Terranes of Mexico Revisited

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Terranes of Mexico Revisited: A 1.3 Billion Year Odyssey

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Abstract

During the Precambrian and Paleozoic, Mexican terranes were either part of or proximal to Laurentia and Middle America (basements of Mesozoic Maya, Oaxaquia, and Chortis terranes that bordered Amazonia). Obduction of the Sierra Madre proximal terrane in the Late Ordovician was followed by Permo-Carboniferous amalgamation of all proximal terranes into Pangea. Middle Jurassic breakup of Pangea resulted in two continental terranes, Maya and Chortis, which were surrounded by small ocean-basin/arc terranes: Gulf of México, Caribbean Sea, Juarez, Motagua terranes, and the Guerrero composite terrane. All of these terranes were obducted onto North America during the Late Cretaceous–Early Cenozoic, Laramide orogeny. Neogene propagation of the East Pacific Rise into the North American margin has led to separation and northwest translation of the Baja California terrane.

Introduction

TERRANE MAPPING was first applied to Mexico by Campa and Coney (1983) and Coney and Campa (1984) as part of projects in the North American Cordillera (Silberling et al., 1992) and around the Pacific Ocean (Howell, 1985), with its primary purpose being an understanding of the plate tectonic evolution (Coney, 1983) and metallic mineral and energy resource distributions. Applying the principles of terrane analysis (Jones and Silberling, 1979; Howell et al., 1985), Campa and Coney (1983) recognized 12 terranes (Fig. 1A), of which 7 were considered to be composite (C), because existing geological maps did not allow subdivision. They grouped the terranes into three categories depending on their provenance: (1) North American provenance—two Precambrian–Mesozoic terranes (Chihuahua and Caborca [C]); (2) Gondwanan provenance—three Paleozoic terranes accreted to North America during the latest Paleozoic Ouachita-Marathon orogeny (Coahuila, Maya, and Sierra Madre, all composite); and (3) Pacific provenance—seven Mesozoic (–Precambrian) terranes accreted to western Mexico in the Late Cretaceous (Alisitos, Vizcaino [C], Guerrero [C], Juarez, Mixteca [C], Oaxaca, and Xolapa).

The next comprehensive terrane analysis of the whole of México appeared 10 years later by Sedlock et al. (1993) who outlined 16 terranes (Fig. 1B), 2 of North American provenance, 7 of Gondwanan provenance, and 7 of Pacific provenance, named after the various indigenous cultures of Mexico. Although the basic outlines of the terranes are similar to those of Campa and Coney (1983), the following changes occurred: (a) in the Gondwanan terranes, the Coahuila terrane and Sierra Madre terranes were each split into two, and the Mixteca and Oaxaca terrane were recognized as being of Gondwanan (rather than Pacific) provenance; (b) the Alisitos and Guerrero terranes were each split into two; and (c) the Vizcaino terrane was subdivided into four subterranes. Sedlock et al. (1993) went on to propose a tectonic evolution for Mexico.

Since 1993, further studies have allowed many of the composite terranes to be subdivided. Thus the Guerrero composite terrane on mainland Mexico has been subdivided into five terranes (Centeno-García et al., 1993, 2000, 2003; Talavera-Mendoza and Suastegui, 2000; Freydier et al., 2000). The ~1 Ga basement of the Oaxaca terrane has been traced into the Sierra Madre terrane, thereby giving rise to the Oaxaquia microcontinent (Ortega-Gutiérrez et al., 1995). Subsequently, Ortega-Gutiérrez et al. (1999) subdivided the Mixteca terrane into ophiolitic and sedimentary units that were inferred to have been juxtaposed in the Late Ordovician–Early Silurian. In 2001, Dickinson and Lawton classified the Mexican terranes in terms of eight, internally coherent Permian–Cretaceous crustal blocks with a detailed explanation of how they relate to previously defined terranes (Table 1 and Fig. 1 of Dickinson and Lawton, 2001), which they used to develop a Carboniferous–Cretaceous plate tectonic model. Again,

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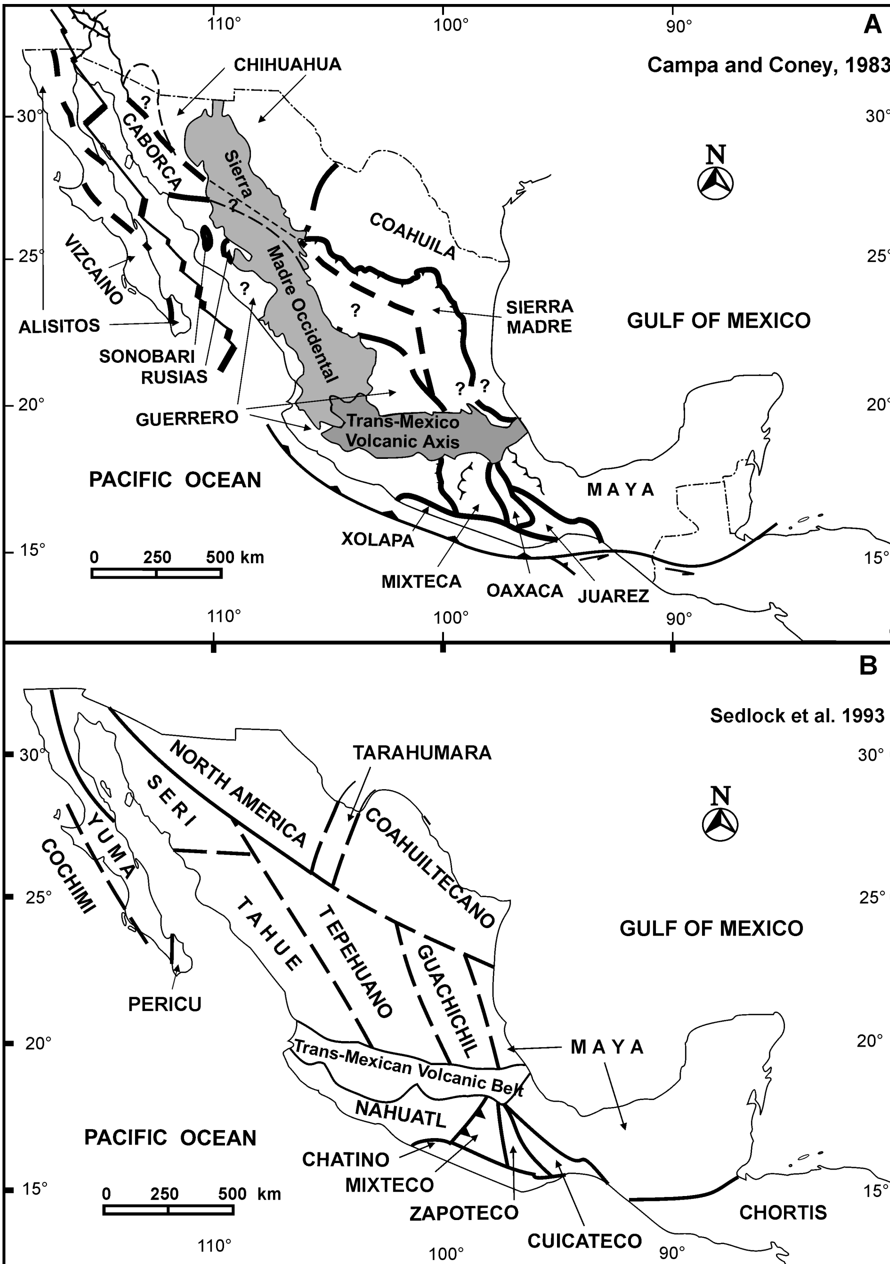
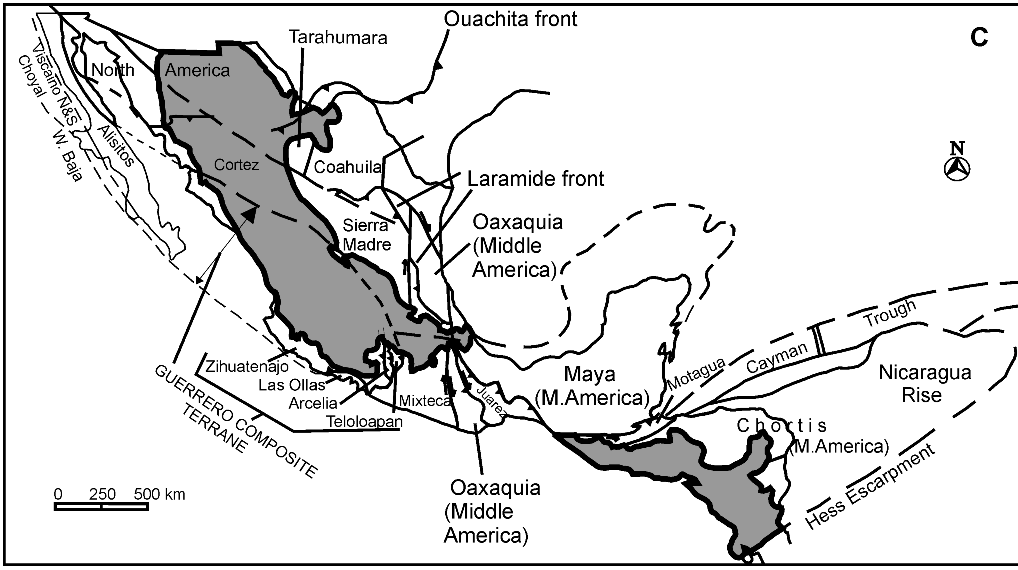


FIG. 1. Terrane maps of (A) Campa and Coney (1983), (B) Sedlock et al. (1993), and (C) this paper (facing page).

these crustal blocks generally build on earlier terrane analyses after the amalgamation of Pangea. The main changes are: (a) the amalgamation of Gondwanan terranes in the Coahuila, Tampico, and Del Sur blocks; (b) the elevation of the Guerrero terrane to an undivided superterrane; and (c) the recognition of two collisional zones—a Permian–Jurassic subduction complex on the western margin of the Gondwanan terranes, and a middle Cretaceous suture zone (closed ocean basin) between the



Guerrero superterrane and North America/Gondwana terranes. Several new terranes have been introduced in abstracts; however, the lack of published maps and tectonostratigraphy makes evaluation difficult.

The present analysis has allowed the following advances: (1) subdivision of the composite terranes; (2) delimitation of the terranes in time; (3) tectonic interpretation of the terrane geological records; (4) provision of better constraints on the provenance; and (5) reconstruction of actualistic palinspastic maps from the Mesoproterozoic to the present. The present analysis (Fig. 1C) also builds on the earlier terrane analyses in: (a) accepting the subdivision of the Guerrero composite terrane (Centeno-García et al., 2000); (b) introducing the Cretaceous, Motagua oceanic terrane between the Maya and Chortis terranes; (c) acquitting four terranes: (i) the Caborca terrane because it is merely an offset part of North America (Dickinson and Lawton, 2001); (ii) the Las Delicias terrane (McKee et al., 1999) as it appears to have been an arc developed on Pangea; (iii) the Xolapa terrane because it has been shown to be a Mesozoic overstep sequence passing from continental on the Acatlán Complex to shallow marine towards the coast (Ortega-Gutiérrez and Elías-Herrera, 2003); and (iv) the Juchatengo terrane, as new data shows the lavas, rather than of oceanic affinity, are continental tholeiites probably similar to those in the Acatlán Complex (Grahales-Nishimura et al., 1999); (d) accepting terrane subdivisions of the Coahuila composite terrane (Sedlock et al., 1993); (e) recognizing peri-North American and peri-Gondwanan elements as terranes in their own right that originated as continental rise, trench complexes, or suture zones, e.g. eugeoclinal rocks of the Cortez terrane bordering the North American craton, and Sierra Madre and Mixteca terranes bordering Middle America (Dickinson and Lawton, 2001); and (f) more clearly defining the birth, life, and death of individual terranes. Given the extensive descriptions of the geological records of the various terranes in earlier works, their geological records are only briefly summarized in the Appendix. In order to provide a stepping stone toward tectonic models, these geological records are interpreted in terms of tectonic settings in three time-and-space diagrams: Figure 2 summarizes terrane evolution, whereas Figures 3 and 4 show transects across northern and southern Mexico.

