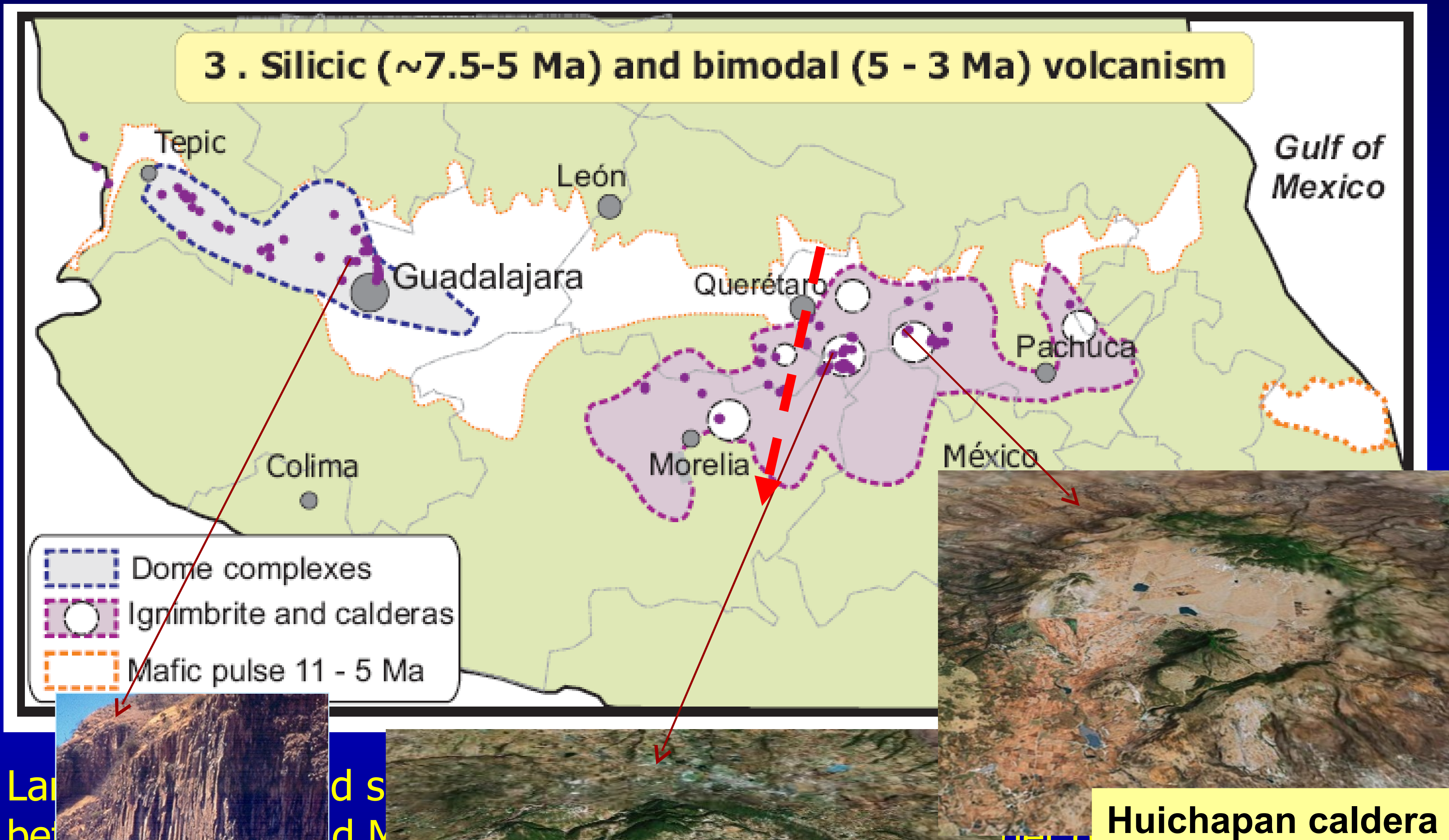
In late Miocene (11 to 5 Ma) a voluminous mafic episode is recognized across the whole central Mexico to the north of the previous arc with ages progressively younger from west to east. Many of these mafic lavas were fissure-fed along prominent extensional fault systems. Their chemical composition span from calcalkaline to Na-alkaline, the latter located mostly at the eastern border of the altiplano and in the Gulf of Mexico plain.

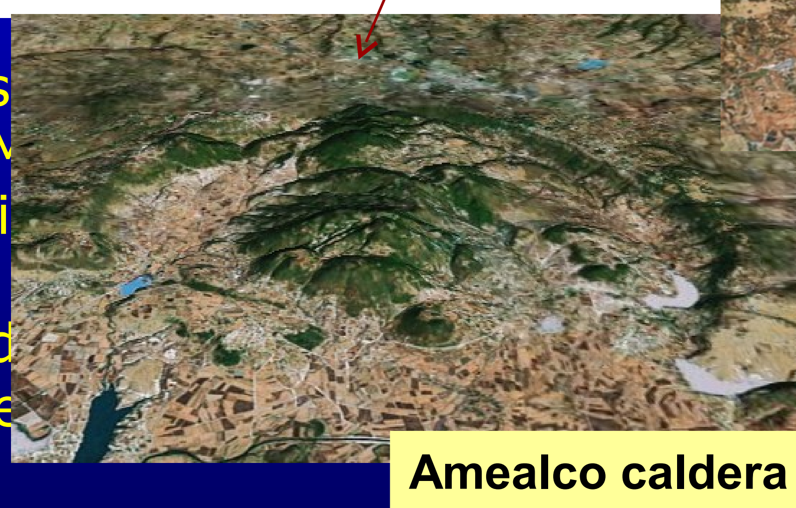
Continuation of the mafic pulse along the Gulf of Mexico



Mafic volcanism continues in the eastern TMVB and along the coast of the Gulf of Mexico. A well defined episode started at 7.5 Ma and lasted 1-3 Ma. Lavas are alkaline with OIB signature. They passively exploited ancient crustal structures formed during Gulf rifting.

Ferrari et al. 2005, JVGR





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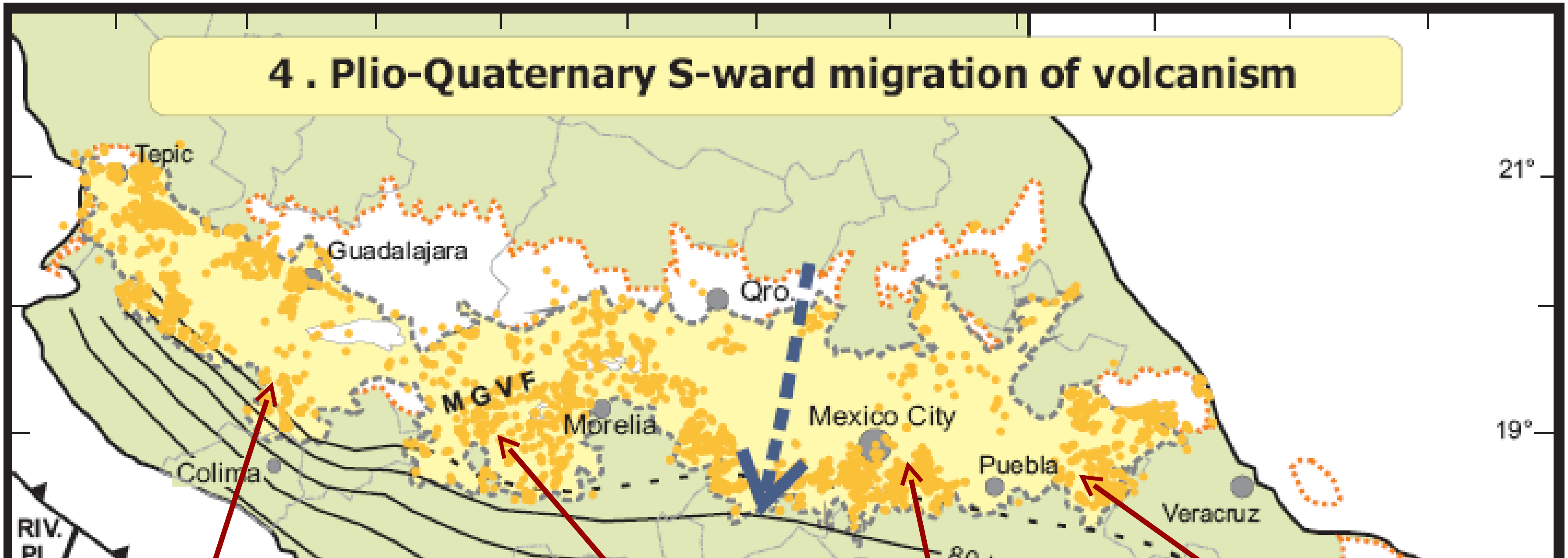
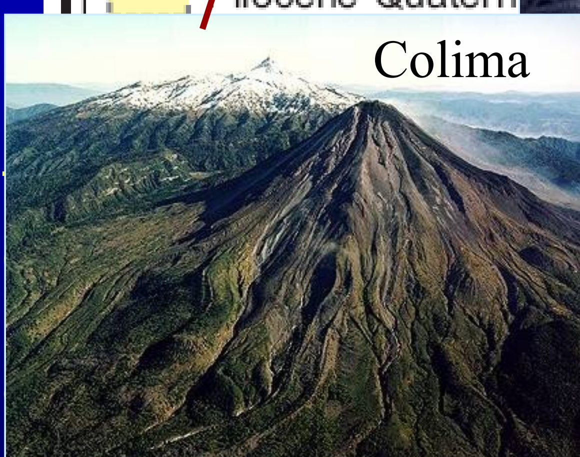
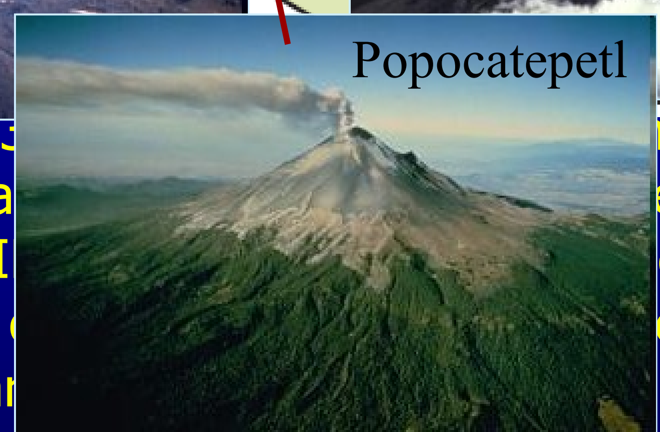
Ori… and … affinity were
em… ne e… easternmost TMVB.