Terminology

Terrane terminology requires their definition in space and time. Although the geographical extent of the Mexican terranes has been relatively clearly defined, time constraints on their existence were generally loosely defined. For example, terranes in an oceanic realm may amalgamate to form a composite terrane before being accreted to a craton—e.g., individual Mesozoic terranes originating in the paleo-Pacific Ocean appear to have

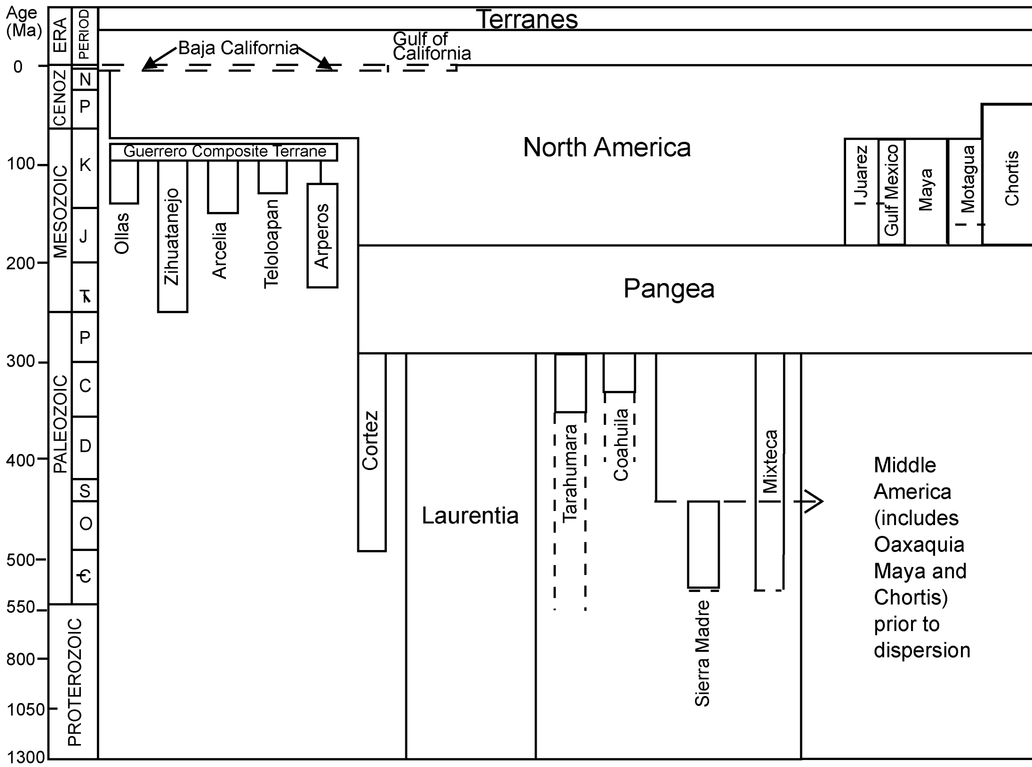


FIG. 2. Time-space summary diagram of terranes identified in this paper. Abbreviations: Є = Cambrian; O = Ordovician; S = Silurian; D = Devonian, C = Carboniferous; P = Permian; T = Traissic; J = Jurassic; K = Cretaceous; P = Paleocene; N = Neogene.

been amalgamated into the Guerrero composite terrane before being accreted to the North American craton in the latest Mesozoic–Early Tertiary (e.g., Centeno-García et al., 1993), and these distinctions need to be reflected in the terminology. A more complex example is the Maya terrane, which has a complex history: (a) during the Precambrian and Paleozoic, it appear to have formed part of a single Middle America terrane on the margin of Amazonia (e.g., Keppie and Ramos, 1999); (b) in the Permo-Triassic, it formed part of Pangea; (c) in the Mesozoic, opening of the Gulf of Mexico separated the Yucatan block from Permo-Triassic Pangea, forming the Maya terrane (e.g., Marton and Buffler, 1994); and (d) during the latest Cretaceous–Early Cenozoic, it was reamalgamated with mainland Mexico by the Laramide orogeny (e.g., Sedlock et al., 1993). However, only the term Maya terrane has been applied to this block and applies only to Mesozoic time. A partial solution to this problem was the application of the term Oaxaquia to the ~1 Ga Precambrian rocks of nuclear Mexico (Ortega-Gutiérrez et al., 1995), however, this included the inferred subsurface extent, and the term has gradually been expanded to include all or parts of the Mixteca, Maya, or Chortis terranes (e.g., Cameron et al., 2004). In as much as a terrane map shows their surface distribution, the term Oaxaquia as originally used must be redefined for use on a terrane map. In this synthesis the term is restricted to the Oaxaca, Huiznopala, and Novillo complexes, the latter extracted from the original Sierra Madre terrane because it is in tectonic contact with ophiolitic mélange of the Granjeno Schist (Carrillo-Bravo, 1991). The ~1 Ga basement of Oaxaquia is generally correlated with that in the Maya and Chortis, for which the term Middle America terrane is introduced in this synthesis. Should this correlation prove robust, the term Oaxaquia would be acquitted, as it would be part of Middle America in the

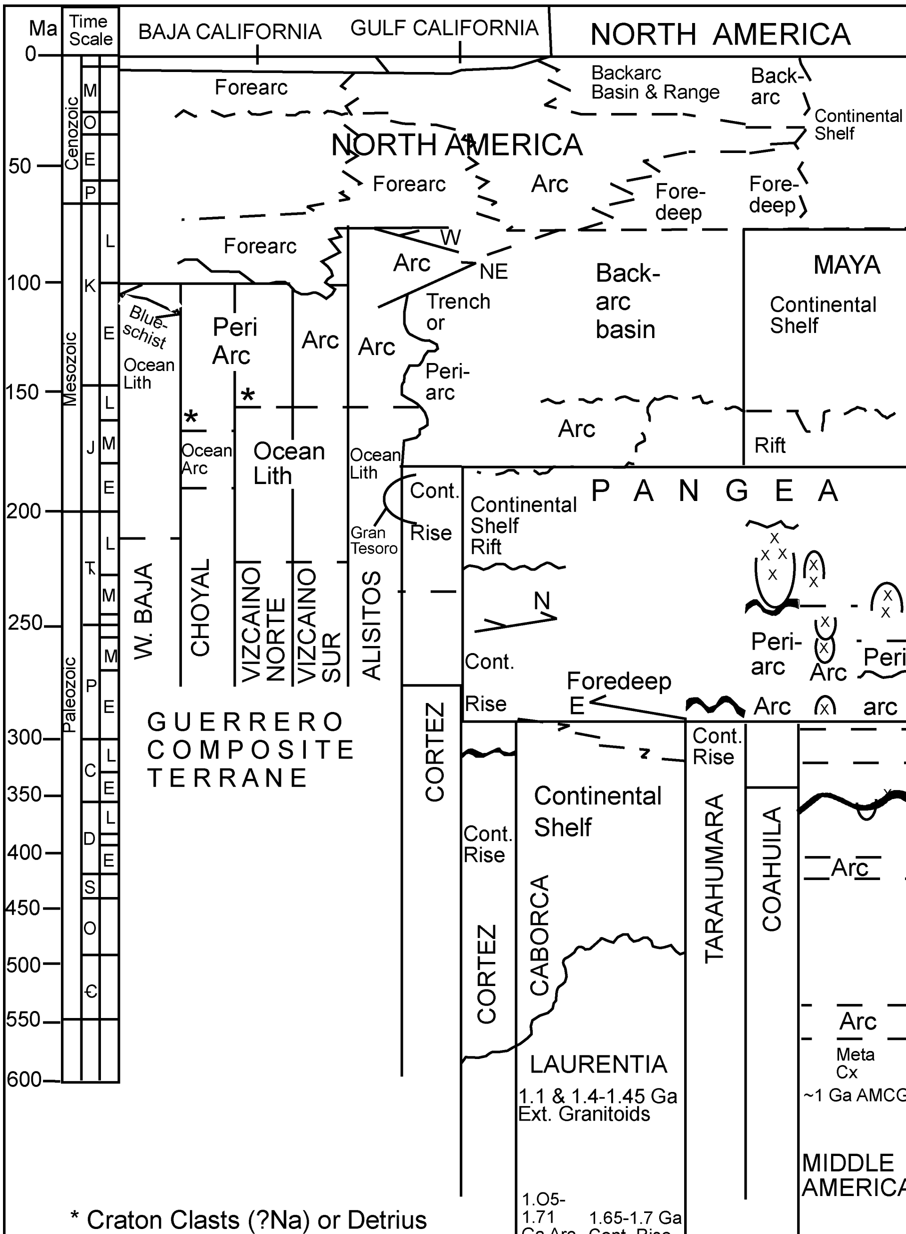


FIG. 3. Time-space diagram for northern Mexico. Abbreviations are the same as in Figure 2, plus X = plutons; E = Early; M = Middle; L = Late, N = North; NE = northeast; W = West; E = east; AMCG = anorthosite-mangerite-charnockite-granite; blues = blueschist; Cont. = continental; Cx = complex; Ext = extensional; Lith = lithosphere; Meta = Metamorphic; O.L. = oceanic lithosphere.

Precambrian and Paleozoic, and part of North America in the Mesozoic and Cenozoic. Individual Mexican terranes have received different names (Campa and Coney, 1983; Sedlock et al., 1993; Dickinson and Lawton, 2001), leading to confusion and/or double-barreled names. In order to simplify

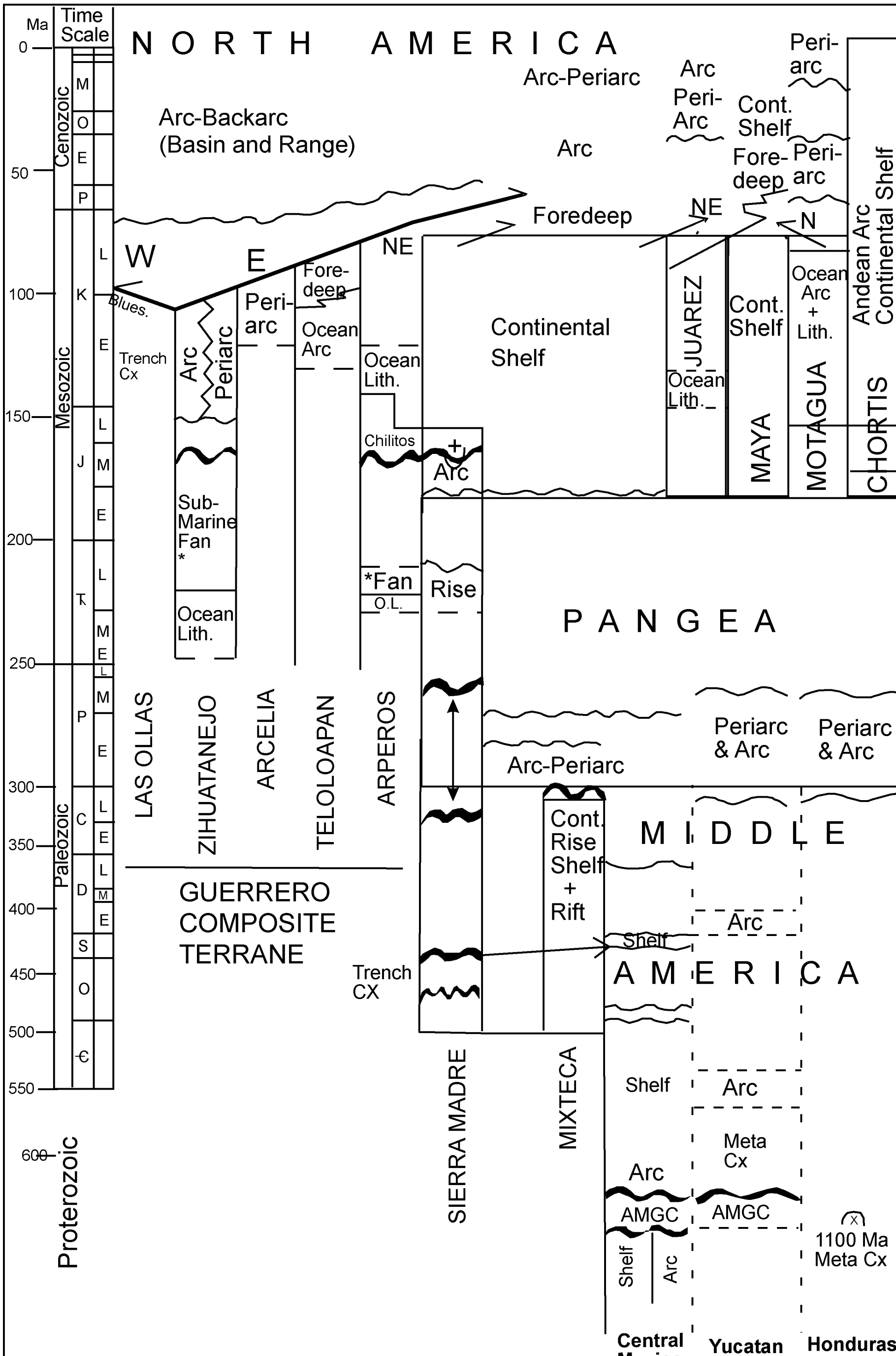


FIG. 4. Time-space diagram for southern Mexico. For abbreviations, see Figures 2 and 3.

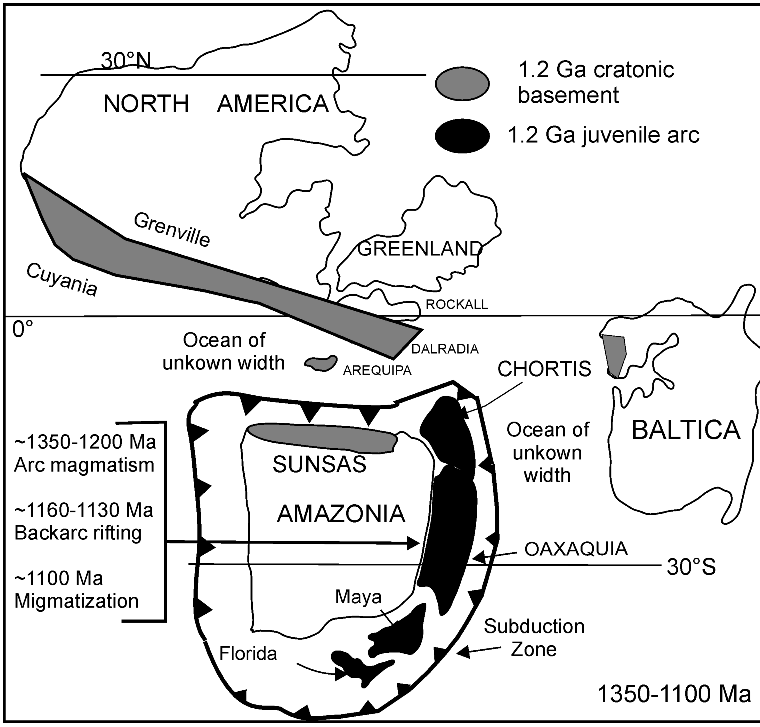


FIG. 5. 1350–1100 Ma reconstruction showing the distribution of juvenile and cratonic 1.2 Ga basement (modified after Dostal et al., 2004). Barbed line is a subduction zone with teeth oriented toward the overriding slab.

the nomenclature, previous names are retained, giving priority to the earliest terms, and only introducing new names where absolutely required (Figs. 2–4).

Cratons, Cratonic Blocks, and Their Edges

A first-order analysis requires recognition of the edges of the North and Middle America–Amazon cratons beyond which lie the accreted terranes. The Oaxaquia, Maya, and Chortis terranes form the basement of Middle America, and are inferred to have formed a belt along the northwestern margin of the Amazon craton of South America (Keppie and Ramos, 1999). In practice, the continent-ocean boundary is covered by a passive margin sequence that may be subdivided into continental shelf and continental rise prism, and the boundary between them is generally close to the oceanic-continental lithospheric transition. This buried boundary may also be identified using Sr, Nd, and Pb isotopes in cross-cutting igneous rocks (Keppie and Ortega-Gutiérrez, 1995). However, this boundary may be significantly offset at the surface by subsequent thrusting.

North American craton

Precambrian terranes in the Laurentian carton are beyond the scope of this paper. The shelf-rise transition in latest Proterozoic–Paleozoic rocks around the *southwestern margin* of North America and the Caborca terrane was documented by Stewart (1988); however, the contact is either a Late Permian–Middle Triassic, north-vergent thrust or a high-angle, Cenozoic, normal fault (Stewart et al., 1990). The 700–950 km, intracratonic, sinistral displacement of the Caborca block relative to North America has been interpreted in terms of transcurrent and transform movements (Anderson et al., 1991; Dickinson and Lawton, 2001); thus the

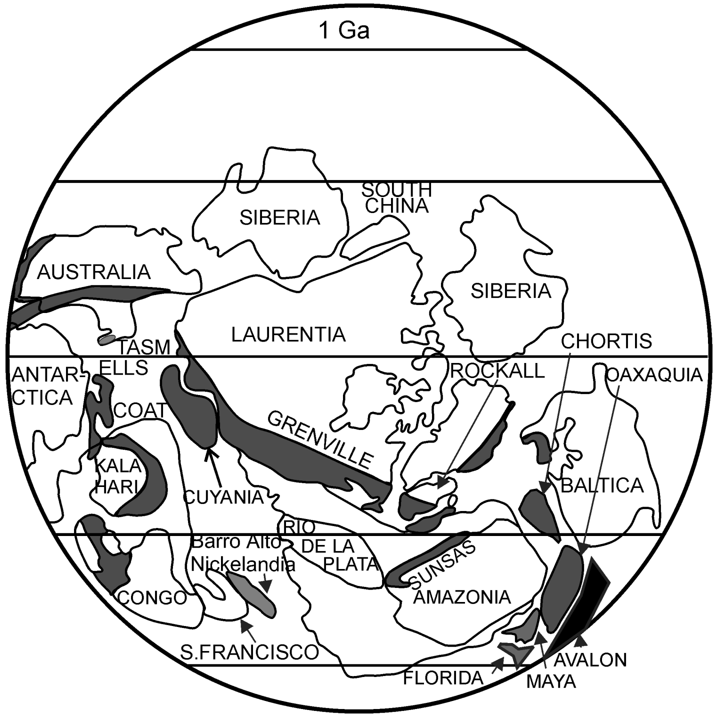


FIG. 6. ~1 Ga reconstruction of Rodinia (modified after Keppie et al., 2003a).

Caborca terrane is acquitted. The ocean-craton boundary off southwestern North America in mainland Mexico is covered in general by Mesozoic and Tertiary rocks. In Baja California and southern California, although the boundary is obscured by intrusion of the Peninsular Ranges batholith and associated high-grade metamorphism, it may be traced in the following changes in its geochemistry (west to east): (i) increasing initial $^{87}Sr/^{86}Sr$ ratios, (ii) increasing $\delta^{18}O$ values, (iii) increasing fractionation of rare-earth elements (REEs), (iv) increasing radiogenic Pb isotopes, and (iv) decreasing ε_{Nd} values of +7.9 to –2.5 (Silver et al., 1979; Hill et al., 1986; Silver and Chappell, 1988).

The *southeastern cratonic* boundary is inferred beneath allochthonous rocks of the Ouachitan orogen (Thomas, 1989). These rocks have been traced into Mexico in the Tarahumara terrane (Sedlock et al., 1993); however, it is not known whether these rocks represent the continental rise prism bordering either North or Middle America, or an intervening oceanic assemblage.

Middle America terrane (i.e., Oaxaquia-Maya-Chortis prior to Jurassic dispersion)

In contrast, the edge of the Middle America terrane has not been so clearly established, partly due to extensive Mesozoic–Cenozoic cover, the similarity of craton and craton-derived sediment, isotopic signatures, metamorphic overprint, and a lack of geochronology. Lower Paleozoic rocks resting unconformably upon ~1 Ga Oaxaquia are interpreted as shelf sequences with Gondwanan faunal affinities (Robison and Pantoja-Alor, 1968; Shergold, 1975; Boucot et al., 1997). The ubiquitous presence in all the ~1 Ga basement inliers in Mexico of ~1008 Ma anorthosite-mangerite-charnockite-granite association (Keppie et al., 2003a), and 1000–980 Ma granulite-facies polyphase deformation (Solari et al., 2003) implies that they are part of one terrane. However, pre-1100 Ma rocks represent either a rift-shelf sequence (northern Oaxacan Complex: Ortega-Gutiérrez, 1984) or an arc sequence (Lawlor et al., 1999; Keppie et al., 2001; Cameron et

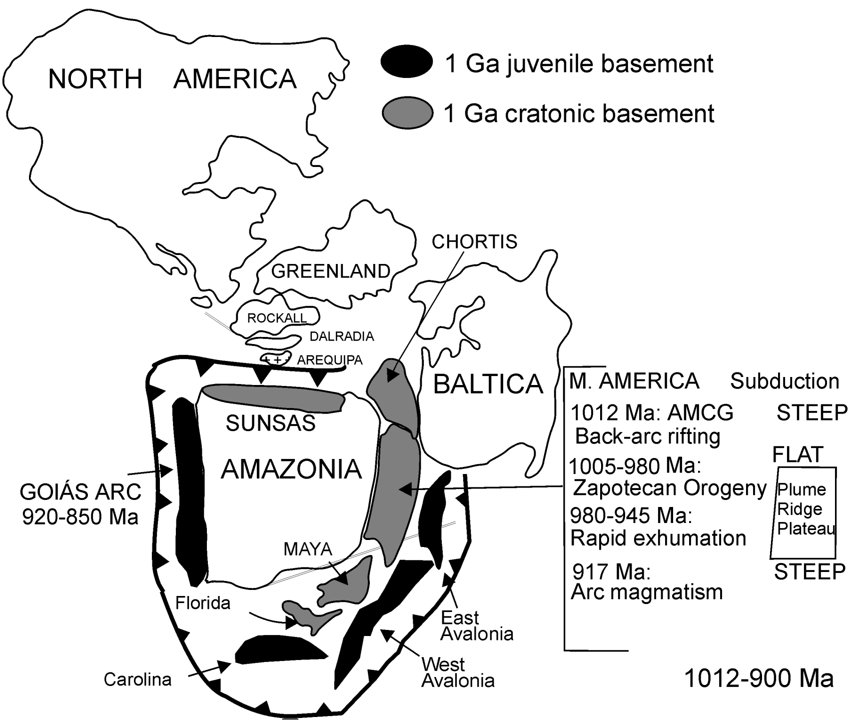


FIG. 7. 1012–900 Ma reconstruction showing ~1 Ga juvenile and cratonic basement surrounding Amazonia (modified after Ortega-Obregón et al., 2003; Solari et al., 2003; and Keppie et al., 2004d).

al., 2004; Dostal et al., 2004) that may, or may not, indicate more than one terrane. On the other hand, the presence of similar metasedimentary rocks in all Mexican, ~1 Ga inliers suggests that the arc may have been developed on one terrane.

During the Paleozoic, the western border of Middle America is best exposed in southern Mexico where Elías-Herrera and Ortega-Gutiérrez (2002) have documented that it is a Permian dextral flower structure. To the west of this boundary, psammitic and pelitic rocks of the Paleozoic Acatlán Complex are inferred to represent either trench-forearc deposits (Ortega-Gutiérrez et al., 1999) or a continental rise prism bordering Middle America (Ramírez-Espinoza et al., 2002); the latter is a conclusion consistent with its comparable Nd signature (Yañez et al., 1991).

The western boundary of Middle America is also exposed near Ciudad Victoria, where Paleozoic ophiolitic mélange (Granjeno Formation interpreted as trench complex) is juxtaposed against ~1 Ga rocks (Novillo Complex) along a dextral fault: a minimum age for the Granjeno is given by 320–260 Ma K-Ar ages on metamorphic mica (references in Sedlock et al., 1993). However, Ordovician obduction is indicated by the presence of Granjeno pebbles in the Wenlockian sediments unconformably overlying the ~1 Ga Novillo Complex (Fries et al., 1962; De Cserna et al., 1977; De Cserna and Ortega-Gutiérrez, 1978). In this region, the Granjeno and Novillo belts crop out in NNW-trending horsts and grabens. Granulite-facies xenoliths of presumed Middle American provenance have been recorded as far west as the edge of the Guerrero composite terrane (references in Sedlock et al., 1993; Ortega-Gutiérrez et al., 1995). This implies a west-dipping thrust contact between oceanic and cratonic rocks that was subsequently displaced by NNW-trending vertical faults.