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Genetic models for the TMVB

Not everybody agree…

The peculiar chemical composition and the poor definition of the geometry of the subducting slab beneath the TMVB prompted some author to deny subduction in the genesis of the arc

Papers that deny subduction in the genesis of the FVTM:

- Verma 1999, JVGR
- Marquez et al., 1999, Geology
- Verma 2000, GSA special paper 334
- Sheth et al., 2000, Int, Geol. Review
- Verma, 2002, Geology
- Torres-Alvarado et al. 2002, *Comment to Ferrari et al.,* Geology
- Torres-Alvarado & Verma 2003*, Comment,* GSAB

Papers explaining the complexity of the FVTM considering the dynamics of subducción

- Ferrari et al., 2001 (Geology), 2005 (JVGR); Ferrari, 2004 (Geology)
- Gomez-Tuena et al., 2003 (G-Cubed), 2007 (GSA SP)

The Marquez et al. (1999) model: A mantle plume to explain the TMVB?

Alkalic (ocean-island basalt type) and calc-alkalic volcanism in the Mexican volcanic belt: A case for plume-related magmatism and propagating rifting at an active margin?

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Roberto Oyarzun Departamento de Cristalografía y Mineralogía, Facultad de Ciencias Geológicas, Universidad Complutense, 28040 Madrid, Spain
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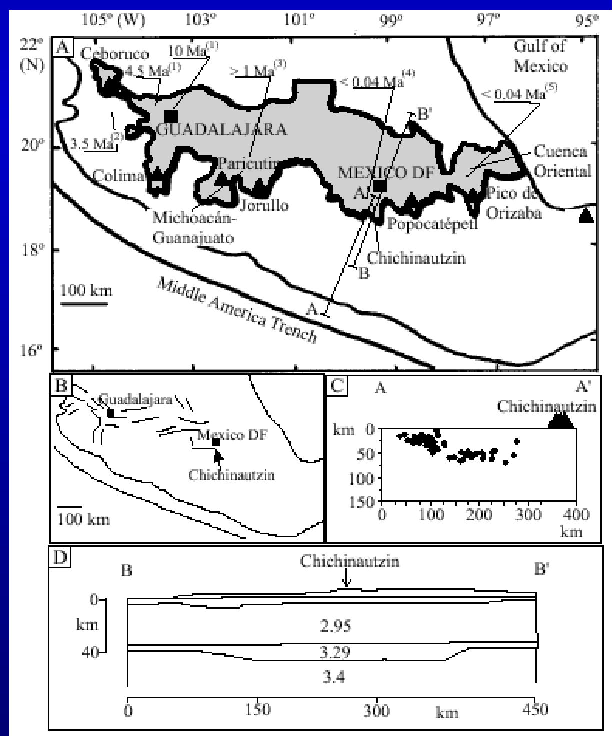
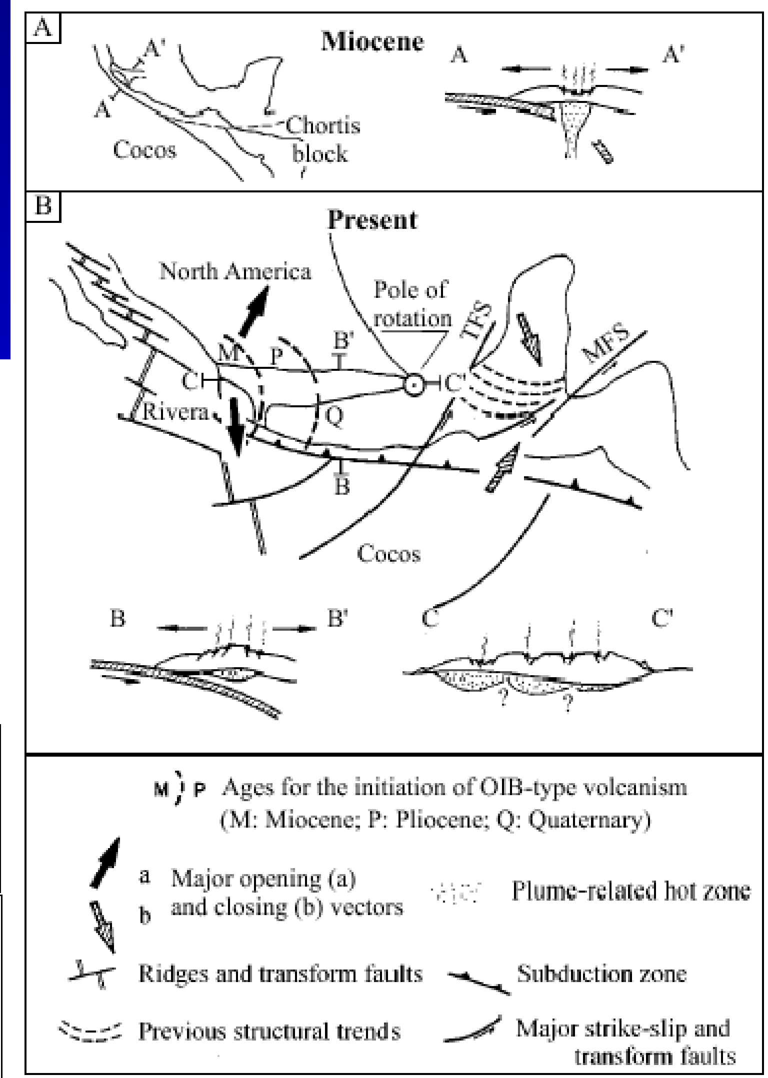
Surendra P. Verma Centro de Investigación en Energía, Universidad Nacional Autónoma de México, Temixco 62580, Morelos, Mexico

Marquez et al. (1999), proposed that the entire TMVB is related to a mantle plume that impacted western Mexico in the late Miocene. In their model the plume first broke the subducting plate but the plate will eventually take revenge by cutting off the plume head.





The Marquez et al. (1999) model: A mantle plume to explain the TMVB?

The model was essentially based on geochemistry and is 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:

- neither the rifting nor the OIBs present the age progression required by the plume model;
- in western Mexico, where the plume should have impacted, there is no evidence of regional uplift;
- 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.

In addition the mechanism is physically very unlikely: there are no example in the world where a plume managed to cut across a slab. The slab is denser en colder than a plume.

Sheth, Torres-Alvarado and Verma (2000, IGR): No plume

The rifting model

Essentially based on geochemistry. A veined mantle beneath the TMVB.
No detailed description of the tectonic mechanism:

- Sheth et al. (2000, International Geology Review, pag. 1127): “under the present extensional conditions the enriched sources undergone melting”
- Verma (2002, Geology, pag. 1098): “partial melting of an upwelling heterogeneous mantle source … facilitated by ongoing rifting process”

Sheth et al., 2000

THE MEXICAN VOLCANIC BELT 1127

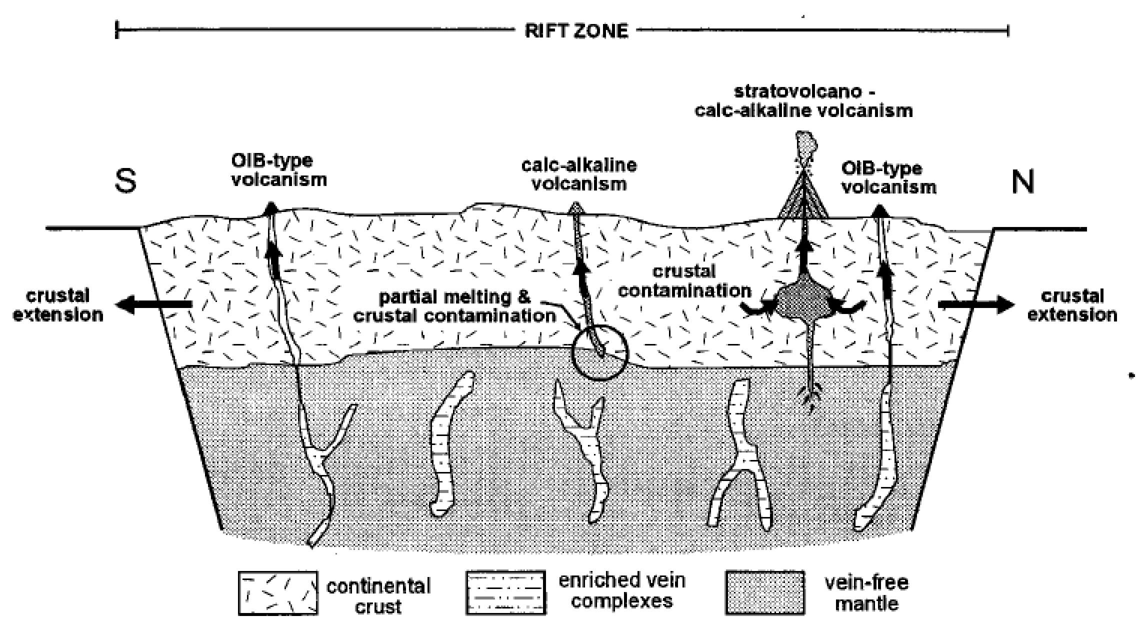


FIG. 7. Schematic diagram showing our proposed model of derivation of OIB-type magmas from metasomatically veined mantle, and calc-alkaline magmas from normal, vein-free mantle, followed by crustal contamination. See text for details.

The rifting model

Absence of Cocos plate subduction-related basic volcanism in southern Mexico: A unique case on Earth?