The *southern margin of Pangea* is separated from the amphibolite-greenschist–facies rocks of the Xolapa terrane by a sinistral-normal fault with relatively little lateral displacement (Ratchbacher et al., 1991; Meschede et al., 1997; Tolson-Jones, 1998) (Fig. 1). The Xolapa Complex consists of quartzo-feldspathic schists and gneisses migma-

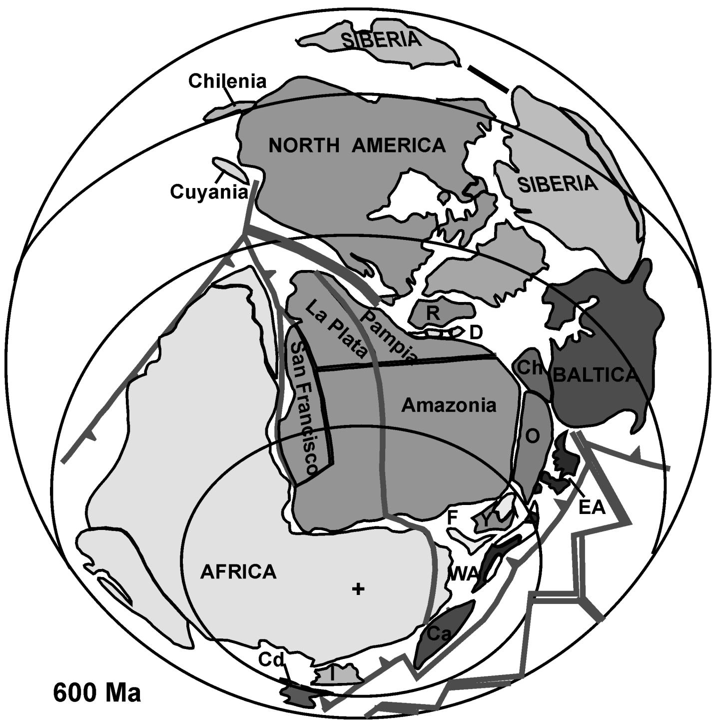


FIG. 8. 600 Ma reconstruction modified after Keppie and Ramos (1999) and Keppie et al. (2003b). Abbreviations: Ca = Carolina; Cd = Cadomia; Ch = Chortis; D = Dalradia; EA = East Avalonia; F = Florida; I = Iberia; O = Oaxaquia; R = Rockall; WA = West Avalonia; Y = Yucatan. Barbed line is a subduction zone with teeth oriented toward the overriding slab; double line is a mid-ocean ridge, and single line is a transform fault.

tized at ~132 ± 2 Ma (nearly concordant, U-Pb, zircon, lower intercept; Herrmann et al., 1994) intruded by 35 to 27 Ma, calcalkaline plutons (Herrmann et al., 1994). Ortega-Gutiérrez and Elías-Herrera (2003) have traced the Xolapa Complex into the Jurassic rocks overstepping the Acatlán Complex, a discovery that acquits the Xolapa terrane.

The Terranes and Constraints on Amalgamation

The geological record and the tectonic interpretation of each terrane are briefly summarized in the Appendix. Constraints on the time of amalgamation include overstep (or overlap) sequences, stitching plutons, exotic pebbles, deformation, and metamorphism (Howell, 1985; Keppie, 1989). They provide a younger limit on the life of a terrane and will now be outlined in historical order.

Paleozoic terranes: Most of Gondwana's provenance

Paleozoic Mixteca terrane. This terrane was defined by Campa and Coney (1983), and subsequently renamed the Mixteco terrane by Sedlock et al. (1993). It consists of two sequences that are tectonically juxtaposed against one another: the low-grade Petlalcingo Group and the eclogitic Piaxtla Group. The Petlalcingo Group consists of a polydeformed sequence of graywackes (Chazumba Formation), variably metamorphosed to psammitic and pelitic schists and migmatized in the Jurassic (Keppie et al., 2004b), overlain by slates and phyllites (Cosoltepec Formation) that are interpreted to represent either trench and forearc deposits (Ortega-Gutiérrez et al., 1999), or a continental rise prism adjacent to Middle America (Ramírez-Espinoza, 2001). The Cosoltepec Formation is tectonically interleaved with the eclogitic Piaxtla Group (Meza-Figueroa et al., 2003) containing mafic rocks of

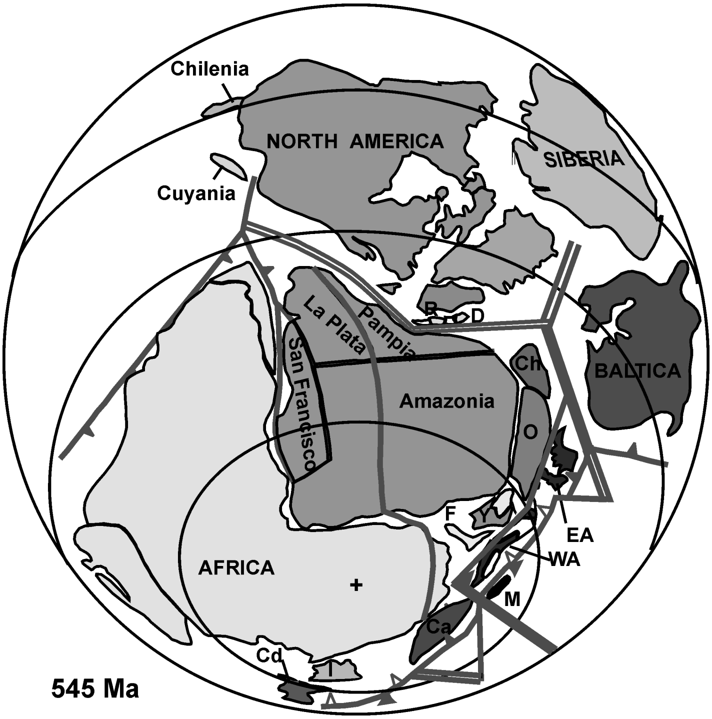


FIG. 9. 545 Ma reconstruction modified after Keppie and Ramos (1999) and Keppie et al. (2003b). Abbreviations and symbols are the same as those in Figure 8, plus M = Meguma.

inferred oceanic affinity that have yielded Sm-Nd garnet-whole rock ages of 388 ± 44 Ma (Yañez et al., 1991). These units are unconformably overlain by the Tecomate Formation.

The general lack of well-constrained fossils in these units has led to inferences based on geochronology: namely that syntectonic granitoid intrusion occurred during the Late Ordovician Acatecan orogeny and the Devonian Mixtecan orogeny (Ortega-Gutiérrez et al., 1999). By extension, this provided a younger age limit of Late Ordovician on the Petlalcingo and Piaxtla groups and Late Devonian on the Tecomate Formation. However, new data is pointing to significant revisions. The Esperanza granitoid, part of the Piaxtla Group, has yielded Ordovician–Silurian protolith ages (concordant U-Pb age of 478 ± 5 Ma: Campa-Uranga et al., 2002; and concordant U-Pb ages of 480–460 Ma: Keppie et al., 2004a). ~1 Ga upper intercept, U-Pb zircon ages in the Esperanza granitoid indicate the presence of such a basement beneath the Acatlán Complex during granite genesis: this is consistent with the similar Nd model ages in these granitoids (Yañez et al., 1991). Granulite-facies xenoliths probably derived from buried Oaxacan Complex have been recorded as far west as the eastern Guerrero composite terrane (Elías-Herrera and Ortega-Gutiérrez, 1997), indicating that the Lower Paleozoic continent-ocean boundary is a west-dipping thrust that was subsequently displaced by a Permian dextral shear zone. The eclogite-facies tectonothermal event has been dated at 346 ± 3 Ma, followed by migmatization at ~350–330 Ma (Keppie et al., 2004a). Emerging geochemical data indicate that parts of the Piaxtla Group consist of craton-derived metasediments and continental rift tholeiites rather than oceanic lithosphere (Keppie et al., 2003c). Furthermore, new U-Pb geochronology and well-dated fossils in the Tecomate Formation indicate a Pennsylvanian–Middle Permian age, which therefore is a facies equivalent of both the Matzitzi and Patlanoaya formations (Malone et al., 2002; Keppie et al., 2004c). Deposition of these units appears to have been synchronous with both an Early–Middle

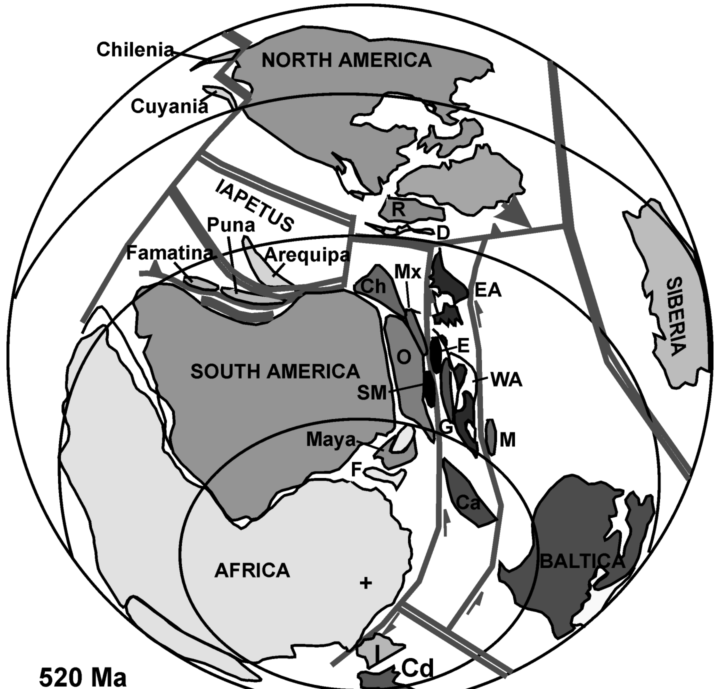


FIG. 10. 520 Ma reconstruction modified after Keppie and Ramos (1999) and Keppie et al. (2003b). Abbreviations and symbols are the same as in Figures 8–9, plus E = Exploits; G = Gander; Mx = Mixteca; SM = Sierra Madre.

Permian tectonothermal event and the arc magmatism along the margin of Pangea (Torres et al., 1999).

The presence of similar, shallow marine–continental Permo-Carboniferous rocks on top of both the Oaxacan and Acatlán complexes (Keppie et al., 2003c) implies that the Mixteca and Oaxaquia terranes were close, if not adjacent, at this time. This is consistent with the observation that the dextral transcurrent boundary between the Acatlán and Oaxacan complexes is overstepped by the Leonardian (Early Permian) Matzitzi Formation (Elías-Herrera and Ortega-Gutiérrez, 2002; Malone et al., 2002).

During Mesozoic time, the continent-ocean boundary on the western side of the Mixteca terrane may be placed at the eastern margin of the oceanic, Early Cretaceous Arperos terrane (Freydier et al., 2000), and on the eastern side of the Triassic Zacatecas Formation (interpreted as continental rise on oceanic crust by Centeno-García and Silva-Romo, 1997).

Paleozoic Sierra Madre terrane. This terrane formerly included both the ~1 Ga basement (Novillo Complex) and the Paleozoic Granjeno Formation, with an unconformity separating the units (Campa and Coney, 1983). However, all such contacts are tectonic and so the ~1 Ga basement is included in the Oaxaquia terrane (Ortega-Gutiérrez et al., 1995), and the Sierra Madre terrane is restricted to the Granjeno Formation and equivalents. Thrusting of the Sierra Madre terrane, which consists of an ophiolitic mélange (Granjeno Formation), over the ~1 Ga Novillo Complex in the Ordovician–Early Silurian is documented by the presence of Granjeno pebbles in Wenlockian sediments unconformably overlying the Novillo Complex (Fries et al., 1962). In the Permian, this thrust boundary was cut by a steeply dipping dextral shear zone (Garrison et al., 1980). The Granjeno Formation is inferred to represent a Paleozoic trench complex. Triassic rocks overstep the boundary between these two terranes.

(?)Paleozoic Tarahumara and Coahuila terranes. The Tarahumara terrane consists of low-grade metasedimentary rocks metamorphosed in the late Paleozoic (Sedlock et al., 1993, and references therein). The adjacent Coahuila terrane is similar except that it also contains Permo-Carboniferous flysch with synchronous calc-alkaline volcanic

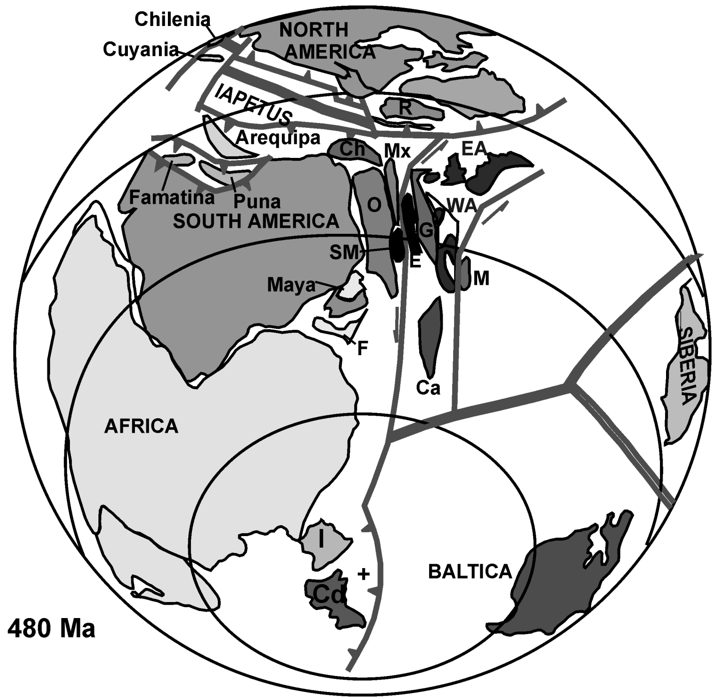


FIG. 11. 480 Ma reconstruction modified after Keppie and Ramos (1999) and Keppie et al. (2003b). Abbreviations and symbols are the same as in Figures 8–10.

detritus and Neoproterozoic, Mesoproterozoic, and Paleoproterozoic boulders deposited in a periarc basin (López et al., 2001). The paleogeographic location of these two terranes is uncertain—adjacent to either North or Middle America or in the intervening ocean basin.

Permo-Triassic Pangea

All of the above terranes were involved in the collision between North and Middle/South America during the assembly of Pangea. The collisional zone is represented by the Ouachita orogen, which terminates in northeastern Mexico against the paleo-Pacific Ocean (Fig. 1C). Proximity of Middle and North America by Missisippian times is indicated by the presence of Midcontinent bachiopod fauna in both regions (Navarro-Santillán et al., 2002).

The Pangea-Pacific boundary appears to have been an active margin at this time, as documented by the presence of a Permo-Triassic arc that may be traced from California through Mexico (McKee et al., 1999; Torres et al., 1999), and Permo-Triassic folding and N-vergent thrusting in the Caborca block (Stewart et al., 1990). A Late Triassic–Jurassic overstep sequence is present in many parts of Mexico and the adjacent United States, which is generally synchronous with the breakup of Pangea.

Mesozoic terranes of Pangean provenance

The fragmentation of Pangea spalled off two large cratonic terranes, Maya and Chortis, which appear to have separated sequentially, the Chortis terrane separating from southern Mexico before mid-late Jurassic times, followed by separation of the Maya terrane from the southern margin of North America in the Callovian–Late Jurassic (see below). Nuclear Mexico (Oaxaquia) remained attached to the North American craton. The Maya terrane is surrounded by rhombochasmic-shaped oceanic lithosphere—the Gulf of Mexico, the proto-Caribbean, and Juarez and Motagua terranes. Paleomagnetic data indicate that the Chortis terrane rotated ≥100° clockwise during the Mesozoic (Gose, 1985), and was also surrounded by oceanic lithosphere—Motagua, proto-Caribbean, and Pacific.

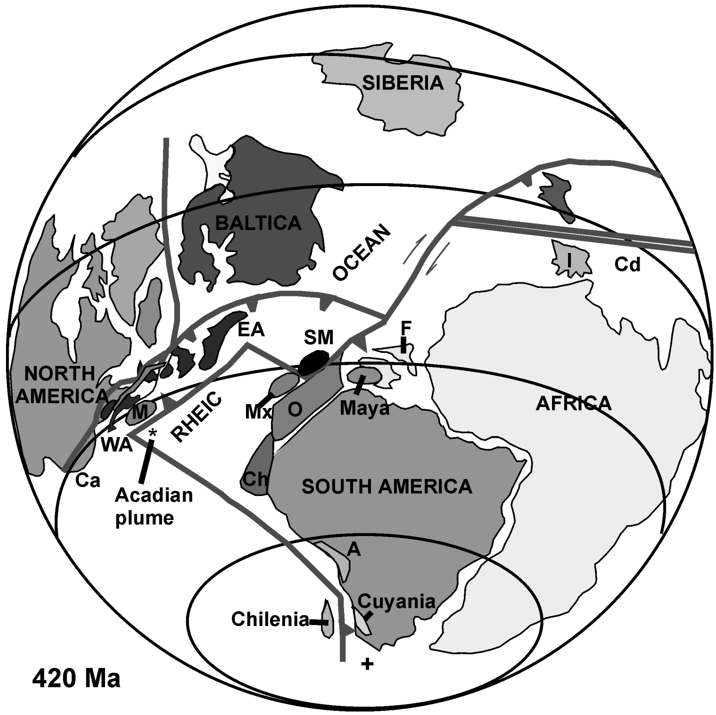


FIG. 12. 420 Ma reconstruction modified after Keppie and Ramos (1999) and Keppie et al. (2003b). Abbreviations and symbols are the same as in Figures 8–10.

Chortis terrane. Many authors have placed the Chortis terrane adjacent to southern Mexico and northwestern South America in pre-Tertiary reconstructions (e.g., Anderson and Schmidt, 1983; Pindell et al., 1988; Ross and Scotese, 1988; Schaaf et al., 1995; Keppie and Ramos, 1999). However, an alternative reconstruction using the Cayman transform results in back-rotation of the Chortis terrane into the Pacific Ocean, so that in the Eocene the southern Mexican coast would have faced an open ocean (Keppie and Moran-Zenteno, 2004). The latter is consistent with the proposals that part of the southern margin of Mexico has been removed by subduction erosion (Moran-Zenteno et al., 1996). On the other hand, there appear to be pre-Cenozoic connections between southern Mexico and the Chortis terrane. Thus, a Precambrian connection between the Chortis and Oaxaquia terranes is suggested by the presence of a ~1 Ga granitoid in northeastern Honduras (Manton, 1996) that is synchronous with similar plutons in Oaxaquia (Keppie et al., 2003a). However, in Honduras, the country rocks are amphibolite facies, whereas they are granulite facies in Mexico, possibly reflecting a metamorphic facies change. Such a change in P-T conditions is also suggested by the presence of lower-greenschist facies, Mesoproterozoic boulders in a Carboniferous conglomerate in the Coahuila terrane (López et al., 2001). A Permo-Carboniferous, tectonomagmatic event has been recorded in the basement rocks of northern Honduras (305 ± 12 Ma Rb-Sr isochron on orthogneisses: Horne et al., 1990), and may be correlated with a similar event in the Acatlán Complex of southern Mexico. Subsequent separation of the Chortis terrane is possibly recorded in southern Mexico if the Xolapa Complex represents a continental rise prism of mid-Jurassic age as suggested by Ortega-Gutiérrez and Elías-Herrera (2003). Such a separation is consistent with the apparent absence in the Chortis terrane of the high-grade, Early Cretaceous tectonothermal event in the Xolapa Complex of southern Mexico. The northern edge of the Chortis terrane is the steeply dipping Jocotan-Chamelecon fault zone, which forms the southern border of the Motagua ophiolitic terrane (Guinta et al., 2001). These ophiolitic

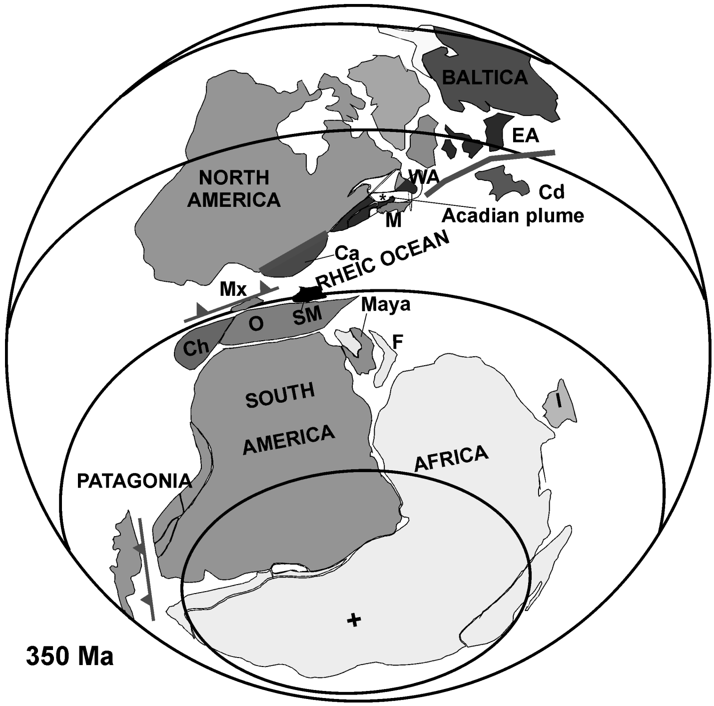


FIG. 13. 350 Ma reconstruction modified after Keppie and Ramos (1999) and Keppie et al. (2003b). Abbreviations and symbols are the same as in Figures 8–10. Asterisk indicates location of the Acadian plume.

massifs are not thrust over the Chortis terrane, an observation consistent with the absence of foredeep deposits.

Given the existence of the oceanic, Middle Jurassic–Late Cretaceous, Motagua terrane between the Chortis and Maya terranes, direct continuity of Mesozoic strata between the latter is improbable, a conclusion similar to that reached by Horne et al. (1990). This ocean was probably relatively narrow because paleomagnetic data indicate that the Chortis terrane lay at a similar paleolatitude relative to southern Mexico during the Mesozoic (Gose, 1985). Final closure of the Motagua ocean during the Late Cretaceous–Paleogene Laramide orogeny is recorded by the latest Cretaceous–Early Eocene flysch on the Maya terrane. The western edge of the Chortis terrane is covered by the Cenozoic arc, the southern margin is inferred to be a continuation of the Hess Escarpment, and the eastern part includes the Nicaragua Rise that is submerged beneath the Caribbean Sea.

Maya terrane. Paleomagnetic data indicate ~42° anticlockwise rotation of the Maya terrane about an Euler pole near the present northeast corner of the Yucatan Peninsula in the Callovian–Late Jurassic (Molina-Garza et al., 1992) to which Dickinson and Lawton (2001) add a further 18° anticlockwise rotation in Late Triassic–Middle Jurassic times.[2] This places the southern side of the Maya terrane (Guatemala-Chiapas massif) on the eastern side of the Coahuila terrane along the northern continuation of the Granjeno-Novillo fault boundary. Recent work in the Chiapas massif indicates a significant event at 260–250 Ma involving intrusion of the Chiapas batholith and high-grade deformation (Weber and Cameron, 2003) indicating that it was part of the magmatic event along the border of Middle-South America. This appears to be approximately synchronous with Permo-Carboniferous migmatization in the Chaucus Formation in Guatemala (Ortega-Gutiérrez et al., 2004).

[2]The Maya terrane is here regarded as one block rather than splitting it into two pieces as done by Dickinson and Lawton (2001).

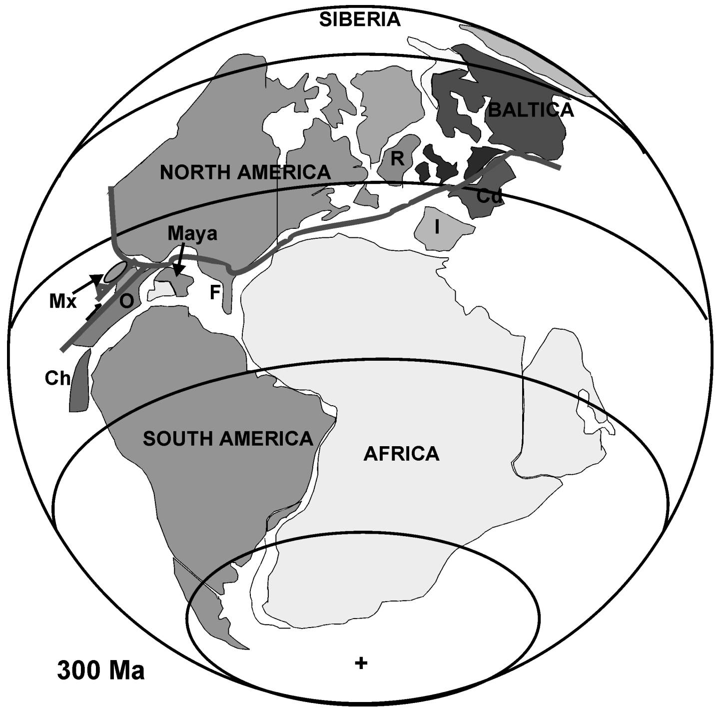


FIG. 14. 300 Ma reconstruction modified after Keppie and Ramos (1999) and Keppie et al. (2003b).

Schouten and Klitgord (1994) suggested that the Maya terrane acted as an independently rotating microplate during the separation of North and South America. Given its rectangular shape, rhombochasms opened along its sides, whereas the corners became compressive zones. This is consistent with the wedge shape of the Gulf of Mexico (Marton and Buffler, 1994), and with the triangular shape of both the eastern Maya margin (Dickinson and Lawton, 2001), and the Juarez terrane (Fig. 1). Such a reconstruction provides a proximal source in the southern Maya terrane for the Mesoproterozoic and Neoproterozoic boulders found in a Carboniferous conglomerate in the Coahuila terrane (López et al., 2001). This reconstruction also suggests that prior to the Mesozoic, the Maya terrane was continuous with Oaxaquia.