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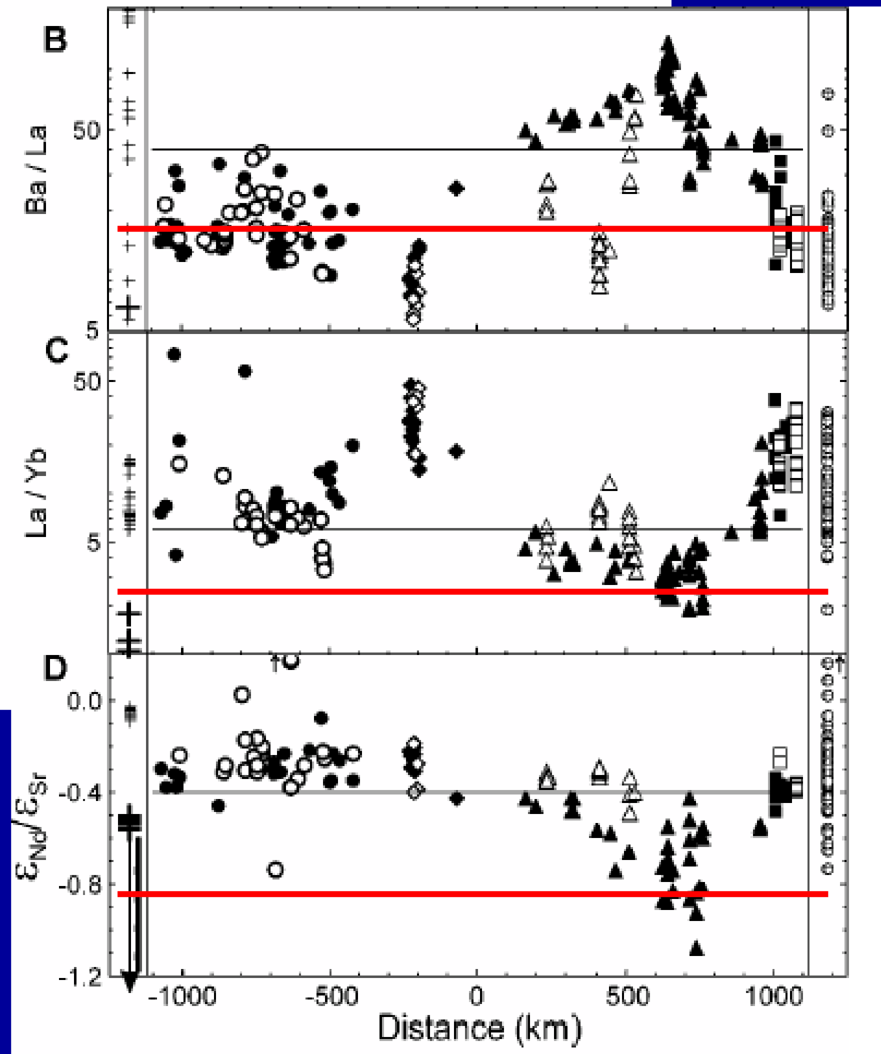
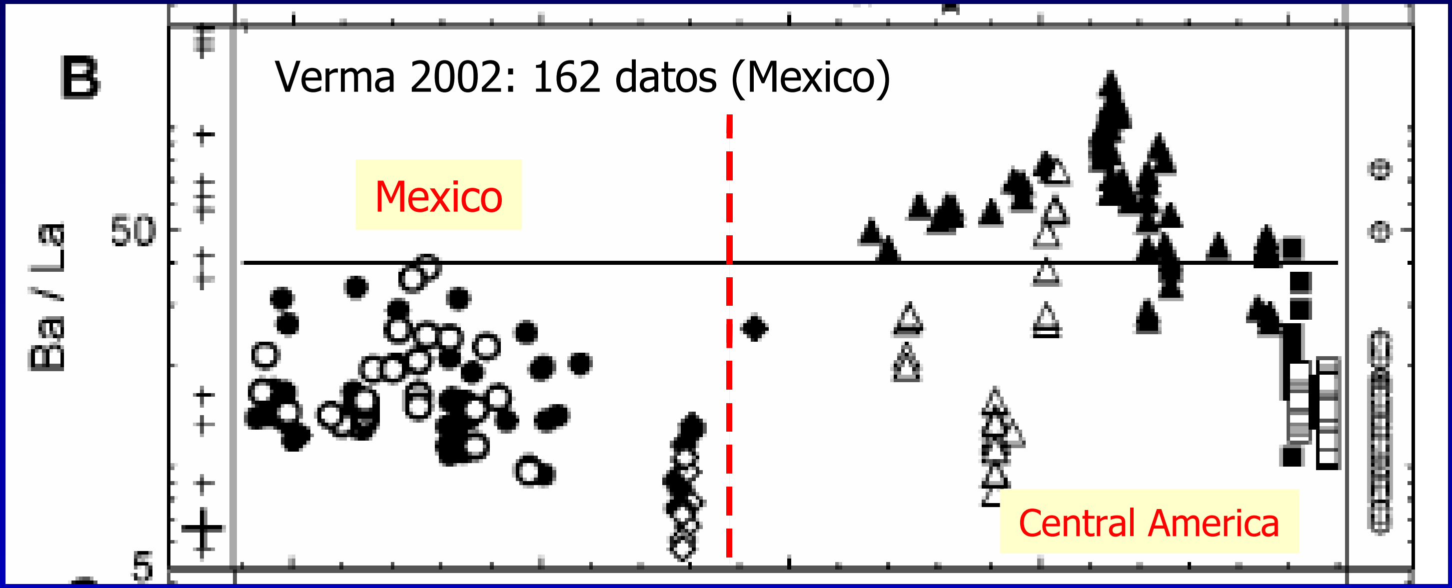
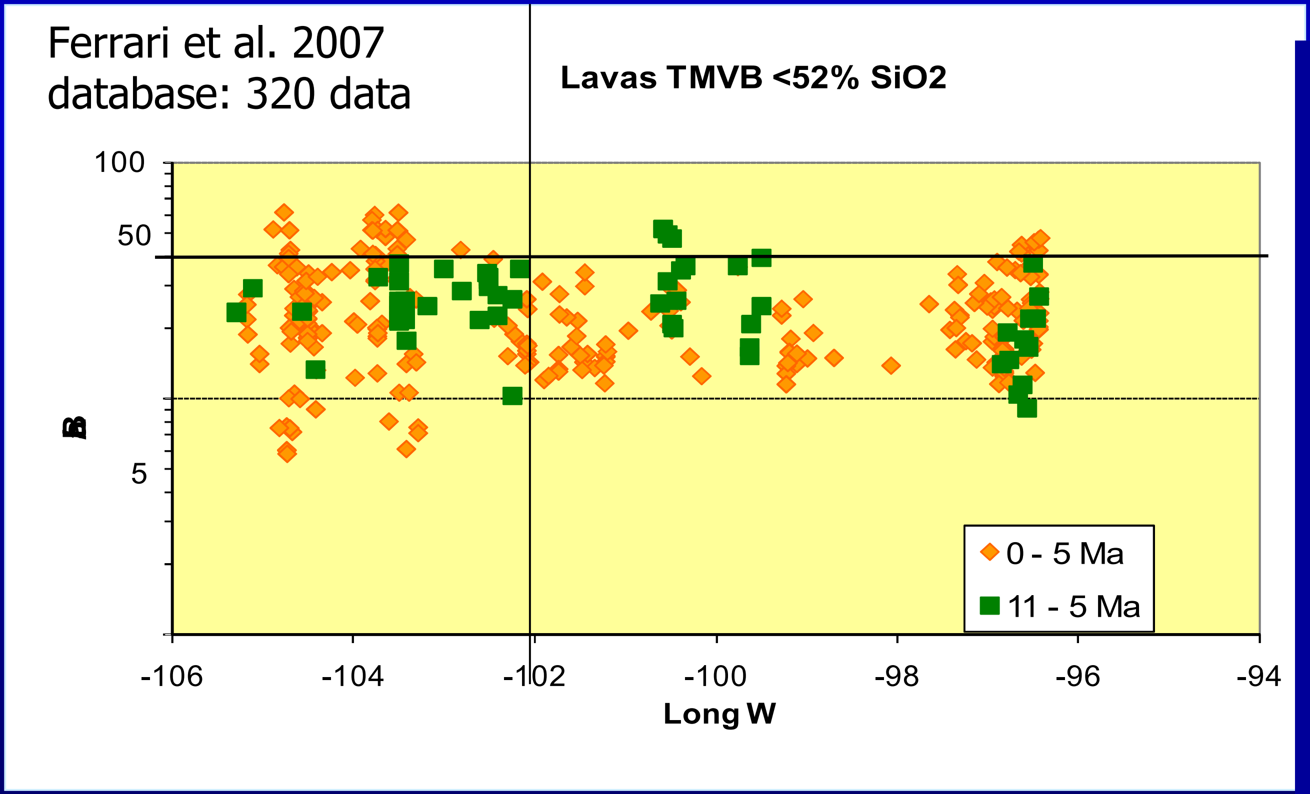
Figure 2. Selected parameters for basic rocks (SiO_2 < 52%) from southern Mexico and Central America plotted against distance along trench axis (Middle America Trench [MAT] in Fig. 1) as measured from close to Mexico-Guatemala border—marked 0 km distance. Distances corresponding to Mexico are expressed as negative values and those for Central America as positive ones. Data are plotted by using same symbol codes as in Figure 1 for sample locations. Also included are data for same parameters for basic rocks from six well-known rifts (crossed circle symbols at right part of diagrams), as well as for mid-ocean-ridge basalt (MORB) and sediments from subducting Cocos plate (crosses at left part of diagrams; large crosses are for MORB and small ones for overlying sediments). A: Depth of earthquake hypocenters from Mexico to Costa Rica (horizontal reference line is for depth = 80 km). B: Ba/La ratio, which when high indicates subduction signature (horizontal reference line is for Ba/La = 40). C: La/Yb ratio, which when high indicates mantle signature (horizontal reference line is for La/Yb = 6). D: $\varepsilon_{Nd}/\varepsilon_{Sr}$, which when high indicates mantle signature, where $\varepsilon = [(R_{sample} - R_{CHUR})/R_{CHUR}] \times 10^4$; R = $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ for ε_{Nd} and ε_{Sr}, respectively. Ratio of $\varepsilon_{Nd}/\varepsilon_{Sr}$ was calculated by using $(^{143}Nd/^{144}Nd)_{CHUR}$ = 0.512638 and $(^{87}Sr/^{86}Sr)_{UR}$ = 0.70475 (horizontal reference line is for $\varepsilon_{Nd}/\varepsilon_{Sr}$ = −0.4). For Cocos plate, mixtures of MORB and sediments are also shown by using solid line and arrow.



Comparing trace element and isotope ratios of the central and eastern TMVB with those of six continental rifts Verma (2002) proposed that subduction plays no role in the genesis of the TMVB.
NOTE: he arbitrarily draws boundary lines between rift-related and subduction-related rocks which do not match the limits of the compared rifts.