Juarez terrane. The Juarez terrane is a southward-widening terrane consisting of poorly dated, (Jurassic-) Cretaceous ophiolitic rocks (gabbro, serpentinite, mafic lava, tuff, greywacke, quartzite, slate, limestone, conglomerate containing pebbles of granulite and phyllite) metamorphosed under greenschist-facies metamorphic conditions at or before ~82 Ma (K-Ar on phyllite: Carfantan, 1983). Its western boundary is a major mylonite zone that has a complex history involving: (1) E-vergent thrusting; (2) Jurassic dextral shear; and (3) Cenozoic listric normal faulting (Alaniz-Alvarez et al., 1996). The eastern boundary is an E-vergent thrust of Late Cretaceous–Early Paleogene age, a younger limit being provided by the presence of undeformed Oligocene–Miocene rocks that form an overstep sequence (references in Sedlock et al., 1993). The triangular shape of the terrane suggests that it opened southwards, whereas it pinches out northwards into a transcurrent shear zone.

Motagua terrane. The Motagua terrane consists of Jurassic–Cretaceous ophiolites of arc and MORB affinities (Guinta et al., 2001), and both high- and low-grade, metasedimentary and meta-igneous rocks that include eclogites. It is inferred that this assemblage represents oceanic lithosphere, oceanic arc, associated sediments, and subducted oceanic lithosphere. The southern edge of the Motagua terrane is the steeply dipping Jocotan-Chamelecon fault zone. Eclogite-facies metamorphism in ophiolitic bodies along this southern margin of the

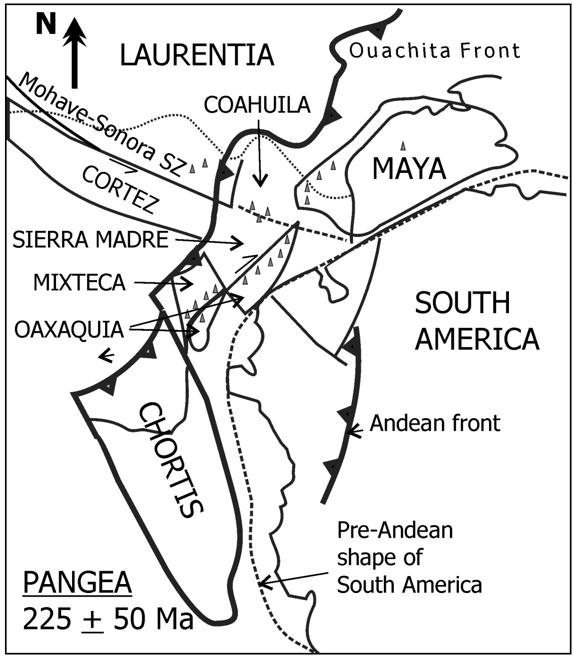


FIG. 15. 225 ± 50 Ma reconstruction of Pangea modified after Dickinson and Lawton (2001) showing magmatic arc (triangles) and Ouachita and Andean thrust fronts.

Motagua terrane formed at 161 ± 20 Ma (Nd model age: Sisson et al., 2003) cooling through ~350°C at 125–113 Ma ($^{40}Ar/^{39}Ar$ age on phengite: Harlow et al., 2004). On the other hand, north of the Motagua fault, phengites yielded $^{40}Ar/^{39}Ar$ ages of 77–65 Ma (Harlow et al., 2004), which are similar to the ~72–48 Ma, K-Ar cooling ages on hornblende and mica recorded by Ortega-Gutiérrez et al. (2004) along the northern margin of the Motagua fault zone. These data imply: (1) separation of the Maya and Chortis terranes with the formation of oceanic lithosphere in the Motagua terrane prior to the mid-Late Jurassic; (2) subduction of the southern margin of the Motagua terrane in the mid-Late Jurassic followed by obduction and exhumation during the Early Cretaceous; and (3) obduction of the Sierra Santa Marta ophiolitic massif onto the southern margin of the Maya terrane during the latest Cretaceous–Paleocene as recorded by the ophiolitic detritus in the Sepur Formation (interpreted as a foredeep deposit by Guinta et al., 2001). Note that the Jurassic subduction is synchronous with the opening of the Gulf of Mexico, suggesting that the two events may be connected. Cenozoic dextral movements on the Motagua fault zone totals ~170 km (Donnelly et al., 1990 and references therein). Tertiary arc volcanic rocks represent an overstep sequence.

Mesozoic terranes of Pacific provenance

Guerrero composite terrane. Much has been written about the Guerrero composite terrane (Sedlock et al., 1993; Centeno-García et al., 2000, 2003, and references therein), and will not be repeated here. Suffice it to say that south of the Trans-Mexican Volcanic Belt it has been subdivided into five subterranes (elevated to terranes herein). From west to east, these are the: (1) Las Ollas (?) Lower Cretaceous blueschist mélange; (2) Zhihuatanejo mid-Triassic to mid-Jurassic oceanic lithosphere (Arteaga Complex) overlain unconformably by a mid-Jurassic to mid-Cretaceous arc-periarc sequence; (3) Arcelia late Lower Cretaceous oceanic periarc assemblage; (4) Teloloapan Lower Cretaceous oceanic arc overlain by Albian-Cenomanian flysch (Talavera-Mendoza and Suastegui, 2000); and (5) Arperos Lower Cretaceous oceanic lithosphere (Figs. 1C and 3). Mid-Cretaceous thrusting of the Zihuatenajo and Arcelia terranes over the Teloloapan terrane is recorded by the Albian–Cenomanian flysch, suggesting intra-oceanic amalgamation that predates by

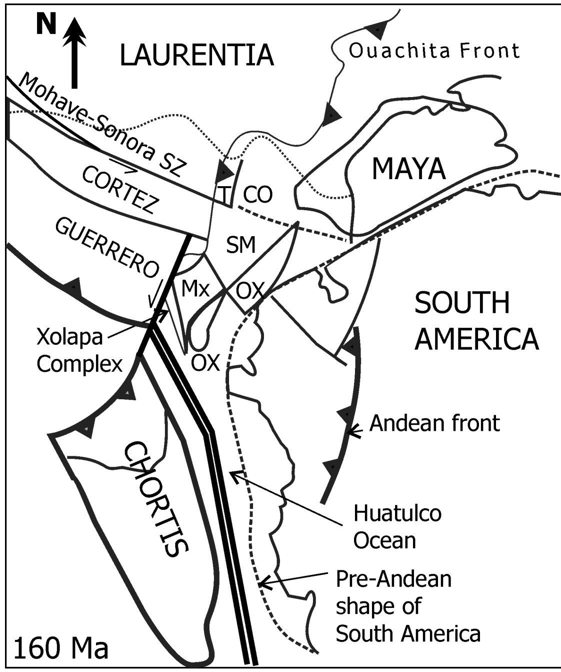


FIG. 16. 160 Ma reconstruction showing the separation of the Chortis terrane. Abbreviations: CO = Coahuila; Mx = Mixteca; OX = Oaxaquia; SM = Sierra Madre; T = Tarahumara.

≥20 m.y. accretion of the Guerrero composite terrane to North America recorded by the late Upper Cretaceous Mexcala flysch.

These terranes have been traced through isolated inliers north of the Trans-Mexican Volcanic Belt; however, their connection with those recorded in Baja California is not clear. Prior to opening of the Gulf of California (Dickinson and Butler, 1998; Keppie and Dostal, 2001), it appears that the mid-Cretaceous blueschist mélanges of Las Ollas and the Western Baja terrane line up. Similarly, the eastern boundary of the Guerrero composite terrane may be traced directly across the future Gulf of California; however, several differences are apparent in passing from Baja California to the mainland (compare Figs. 3 and 4): (1) the age of the ocean floor is ~25 m.y. older in the north; (2) the eastern Guerrero arc began ~20 m.y. earlier in the north; (3) the arc straddles the ocean-continent boundary in the north, passing southward into a predominantly oceanic arc; and (5) beneath the western Guerrero arc, the oceanic lithosphere is ~30 m.y. younger in the north. The first three observations may be explained in terms of either a southward-migrating triple point (Dickinson and Lawton, 2001), or the existence of two subparallel arcs (Moores, 1998). It is significant that the western arc terranes (Zihuatenajo and Choyal) contain continent-derived detritus (Boles and Landis, 1984; Centeno-García et al., 1993). In the case of the Choyal terrane, Boles and Landis (1984) suggested that the continental detritus was derived from North America, a conclusion consistent with deposition of mid-Jurassic arc volcanic rocks upon, and intrusion of mid-Jurassic parts of the Peninsular Ranges batholith into, eugeoclinal rocks of the Cortez terrane bordering the Caborca block (Sedlock et al., 1993). Correlation of the continentally derived, Upper Triassic–Lower Jurassic sediments of the Arteaga Complex at the base of the Zihuatenajo terrane with the Zacatecas sandstone along the periphery of North-Middle America supports the idea that the Arteaga Complex was rifted off western North America (Centeno-García and Silva-Romo, 1997).

Accretion of the Guerrero composite terrane onto western North America is recorded by the uppermost Cretaceous–Lower Cenozoic Mexcala flysch in the foreland basin in front of the advancing Laramide nappes, which eventually advanced within 100 km of the present coast of the Gulf of Mexico. The

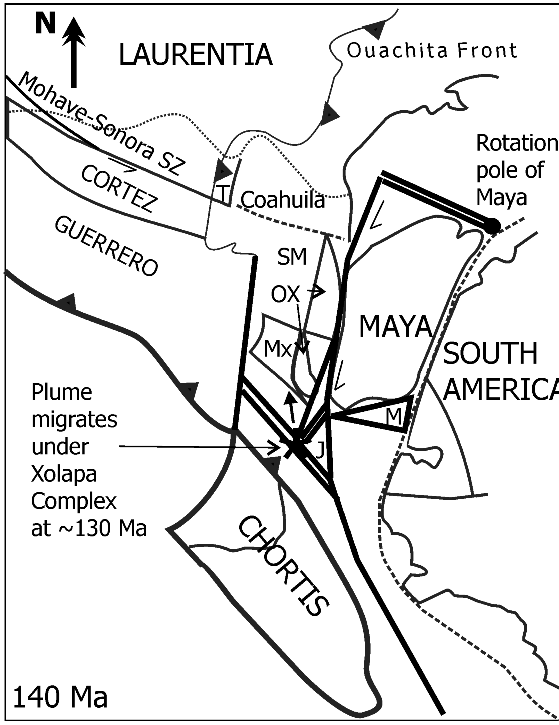


FIG. 17. 140 Ma reconstruction showing rotation of the Maya terrane. Abbreviations are the same as in Figure 16, plus J = Juarez; Mo = Motagua.

eastward migration of the Laramide deformation front is synchronous with eastward migration of the magmatic arc, and both have been related to flattening of the subducting slab in response to increased convergence rates and/or subduction of progressively younger oceanic lithosphere (Clark et al., 1982; Coney, 1983). Subsequently, these Laramide structures were overstepped by Cenozoic rocks (Figs. 3 and 4) that define the present extent of North America.

Baja California terrane. Impingement of the East Pacific Rise with the trench off western North America produced a T-R-F triple point that migrated southwards (Lonsdale, 1989; Atwater and Stock, 1998). At ~13 Ma the triple point reached the mouth of the Gulf of California, following which the East Pacific Rise extended inland leading to the separation of Baja California at ~6 Ma, which now rides northwestward on the Pacific plate. Thus Baja California has become a terrane.