Ba/La plot from Verma (2002) only include 162 data and leaves out ~30% of the TMVB by cutting the graph at Long. 102° W.
Compare it with Ferrari et al. (2007) database for the whole TMVB. It shows that the western TMVB has values similar to most Central America except Nicaragua.

SUTER et al.

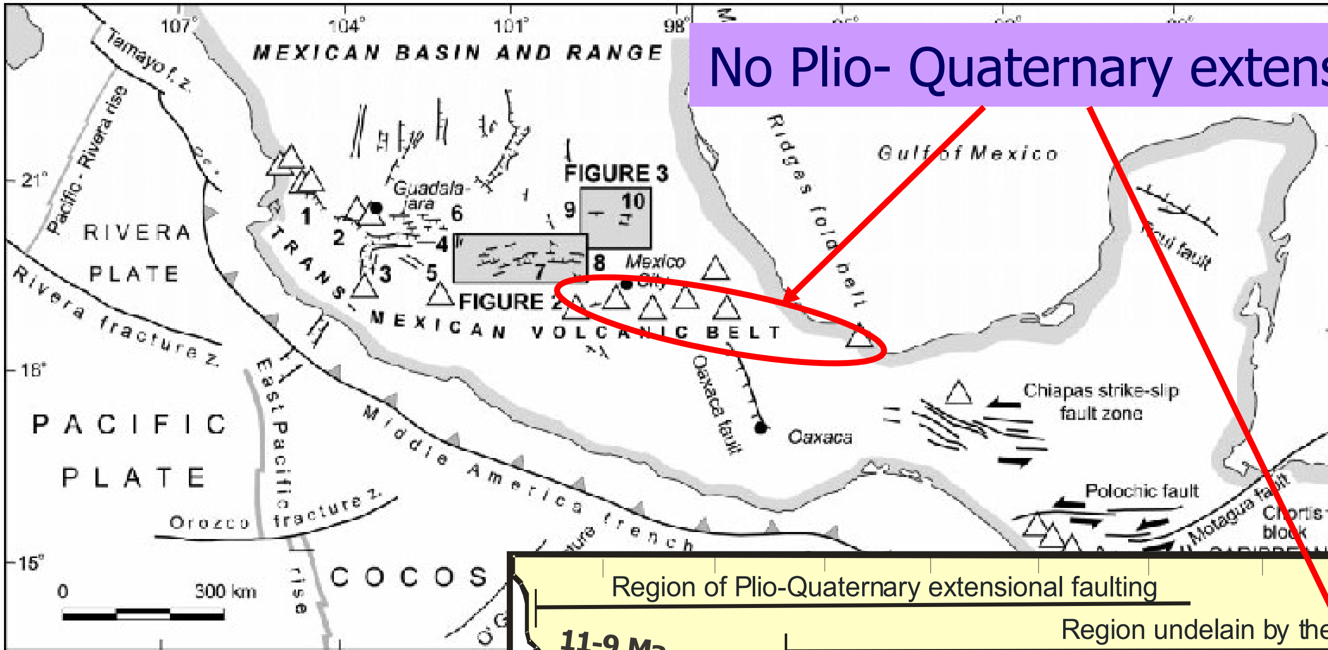
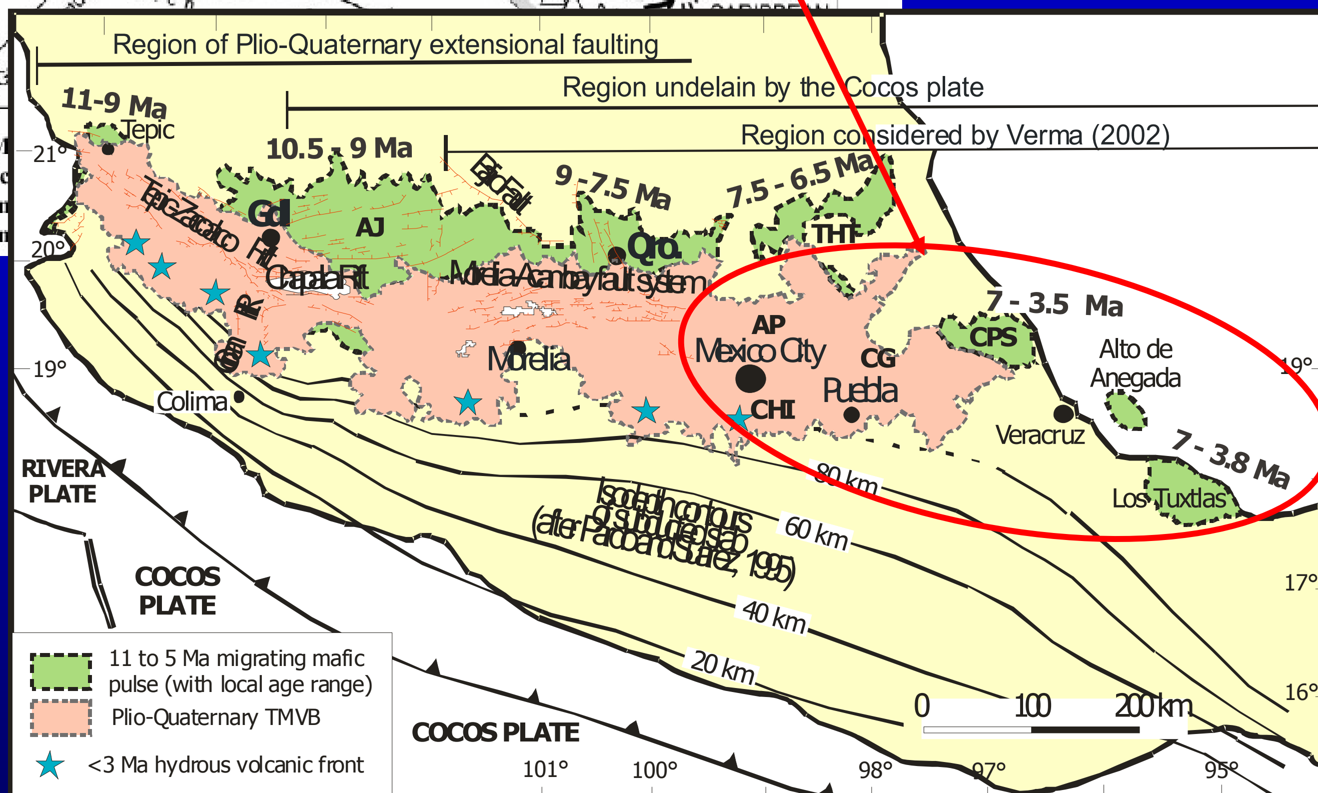


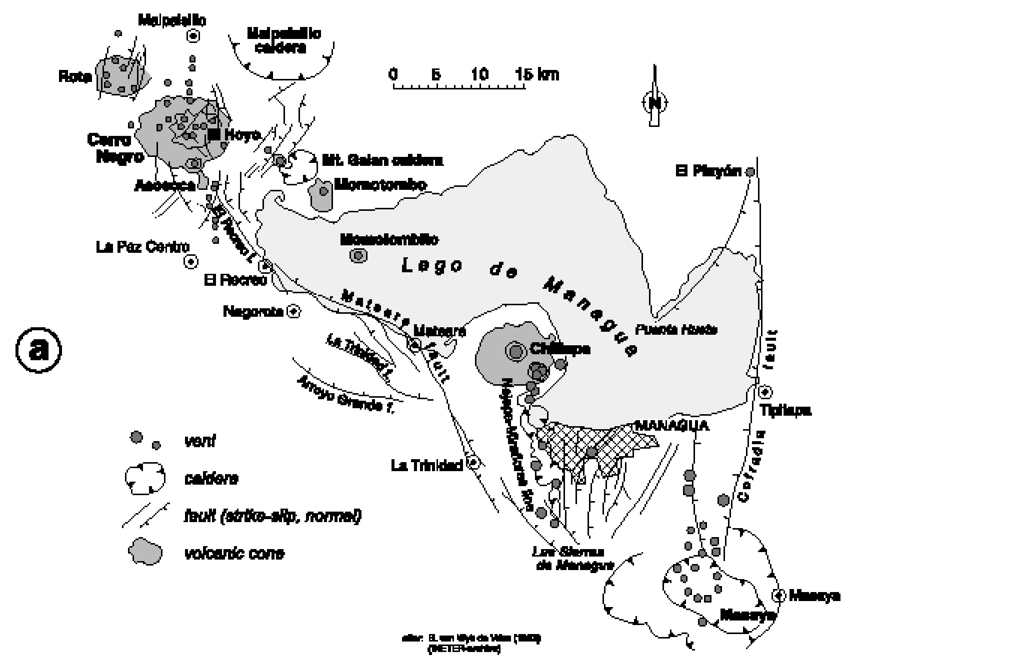
Figure 1. Neotectonic map of central and southern M
belt: 1—Amatlán de Cañas half-graben; 2—Zacoalc
de Jalisco fault zone; 7—Cuitzeo graben; 8—Acan
major volcanoes of the Mexican and Guatemaltecan

No Plio- Quaternary extensional faulting here

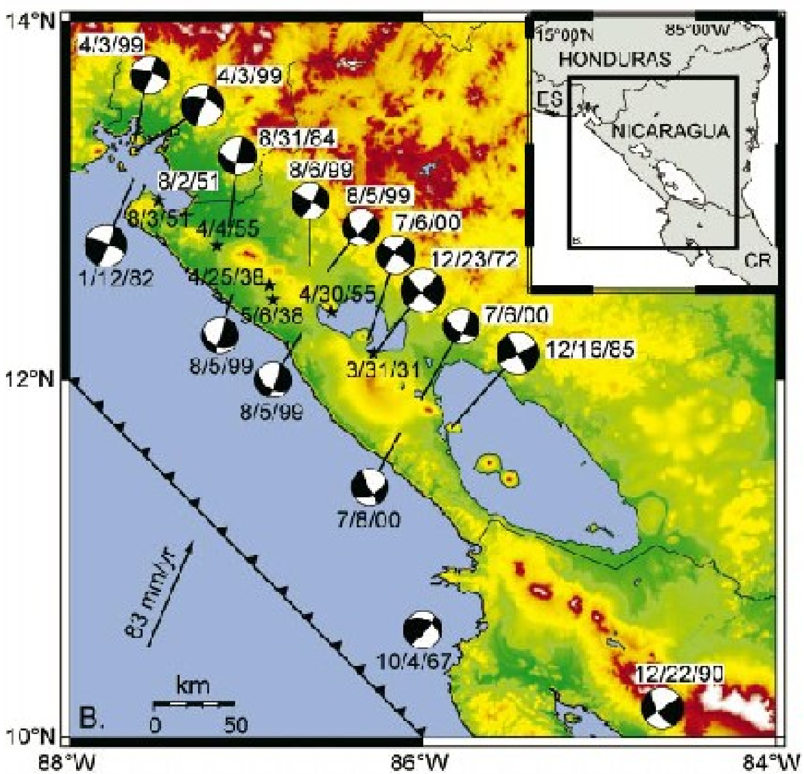


The main inconsistency of the model is that Plio-Quaternary extensional faulting is missing in about 70% of the region where rifting is predicted to occur by *Verma* (2002), i.e. east of longitude 102°W

Paradoxically Nicaragua, predicted to have the strongest slab signature by Verma (2002) is characterized by a major transtensional system with prominent grabens (also known as the Central America graben).



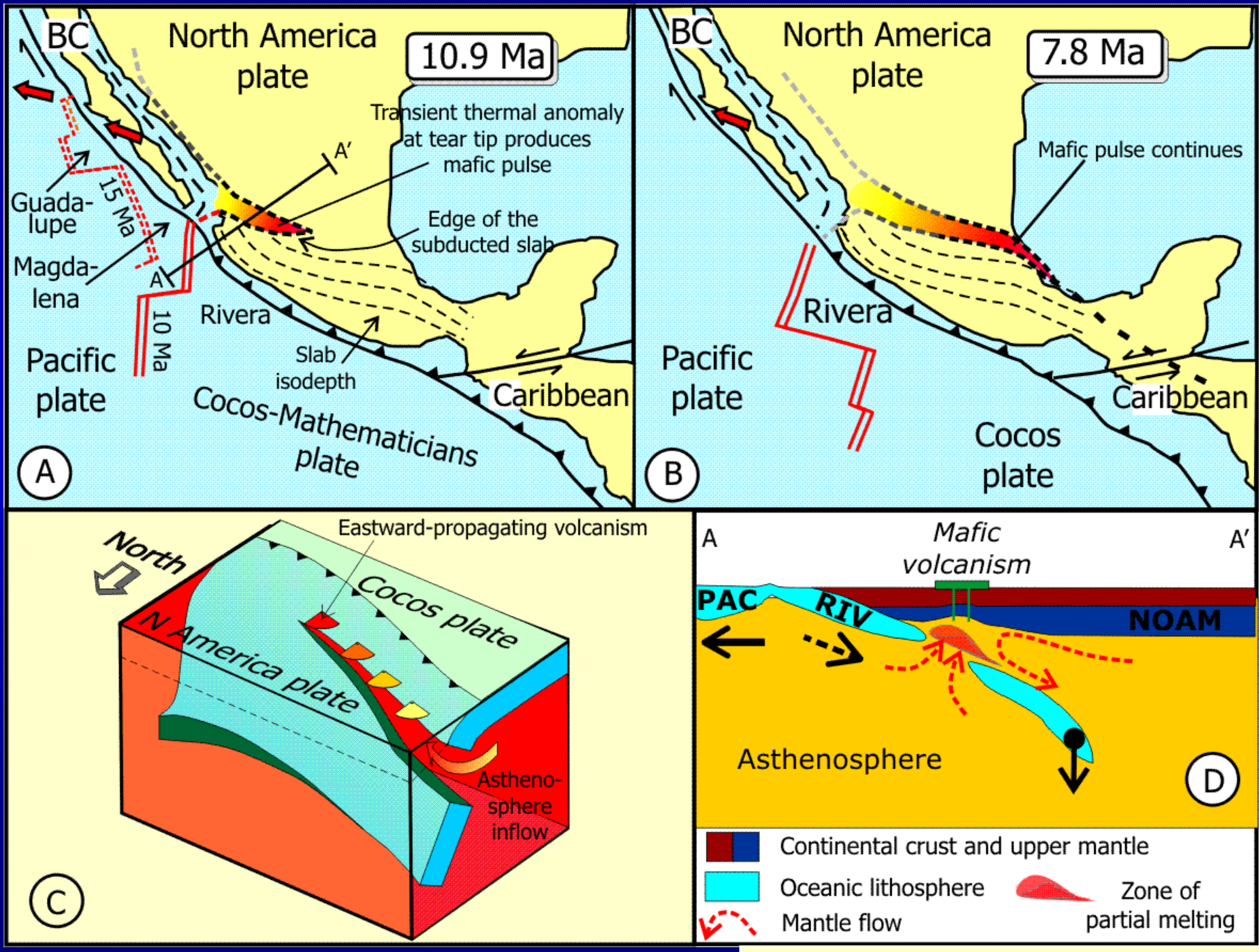
Observed structures and subrecent volcanic features in the surroundings of Lake Managua (after van WYK DE VRIES, 1993).



This occur when geochemists work without geologic supervision…

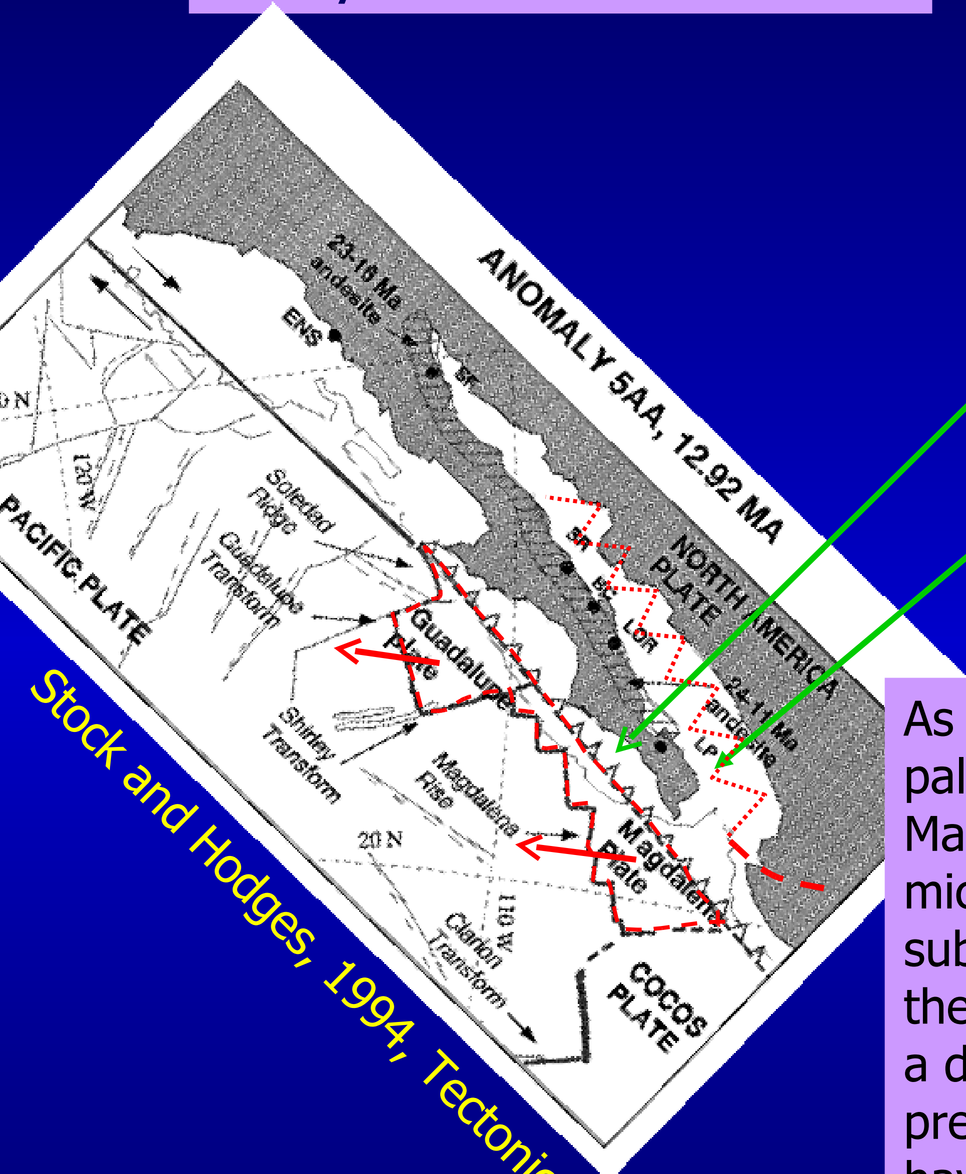
Lateral propagation of slab detachment: a model to explain the eastward mafic pulse and the compositional variety of the TMVB

In my 2004 model I predicted that the slab broke off in the Gulf of California after subdcution ceased at 12.5 ma. I proposed that the tear propagated laterally to the ESE, more or less parallel to the active Cocos subduction zone. This would produce the E-ward migrating pulse of mafic volcanism observed from ~11 to 5 Ma in the northern TMVB.

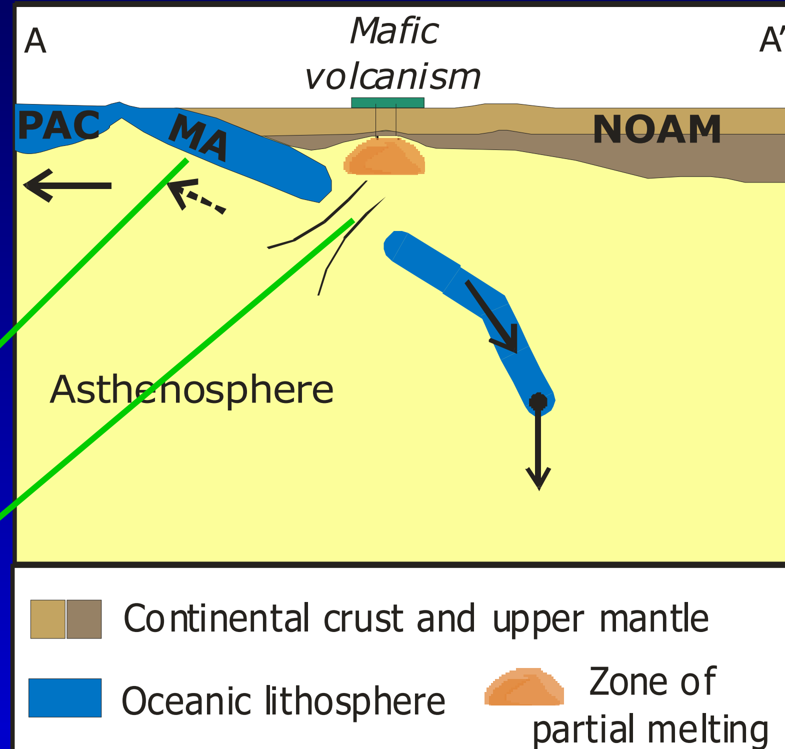


Ferrari, 2004, Geology

¿Why the slab broke off?