Plate Tectonic Reconstructions

Advances in terrane mapping in Mexico have generally gone hand-in-hand with development of plate tectonic models. Thus, Coney (1983) modeled the Mesozoic and Cenozoic using the terrane subdivision of Campa and Coney (1983). Sedlock et al. (1993) combined their terrane map of Mexico with a series of paleogeographic maps from 600 Ma to the present. Dickinson and Lawton (2001) subdivided Mexico into a series of Permian-Cretaceous blocks (terranes) as the basis for palinspastic, plate tectonic maps. Based on the terrane map of Mexico presented in this paper, a series of paleogeographic maps for the Mesoproterozoic–Present tectonic evolution of Mexico is constructed (Figs. 5–19). These draw heavily upon previous maps modified, where needed, by data presented in the present terrane analysis. This is a two-stage process involving determining the provenance of a terrane followed by

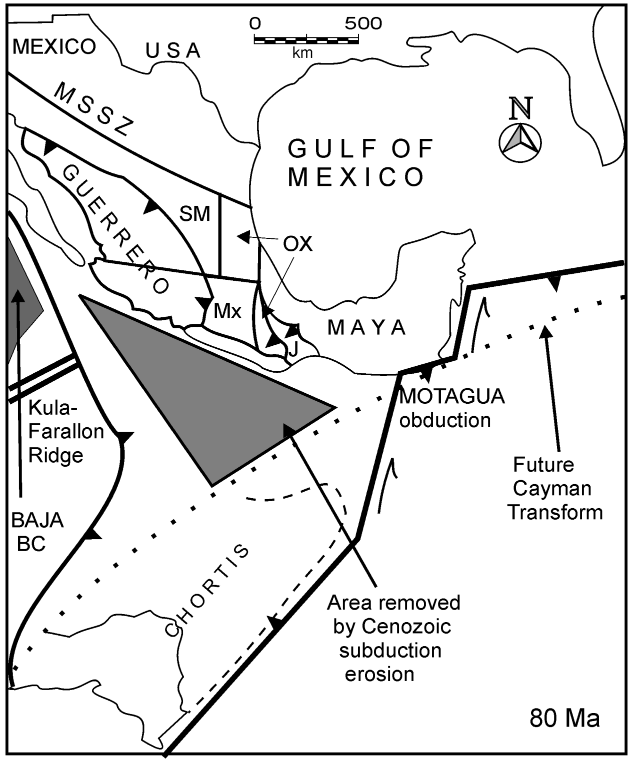


FIG. 18. 80 Ma reconstruction showing obduction of the Guerrero composite terrane during the Laramide Orogeny. Abbreviations are the same as in Figure 16.

devising a plate tectonic model for its history. The reader is also referred to more detailed palinspastic models for: (1) the Mesozoic evolution of the Guerrero composite terrane presented by Dickinson and Lawton (2001); and (2) the Cenozoic locations of the Chortis terrane (Keppie and Moran-Zenteno, 2004).

Precambrian–Paleozoic

The Gondwanan provenance of the Middle America terrane was initially based upon its Ordovician and Silurian fauna (Robison and Pantoja-Alor, 1968; Boucot et al., 1997); however, its location on this margin has varied from Venezuela to Bolivia. Cocks and Fortey (1988) identified two Ordovician facies zones surrounding Gondwana. However, a gap opposite Venezuela and Colombia is neatly filled by the Middle America terrane (combined Maya-Oaxaquia-Chortis) represented by the shelf facies of the Tremadocian Tiñu Formation (lying unconformably upon the Oaxacan Complex; c.f. Cocks and Torsvik, 2002, Fortey and Cocks, 2003). This location is consistent with the correlation between the Silurian rocks at Ciudad Victoria and Venezuela (Boucot et al., 1997).

The presence of ~1 Ga basement throughout Middle America (Maya-Oaxaquia-Chortis) is also consistent with an origin off Venezuela-Colombia as part of the circum-Amazonian ~1 Ga orogens, which includes the Sunsas orogen, the Andean massifs, and the Tocantins Province (Figs. 5–7; Restrepo-Pace et al., 1997; Ramos and Aleman, 2000; Pimentel et al., 2000; Keppie et al., 2001, 2003a). In this location, Middle America experienced several stages.

1. At ~1.3–1.2 Ga, development arc magmatism in a primitive island-arc system (Fig. 5; Lawlor et al., 1999; Keppie et al., 2001; Dostal et al., 2004).

2. At ~1.16–1.13 Ga, intrusion of rift-related plutons, followed at ~1.1 Ga by migmatization, and at ~1012 Ma by renewed AMCG, rift-related plutons, all possibly occurring in a backarc setting as the trench migrated seaward leading to the birth of the Avalonian primitive island arc outboard of Middle America (Figs. 5–7; Keppie et al., 2003a).

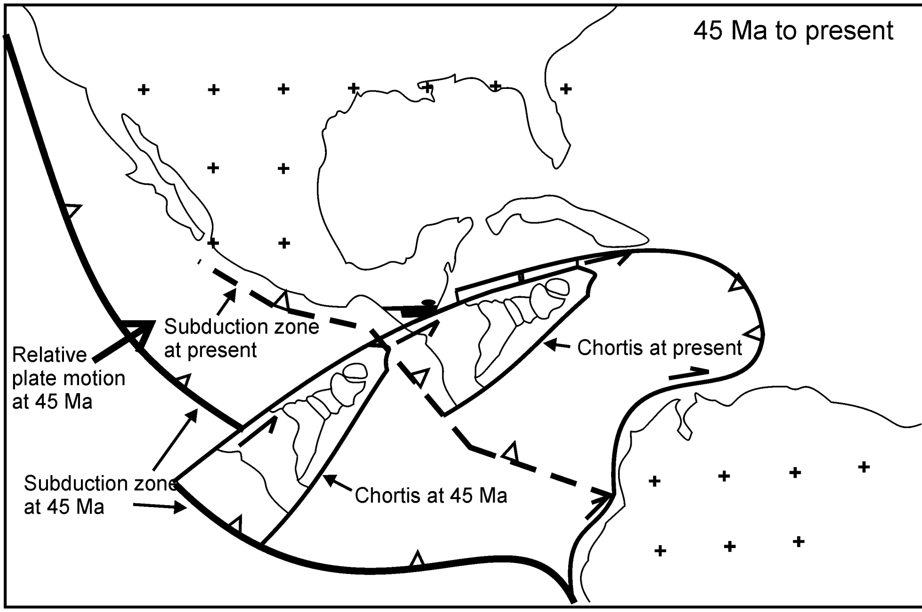


FIG. 19. 45 Ma to Present reconstruction showing rotation of the Chortis terrane to its present position contemporaneous with NE migration of the subduction zone, and tectonic erosion of the southern coast of Mexico (modified after Keppie and Moran-Zenteno, 2004).

3. At ~1,005–980 Ma, polyphase deformation at granulite facies, followed by rapid exhumation between 980 and 945 Ma, possibly related to flat-slab subduction as a result of collision of a ridge, a plume, or an oceanic plateau with the trench (Fig. 7; Ortega-Obregón et al., 2003; Solari et al., 2003; Keppie et al., 2004c).

4. At ~917 Ma, intrusion of an arc-related pluton accompanied by extensive hydration, possibly due to steepening of the subduction zone (Fig. 7; Keppie et al., 2001; Ortega-Obregón et al., 2003). The main ~1 Ga juvenile arc may be represented by the Avalonian basement, which is inferred to have lain outboard of Middle America, and appears to pass laterally into similar juvenile basement in the 900–850 Ma, Goiás magmatic arc (Arenópolis and Mara Rosa arcs: Pimentel et al., 2000) on the eastern side of the Amazon craton.

5. Between 700 and 600–550 Ma, subduction beneath Avalonia and the Yucatan produced voluminous arc magmatism (Keppie et al., 2003b) synchronous with a tectonothermal event that has also been recorded in the southern Oaxacan Complex (Krogh et al., 1993a, 1993b; Schulze et al., 2004): diachronous switching of arc to rift magmatism in Avalonia has been related to ridge-trench collision (Figs. 8–9; Nance et al., 2002; Keppie et al., 2003b).

6. Separation of Avalonia from Middle America is inferred to have been a two-stage process: in the latest Precambrian–earliest Cambrian rifting is inferred to have taken place by a mechanism analogous with separation of Baja California or Baja British Columbia (i.e., extension of the ridge into the continental margin), and this was followed in latest Cambrian–earliest Ordovician by a rift-drift transition (Figs. 10–11; Keppie et al., 2003b). As a consequence, continental rise prisms developed on the margins of Avalonia and Middle America—the Gander and Mixteca terranes, respectively. The intervening Rheic Ocean is represented by the Exploits oceanic terrane. The Tarahumara and Coahuila terranes also represent parts of the intervening area between North and Middle America.

7. During the Late Ordovician, Avalonia and the Gander terrane were accreted to North America (Fig. 12; Keppie et al., 2003b). At the same time, the Sierra Madre terrane was obducted onto Oaxaquia.

8. During the Mississippian, the Mixteca terrane was subducted, followed by Early–Middle Permian,

tectonic imbrication (Figs. 12–14). This appears to have been synchronous with amalgamation of Pangea and subduction along the western margin of Pangea (Fig. 15).

Throughout the Paleozoic, the Middle America terrane is inferred to have traveled passively with South America until it collided with the southern margin of Laurentia during the Carboniferous and Permian to form Pangea (Keppie and Ramos, 1999).

Mesozoic–Cenozoic

The breakup of Pangea led to the birth of several terranes that were subsequently accreted to North America:

1. Prior to the mid-Jurassic, the Chortis terrane separated from southern Mexico as recorded by the southward-thickening passive margin sequence (Tecocoyunca Group–Xolapa Complex; Ortega-Gutiérrez and Elías-Herrera, 2003) passing into the Huatulco Ocean (Figs. 15–16).

2. Callovian–Late Jurassic separation of the Maya terrane led to opening of the Gulf of Mexico, and the Juarez and Motagua terranes, all floored by oceanic lithosphere: it is inferred that a plume may have formed at the R-R-R triple point at the junction of the Juarez and Huatulco oceans (Fig. 17). This was synchronous with backarc rifting that separated the Zihuatanejo terrane (Guerrero composite terrane) from Pangea (Centeno-García and Silva-Romo, 1997)

3. Late Jurassic–Early Cretaceous development of the Guerrero composite arc terrane (Centeno-García et al., 1993, 2000, 2003) and subduction along the margin of the Chortis block. At ~130 Ma, the southern margin of Mexico overrode a plume, producing high-temperature/low-pressure metamorphism in the Xolapa Complex (Fig. 17).

4. In the mid-Cretaceous (~90 Ma), Baja British Columbia collided with the Guerrero composite terrane (Keppie and Dostal., 2001), which initiated amalgamation of the Guerrero composite terrane (Fig. 18). This was followed by birth of the Kula plate, which led to northward transport of Baja British Columbia.

5. Late Cretaceous–Paleocene flattening of the subducting slab, possibly the result of Kula ridge/trench collision, and/or increased convergence rates, led to accretion of the Guerrero composite terrane to North America during the Laramide orogeny and obduction of the Juarez and Motagua terranes onto the Maya terrane (Fig. 18).

6. Sinistral Cenozoic rotation of the Chortis terrane ~1100 km along the Cayman tranform fault occurred concurrently with subduction erosion of a triangular area south of Mexico and flattening of the subduction zone, possibly due to collision of the Tehuantepec Ridge with the subduction zone, anticlockwise rotation of the volcanic arc to its present position along the Trans-Mexican Volcanic Belt, and development of the Chiapas foldbelt (Fig. 19; Keppie and Moran-Zenteno, 2004).

7. In the Late Neogene, propagation of the East Pacific Rise into the continental margin led to the transfer of Baja California from the North American plate to the Pacific plate.

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Appendix. Terrane Descriptions

Chortis terrane: (A) Mesoproterozoic amphibolite facies para- and ortho-gneisses yielded concordant U-Pb SHRIMP zircon ages of 1074 ± 10 Ma (magmatic age) and 1017 ± 20 Ma (metamorphic age; Manton, pers. comm.); (B) greenschist–lower amphibolite facies metasediments and metavolcanics of unknown age; intruded by (C) deformed granitoid plutons with early Mesozoic Rb-Sr ages; (D) nonconformably overlain by Mesozoic sedimentary and volcanic rocks (Middle Jurassic–Lower Cretaceous siliciclastic rocks and volcanic rocks, Lower–Upper Cretaceous carbonates and andesitic volcanic rocks, and Upper Cretaceous–Paleogene redbeds) that were folded and eroded before deposition of (E) overstepping mid-Tertiary to Recent volcanic arc rocks (Donnelly et al., 1990).

Motagua terrane: (A) Mantle peridotites (metamorphosed to eclogites, jadeitites, amphibolites, and serpentinized peridotites); (B) Upper Jurassic–Lower Cretaceous gabbro, amphibolite, pillow basalt (MORB, OIB, and island-arc tholeiitic [IAT] affinities), and radiolarian chert; (C) Mid-Cretaceous eclogite-facies metamorphism and obduction in the southern Motagua terrane (Harlow et al., 2004); (D) Upper Cretaceous, calc-alkaline, island-arc basalt-andesite, radiolarian chert, limestone, and phyllite synchronous with eclogite-facies metamorphism and exhumation in the northern Motgua terrane (Harlow et al., 2004); unconformably overlain by (D) overstepping Eocene molasses and volcanicalstics; unconformably overlain by (E) Miocene-Quaternary sediments (Guinta et al., 2001).