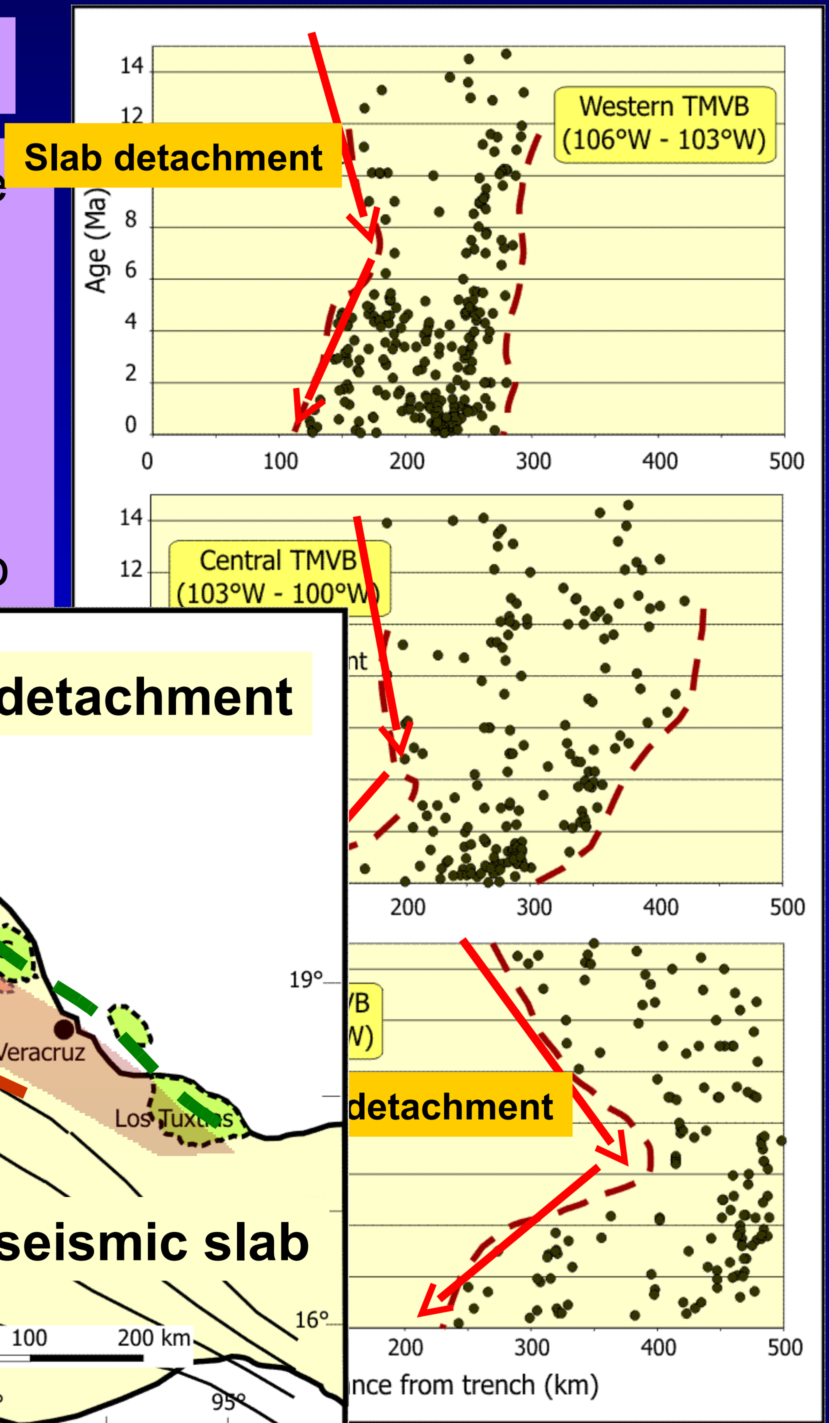
Stock and Hodges, 1994, Tectonics

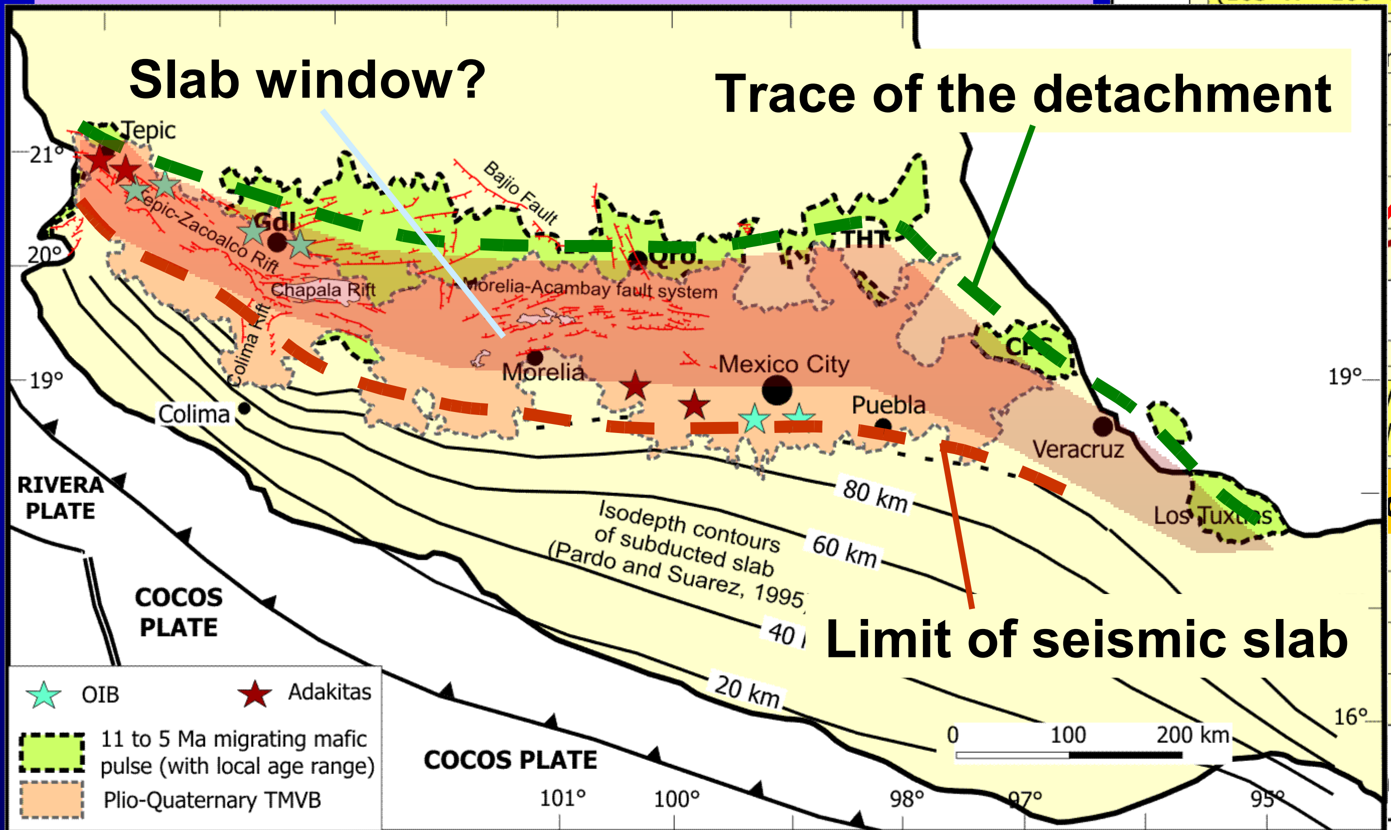


As the East Pacific Rise approached the paleotrench off Baja California the young (<3 Ma) Magdalena (MA) and Guadalupe microplates became increasingly hard to subduct. They were eventually captured by the Pacific plate and started to move with it in a direction almost orthogonal with their previous motion. The subducted plate must have ruptured below the zone of coupling with Baja California (the site of the future Gulf of California).

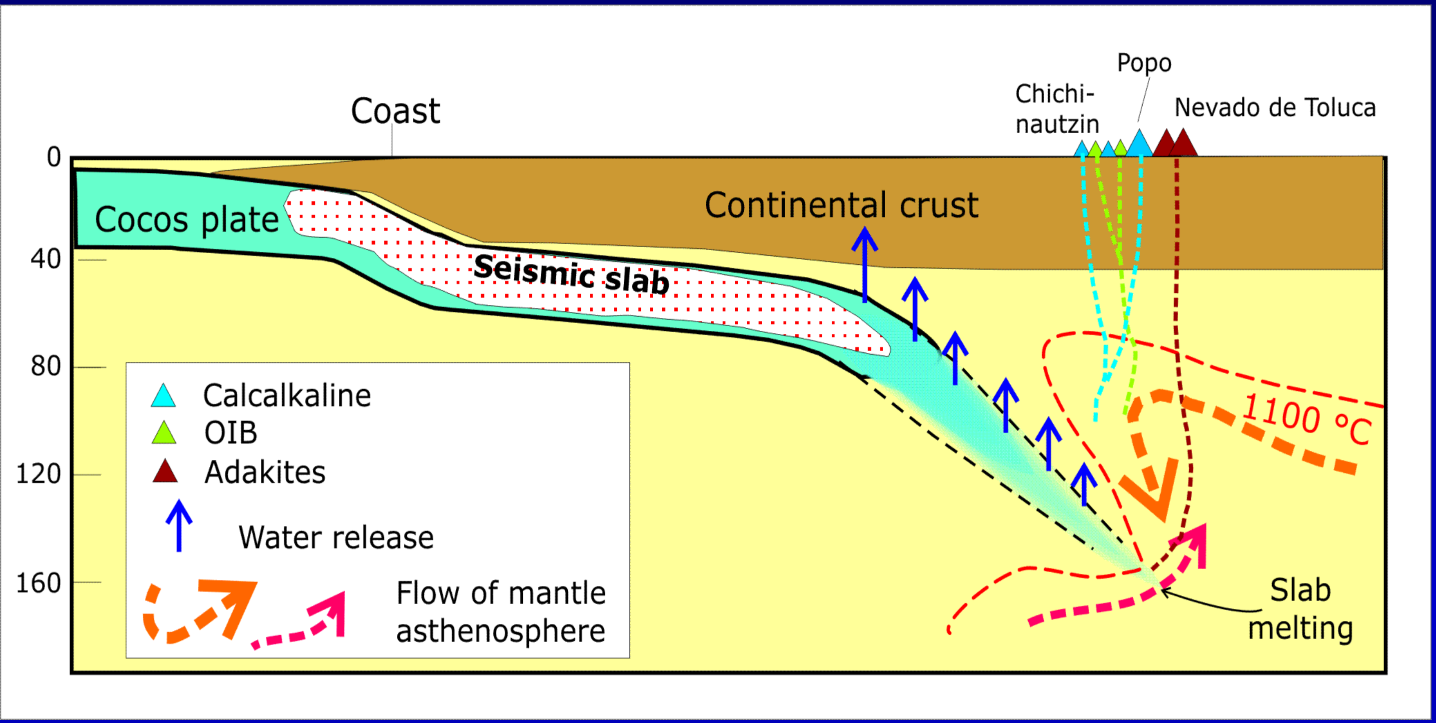
Arc evolution since Middle Miocene

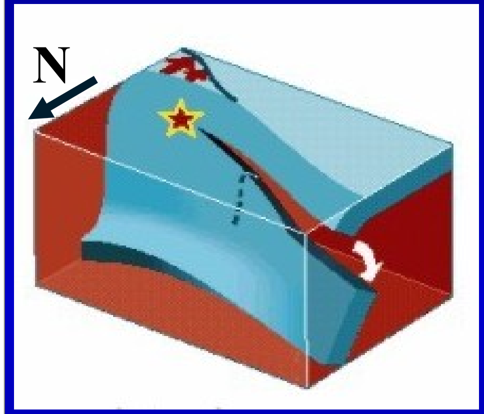
- ~19 -10 Ma: arc migration away from the trench
- 2) ~11-5 Ma: slab detachment, E-ward migrating mafic pulse
- 3) 7.5 - ~3 Ma: arc start to migrate back toward the trench, silicic pulse
- 3.5-0 Ma: volcanic fron migrate further to





Evolution since ~8 Ma





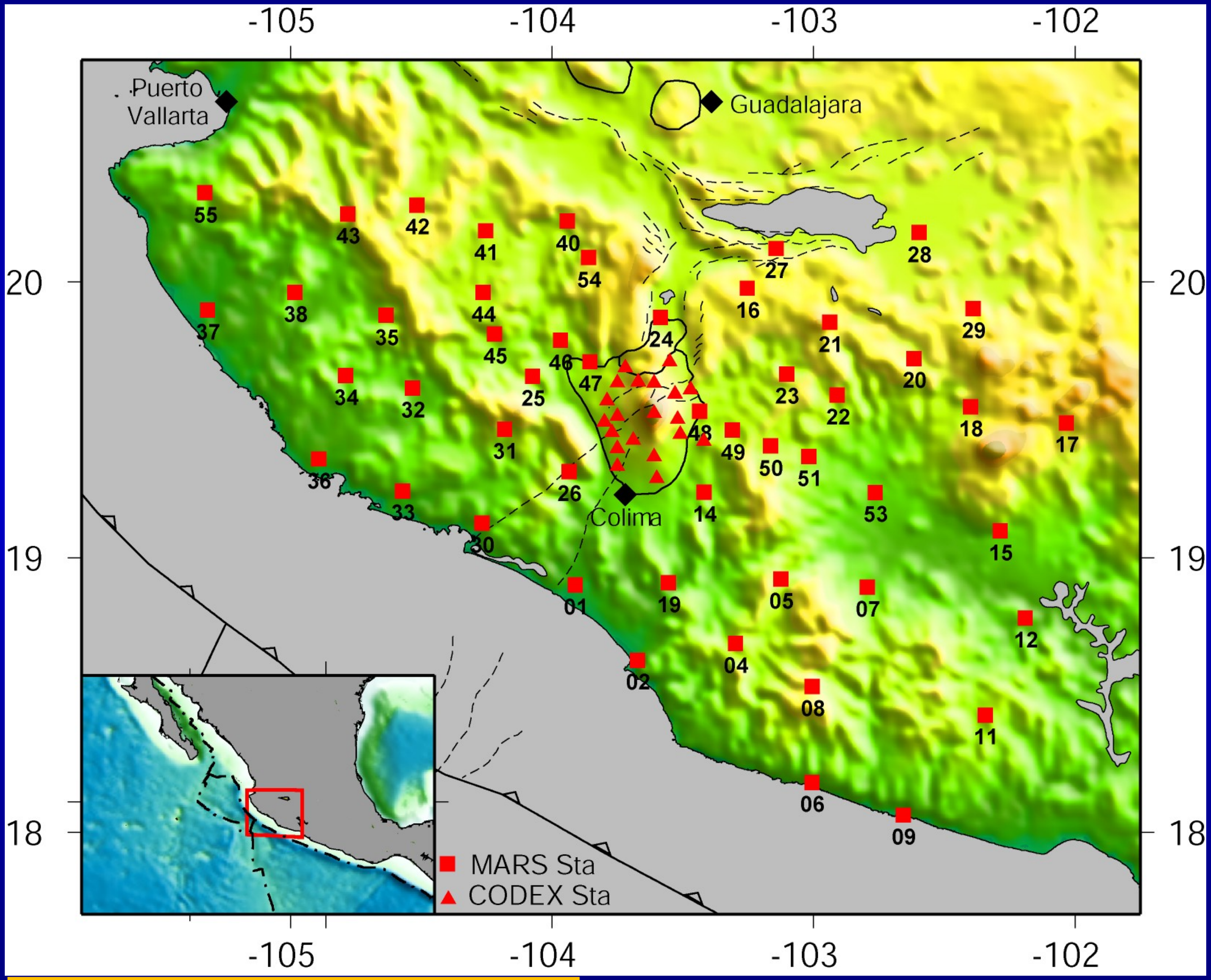
- Slab detachment decreased slab pull and convergence rate → slab rolled back → trenchward migration of volcanic front
- Inflow of enriched asthenosferic material into the mantle wedge

→ Heterogeneous mantle

→ Intraplate (OIB) lavas coexist with subduction products

- Melting at the plate edge → adakites

Preliminary results from recent seismic experiments: MApping Rivera Subduction zone (MARS), UTEXAS, Austin