Maya terrane: (A) metasedimentary rocks and ~1238 Ma AMCG suite metamorphosed to granulite facies at ~990-975 Ma (Weber and Köhler, 1997; Ruiz et al., 1999; Weber and Hecht, 2003); (B) Basement clasts in the Chicxulub crater include quartzite, quartz-mica schist, felsic-intermediate granitic gneiss, volcanic arc granitoids (quartz diorite, granodiorite, and tonalite with a SiO_2 range of 48–68%), and mafic, arc volcanic rocks (basaltic andesite and olivine tholeiite; Vera-Sánchez, 2000): granitic gneiss clasts yielded a depleted mantle model Nd age of 1.2–1.4 Ga (Kettrup et al., 2000); melt rocks have yielded depleted mantle Nd model ages of 1,060 ± 20 Ma (Blum et al., 1993) to 1.1–1.2 Ga (Kettrup et al., 2000); U-Pb analyses from Chicxulub breccia have yielded ages of 2,725 ± 57 Ma (one zircon), 550 ± 15 Ma (predominant: 6 zircons), 286 ± 14 Ma (1 titanite), and from distal ejecta of 544 ± 5 Ma and 559 ± 5 Ma (Colorado), 418 ± 6 Ma (Haiti and Chicxulub—3 zircons), 320 ± 31 Ma (Colorado; Krogh et al., 1993a, 1993b; Kamo and Krogh, 1995). Magmatic arc diorite-granodiorite-granite in the Maya Mountains of Belize yielded an intrusive age of 418 ± 4 Ma (upper intercept, U-Pb zircon data) and an inheritance age of 1210 ± 136 Ma (upper intercept, U-Pb zircon data: Steiner and Walker, 1996); (C) Upper Pennsylvanian–mid Permian (late Leonardian) shelf clastic, carbonate, and volcanic rocks displaying folds accompanied by lower greenschist-facies metamorphism (Steiner and Walker, 1996), and migmatization of the Chaucus Group (Ortega-Gutiérrez et al., 2004); unconformably overlain by (D) overstepping Upper Jurassic–lowermost Cretaceous continental sediments overlain by Cretaceous and Lower Tertiary marine carbonates: upper Campanian–lower Eocene turbiditic flysch records thrusting of Motagua ophiolites onto the southern margin of the Maya terrane (Guinta et al., 2001), followed by Miocene folds and SW-vergent thrusts in the Chiapas foldbelt (de Cserna, 1989) that are unconformably overlain by (E) Plio-Pleistocene clastic and volcanic rocks.

Juárez terrane: (A) metamorphosed serpentinite, gabbro, mafic volcanics, felsic tuff, greywacke; (B) Lower Cretaceous andesite, volcaniclastic rocks, tuff, flysch, and schist, and Berriasian–Valanginian (Lower Cretaceous) flysch, slate, and limestone deformed and metamorphosed at ~131–137 Ma ($^{40}Ar/^{39}Ar$ hornblende plateau ages; Sedlock et al., 1993); unconformably overlain by (C) overstepping Campanian–Maastrichtian flysch deformed in latest Cretaceous–Paleogene Laramide Orogeny; unconformably overlain by Cenozoic clastic and volcanic rocks (Sedlock et al., 1993 and references therein).

Oaxaquia terrane: (A) paragneisses, arc volcanic rocks, intruded by within-plate, rift-related, ≥1140 Ma orthogneisses; (B) deformed during the ~1100 Ma Olmecan migmatitic, tectonothermal event; (C) intruded by 1012 ± 12 Ma, anorthosite-charnockite- granite suite; (D) deformed by 1004 ± 3 to 979 ± 3 Ma Zapotecan orogeny under granulite-facies metamorphic conditions (Keppie et al., 2003a; Solari et al., 2003); (E) intrusion of 917 ± 6 Ma, arc-related, granitoid pluton (Ortega-Obregón et al., 2003); (F) unconformably overlain by Tremadocian clastic and carbonate rocks containing a

Gondwanan faunal assemblage in the south and Silurian, shallow-marine clastic rocks with Gondwanan fauna in the north (Robison and Pantoja-Alor, 1968; Boucot et al., 1997); (G) unconformably overlain by Carboniferous–Permian clastic and carbonate rocks; (H) overstepped by Upper Jurassic and Cretaceous continental-shallow marine clastic and carbonate rocks; (I) Cenozoic red beds and volcanic arc rocks.

Mixteca terrane: (A) metamorphosed psammites and pelites of uncertain age containing detrital zircons as young as Ordovician (Ramírez-Espinoza et al. 2002); (B) thrust slices of psammitic and pelitic metasediments intruded by mafic-felsic igneous rocks (~478–440 Ma U-Pb zircon ages; Ortega-Gutiérrez et al., 1999; Campa et al., 2002; Keppie et al., 2004a); (C) Mississippian eclogite-facies metamorphism and exhumation (346 ± 3 Ma U-Pb zircon age; Keppie et al., 2004a); (D) deposition of Upper Devonian–Middle Permian, shallow-marine clastic and carbonate rocks and arc-backarc volcanic rocks (Vachard et al., 2000; Vachard and Flores de Dios, 2002; Keppie et al., 2004c); (F) deformed and metamorphosed at greenschist (-amphibolite) facies during the Early–Middle Permian with synchronous intrusion of arc plutons; overstepped by (G) unconformably overlain Lower Jurassic–Cretaceous, continental-marine clastic and carbonate rocks; (H) deformed by Late Cretaceous–Eocene Laramide Orogeny; (I) unconformably overlain by Cenozoic continental clastic and volcanic-arc rocks.

Sierra Madre terrane (redefined to exclude the ~1 Ga Novillo gneiss and overlying Siluro-Devonian rocks): (A) pelitic and psammitic schist with lenses of serpentinite, metagabbro, metabasalt, and metachert of the Granjeno Formation (Carrillo-Bravo, 1991; Castillo-Rodríguez, 1988); (B) polyphase deformation accompanied by greenschist-facies metamorphism prior to deposition of pebbles in Wenlockian sediments unconformably overlying the Novillo Complex (Fries et al., 1962; de Cserna et al., 1977; de Cserna and Ortega-Gutiérrez, 1978); unconformably overlain by (C) overstepping Triassic–Lower Jurassic redbeds, and shallow-marine clastic rocks, with minor volcanic rocks, that were locally folded before deposition of (D) Middle Jurassic–Cretaceous redbeds, evaporites, shallow-marine clastic and carbonate rocks, felsic volcanic rocks, that were deformed by the Laramide orogeny before deposition of (E) the unconformably overlying Cenozoic, continental rocks.

Coahuila terrane: (A) Upper Pennsylvanian–Permian, low-grade, volcaniclastic flysch, calcalkaline volcanic rocks, and clastic and carbonate rocks, intruded by Triassic granitoids that were deformed prior to deposition of (B) overstepping and unconformably overlying Upper Jurassic–Cretaceous, shallow-marine limestone, shale, evaporite, siltstone, sandstone, and local coal, overlain by (C) Paleocene–Miocene continental-shallow marine clastic rocks and Oligocene-Quaternary felsic and alkaline volcanic rocks (Sedlock et al., 1993, and references therein).

Tarahumara terrane: (A) basinal sedimentary rocks similar to those in the Ouachita orogenic belt that were deformed and metamorphosed at greenschist facies in the Permian before being unconformably overlain by (B) overstepping Upper Jurassic–Cretaceous clastic, carbonate, and evaporitic rocks, which were deformed during the Laramide orogeny before being unconformably overlain by (C) Cenozoic, calcalkaline volcanic rocks (Sedlock et al., 1993, and references therein).

Cortez terrane: (A) Upper Ordovician, quartzite, carbonates and chert; (B) Devonian, Carboniferous and Permian, psammitic and pelitic rocks, rare chert and limestone; overstepped by (C) Upper Jurassic–Lower Cretaceous, magmatic arc rocks and associated sedimentary rocks that were affected by the Laramide orogeny before being unconformably overlain by (D) Upper Cretaceous–Quaternary, andesitic-rhyolitic volcanic rocks (associated with plutons) and continental rocks (Sedlock et al., 1993; Sánchez-Zavala et al., 1999).

The Guerrero Composite Terrane is characterized by Upper Jurassic–early Upper Cretaceous, submarine (-subaerial) volcanic and sedimentary rocks that were accreted to cratonic Mexico in the Late Cretaceous, producing the Turonian-Maastrichtian foreland basin deposits (Centeno-García et al., 2000, 2003). The terranes are best defined south of the Trans-Mexican Volcanic Belt (TMVB)—potential equivalents north of the TMVB are shown in brackets. Terranes 6–10 occur in Baja California and have been defined by Sedlock et al. (1993).

1. Arperos terrane (shown as a suture on Fig. 1C): (A) Lower Cretaceous, basalts produced by mixing of OIB and N-MORB siliceous sediments, pelagic carbonates, and turbidites (Freydier et al., 2000).

2. Teloloapan terrane: (A) Lower Jurassic, andesitic-dacitic, volcanic rocks, phyllite, and sericitic tuff contemporaneous with granite that yielded U-Pb zircon data with intercepts at 186 ± 7 Ma and 1242 ± 126 Ma (Elías-Herrera et al., 2000); (B) Neocomian–Albian, volcanic-arc rocks, limesones, shale, and sandstone that are thrust eastward over Aptian–Turonian rocks of the Mixteca terrane during the Laramide orogeny.

3. Arcelia(-Guanajuato) terrane: (A) Albian–Cenomanian, primitive island arc, back-arc basin, OIB, and MORB basalts, ultramafic rocks, pelagic limestone, radiolarian chert, and black shales that are thrust eastward over the Teloloapan terrane during the Laramide orogeny.

4. Zihuatenejo(-San José de Gracia) terrane: (A) Triassic, siliceous continent–derived sediments with ε_{Ndi} = –6 to –7 and T_{DM} ages = 1.3–1.4 Ga, and basalts, that were deformed and metamorphosed in the Early–Middle Jurassic and intruded by Middle Jurassic granitoids before being unconformably overlain by (B) Lower Cretaceous (Neocomian–Albian) arc-volcanic rocks (andesitic-dacitic flows) and associated sedimentary rocks that are thrust westward over the Las Ollas terrane during the Laramide orogeny, and overstepped on the east by (C) mid-Tertiary ignimbrites. Paleozoic rocks appear to underlie the Cretaceous arc rocks in the San Jose de Gracia terrane.

5. Las Ollas terrane: (A) probable Lower Cretaceous, ophiolitic mélange consisting of blocks of ultramafic rocks, immature island-arc tholeiitic gabbro, basalt, amphibolite, dolerite, limestone, quartzite, and chert in a matrix of flysch and serpentine with blueschist metamorphic minerals.

6. Alisitos terrane: (A) Upper Jurassic–late Lower Cretaceous, calc-alkaline, arc-volcanic and volcanogenic rocks, and limestone that are coeval with older parts of the Peninsular Ranges batholith that apparently straddled the continent-ocean boundary: the arc passes east and west into periarc sandstones; unconformably overlain by (B) Upper Cretaceous–Eocene marine clastic rocks and minor tuff overlain by mid-Miocene marine clastic rocks and calc-alkaline volcanic rocks passing upwards into upper Miocene–Cenozoic alkalic-tholeiitic volcanic and sedimentary rocks.

7. Vizcaino Sur terrane: (A) Upper Triassic ophiolite, chert, limestone, breccia, and sandstone; (B) Lower Jurassic volcanic and volcaniclastic rocks.

8. Vizcaino Norte terrane: (A) Upper Triassic ophiolite and tuffaceous sediments; (B) Upper Jurassic–Upper Cretaceous volcanogenic rocks containing granitoid clasts with discordia intercepts of 1,340 ± 3 Ma and 150 ± 3 Ma.

9. Choyal terrane: (A) Middle Jurassic, mafic-felsic volcanic, volcaniclastic clastic, and ophiolitic rocks intruded by granitoids, (B) Middle and Upper Jurassic clastic rocks of continental derivation (including Pennsylvanian limestone and quartzite clasts). Terranes 7, 8, and 9 are overstepped by Albian–Campanian siliclastic turbidites unconformably overlain by Miocene–Pliocene shallow-marine strata.

10. Western Baja terrane: (A) Upper Triassic to mid-Cretaceous, ocean-floor basalt, siliciclastic metasedimentary rocks, chert, and rare limestone affected by deformation and blueschist-facies metamorphism. The boundary between this terrane and nos. 7–9 is a serpentinite-matrix mélange containing blocks of orthogneiss, eclogite, ultramafic rocks, blueschist, amphibolite, and greenschist that have yielded ages ranging from Middle Jurassic to mid-Cretaceous.

Baja California terrane: (A) Mesozoic rocks of the Guerrero composite terrane (nos. 6–10); (B) Middle Miocene–Holocene, rift–passive margin, volcanic, and associated sedimentary rocks.