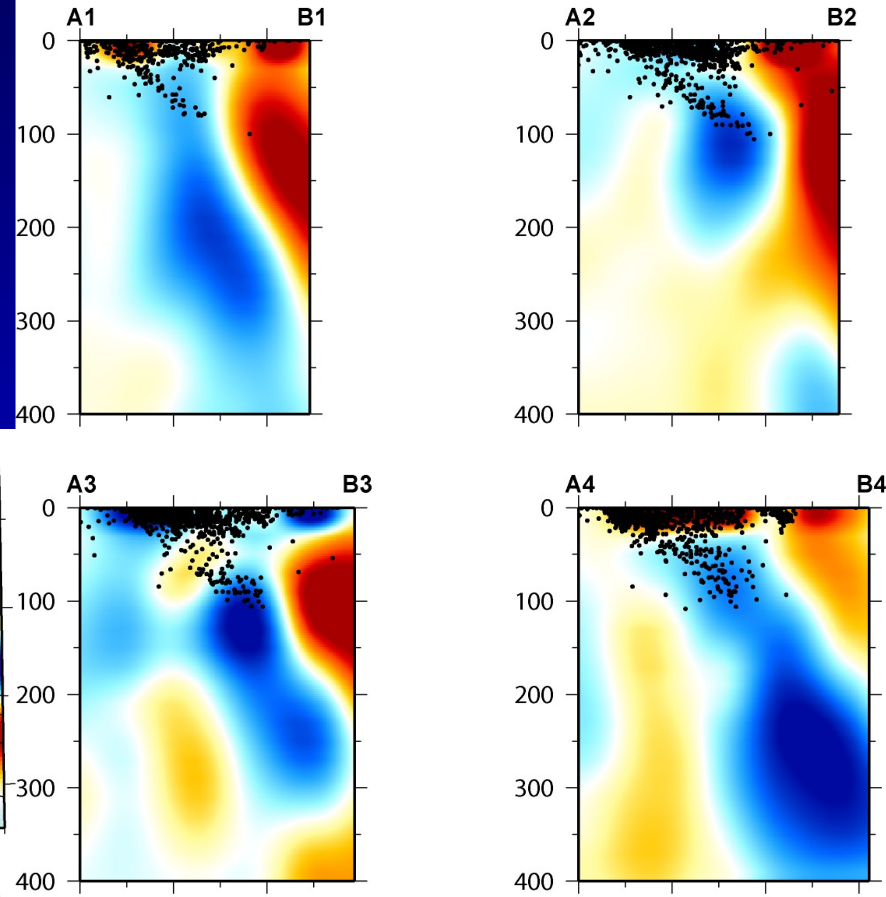


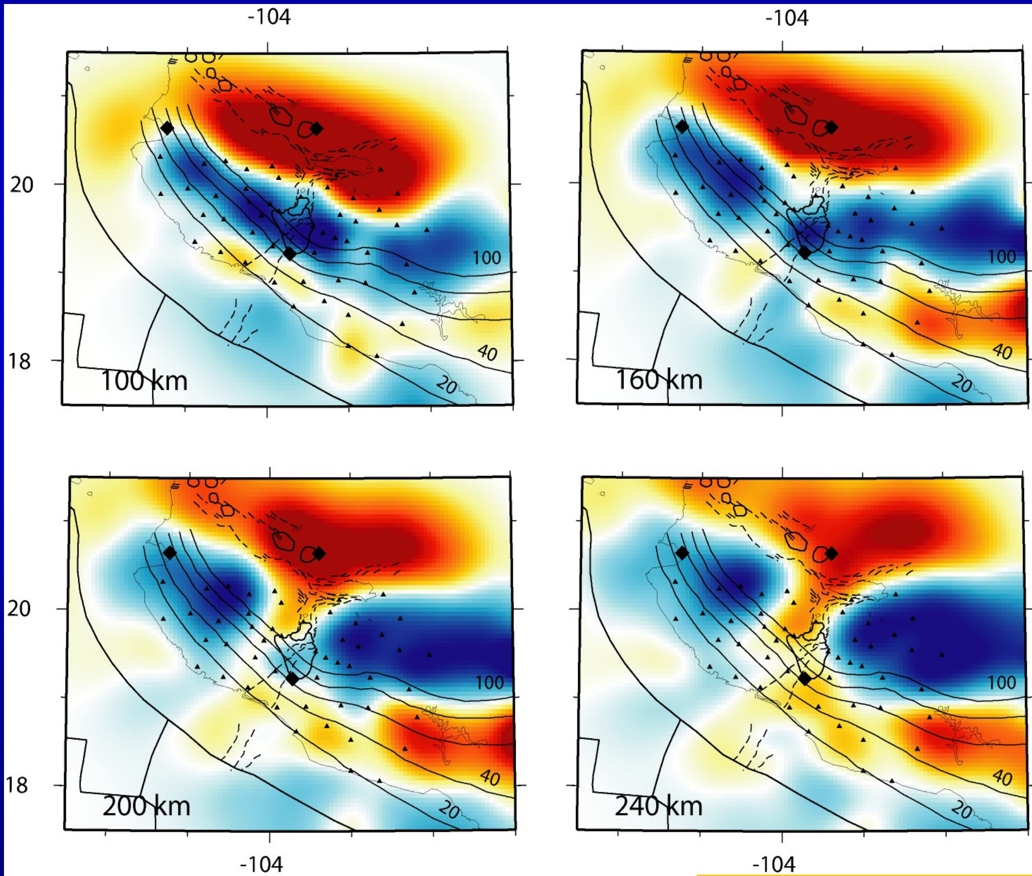
(courtesy of Steve Grand)

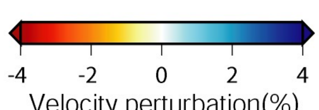
The MARS array consists of ~50 portable seismic stations deployed for almost two years in a grid covering the Jalisco block and the western Michoacan block as well as the southern part of the TMVB.

The project is funded by University of Texas at Austin and led by Steve Grand. Centro de Geociencias, UNAM (M. Guzman and J.M. Gomez) and Colima University (T. Dominguez) cooperate in the project. Results are about to be published.

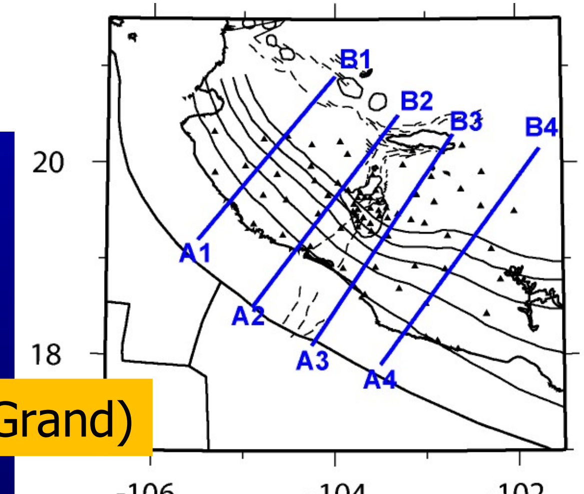
Preliminary results show a steeply dipping Rivera slab. A tear in the slab separate Rivera from Cocos plates at depth >200 km. It would confirm the model of Ferrari et al. (2001).







(courtesy of Steve Grand)

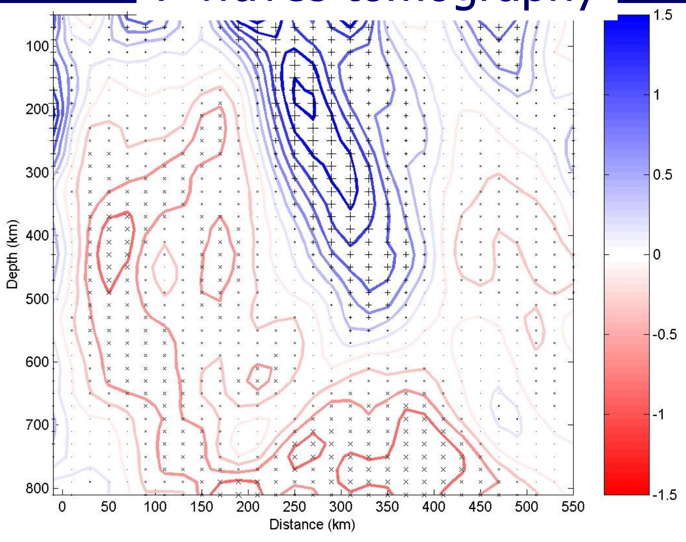


Preliminary results from recent seismic experiments: Middle America Subduction Experiment (MASE)

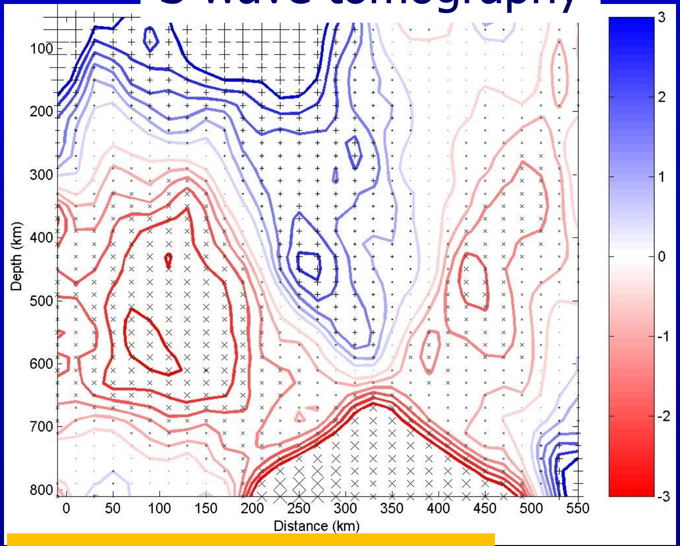
The MASE array consists of ~100 portable seismic stations deployed along a ~N-S profile from Acapulco to the Gulf of Mexico and crossing the TMVB at Mexico city. The seismic stations recorded for about 2 years.

The project is funded by Caltech. Institute of Geophysics and Center of Geoscience, UNAM participate in the project. Results are about to be published.

P waves tomography

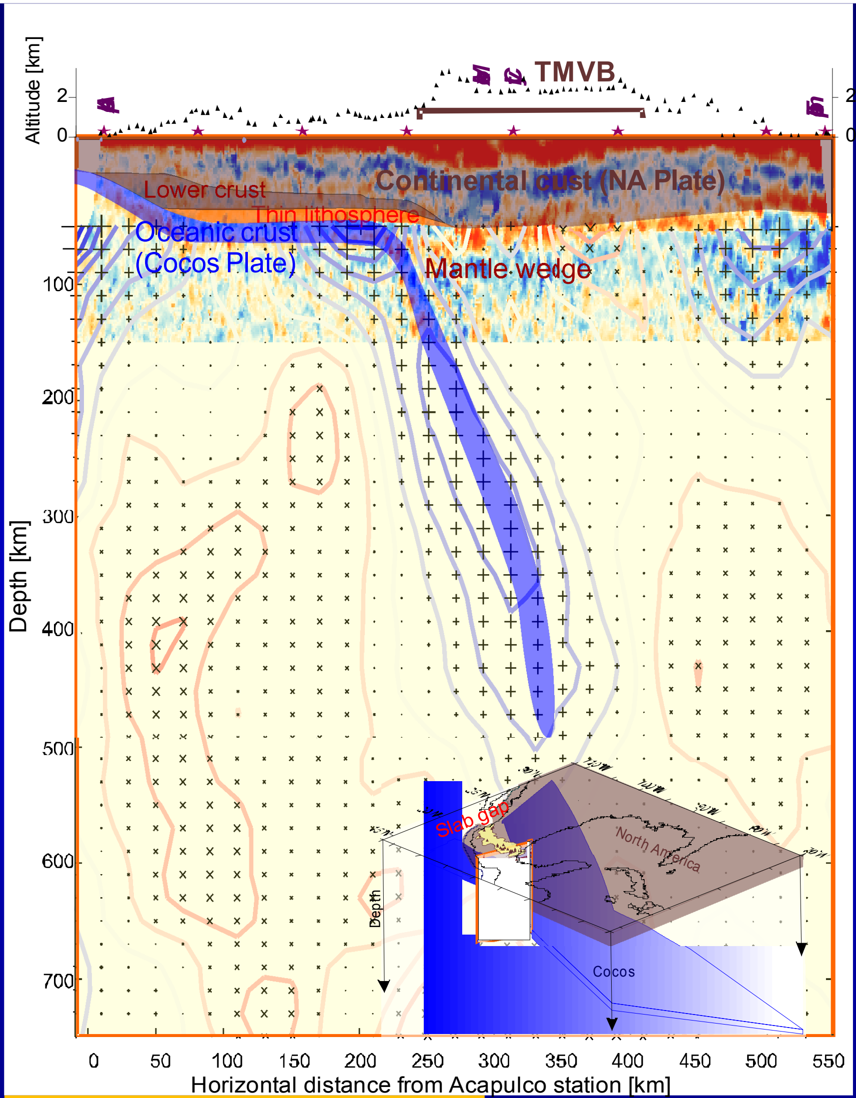


S wave tomography



(courtesy of A. Husker)

Receiver functions + P wave tomography



(courtesy of V. Manea)

Preliminary results show the Cocos slab broken at ~500 km depth, confirming the slab detachment model (Ferrari, 2004).

Some general conclusions

- Subduction and arc volcanism change constantly: they must be analyzed in 4D!
- Subduction dynamics (changes in slab dip and velocity with time, slab tearing and detachment) constantly modifies the geometry and the composition of the mantle wedge as well as the location and extent of melting
- In Mexico history of subduction is the first order factor in controlling volcanism and tectonics of the upper plate;
- The continental crust appear to modulate finer aspects of volcanism (local distribution of volcanism, crustal contamination etc.)