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Universidad Nacional Autónoma de México, Instituto de Geología, México, D.F.

PETROGENESIS AND TECTONIC EVOLUTION OF CENTRAL MEXICO DURING TRIASSIC–JURASSIC TIME

Elena Centeno-García[1], and
Gilberto Silva-Romo[2]

ABSTRACT

The Zacatecas Formation that crops out near Zacatecas city in central Mexico, is made up of alternating shale, quartz-rich sandstone, tuff, scarce limestone and basaltic pillow lava. Rocks of similar age are exposed in the Peñón Blanco area that are called La Ballena formation. This is composed of shale and quartz-rich sandstone, but does not contain pillowed basalts. Both formations are Triassic in age and they were affected by two phases of deformation. The first phase is pre-Kimmeridgian in age, and the second occurred during Late Cretaceous. Regional distribution of the units suggests that the Zacatecas Formation is located at the limit between the Guerrero and Sierra Madre terranes, or within the Guerrero terrane. La Ballena formation is part of the Sierra Madre terrane

Whole-rock trace element and Nd isotopic analyses from sedimentary rocks sampled from both formations are similar and suggest an evolved continental source. They are enriched in light rare earth elements and show patterns similar to average North American shale (NASC). Initial ε_{Nd} are -5.45 and -5.18, and model ages are 1.57 and 1.28 Ga. These data suggest that the sediments from both formations might have been derived from similar sources or might have evolved in the same continental margin. Basaltic pillow lavas from the Zacatecas Formation are depleted in rare earth elements, and they have initial ε_{Nd} values of 6.8 and 7.4. These data are similar to present mid-ocean ridge basalts or primitive intra-oceanic island arcs. Based on its stratigraphy and geochemistry, the Zacatecas Formation is interpreted to have been formed in an oceanic-basin setting, and the La Ballena formation in a continental-slope setting. Therefore, they define approximately the limit of the western continental margin of Mexico during Late Triassic to Middle Jurassic.

Key words: Geology, tectonics, Nd isotopes, REE, Triassic, Jurassic, Mexico.

RESUMEN

La Formación Zacatecas está constituida por lutitas, areniscas cuarcíticas y tobas, con escasas calizas y lavas almohadilladas y aflora al oeste de la ciudad de Zacatecas. Rocas similares están expuestas en el área de Peñón Blanco (Formación La Ballena) al oriente del Estado de Zacatecas, donde están formadas por lutitas y areniscas cuarcíticas, pero sin rocas basálticas. Ambas formaciones son de edad triásica tardía, y fueron afectadas por dos fases de deformación, la primera de edad pre-kimeridgiana y la segunda de edad cretácica tardía. Relaciones estratigráficas regionales sugieren que la Formación Zacatecas se encuentra en el límite entre los terrenos Guerrero y Sierra Madre o forma parte del terreno Guerrero. En cambio, la Formación La Ballena pertenece al terreno Sierra Madre.

Los análisis de roca total de elementos en indicios (*trace elements*) e isótopos de neodimio de los sedimentos de ambas formaciones sugieren una fuente de aporte continental evolucionada, ya que están enriquecidos en tierras raras ligeras y muestran patrones similares a la media de las lutitas de América del Norte (NASC). Los valores de ε_{Nd} inicial de sedimentos son -5.45 y -5.18, y las edades modelo son de 1.57 y 1.28 Ga, respectivamente. Esto sugiere que los sedimentos de ambas formaciones fueron derivados de una fuente similar, por lo cual pudieron haberse generado asociados a la misma margen continental. Las lavas almohadilladas de la Formación Zacatecas están empobrecidas en tierras raras ligeras y presentan valores de ε_{Nd} inicial de 6.8 y 7.4, que son similares a valores observados en basaltos de dorsal oceánica (MORB) o en arcos intraoceánicos primitivos. Con base en la estratigrafía y la geoquímica, se sugiere un.ambiente de piso oceánico para la Formación Zacatecas y un ambiente de talud continental para la Formación La Ballena. Por lo tanto, definen de forma aproximada la localización de la margen continental occidental de México para el Triásico Tardío-Jurásico Medio.

Palabras clave: Geología, tectónica, isótopos de Nd, tierras raras, Triásico, Jurásico, México.

INTRODUCTION

The importance of central Mexico for understanding the tectonic evolution of North America lies in its location. It is a region that broadly corresponds to the junction between two different tectonic settings that were active along the North American margins throughout the Mesozoic. On eastern Mexico, the breakup of Pangea and opening of the Gulf of

[1]*Estación Regional del Noroeste, Instituto de Geología, Universidad Nacional Autónoma de México, Apartado Postal 1039, 83000 Hermosillo, Sonora, México. E-mail address: centeno@servidor.unam.mx*
Present address: Instituto de Geología, Universidad Nacional Autónoma de México, Ciudad Universitaria, Delegación Coyoacán, 04510 Distrito Federal, Mexico.
[2]*División de Ciencias de la Tierra, Facultad de Ingeniería, Uinversidad Nacional Autónoma de México, Ciudad Universitaria, Delegación Coyoacán, 04510 Distrito Federal, Mexico. E-mail address: silvarg@servidor.unam.mx*

Mexico were accompanied by rifting and extensional tectonics beginning in Late Triassic time (Pindell, 1985; Morán-Zenteno *et al.*, 1988; Ross and Scotese, 1988; Molina-Garza *et al.*, 1992). In contrast, western Mexico was characterized by Cordilleran tectonics, involving subduction, strike-slip faulting and/or accretion of terranes (Sedlock *et al.*, 1993; Centeno-García *et al.*, 1993a; Saleeby and Busby-Spera, 1992). These scenarios lead to a complex geology in some parts of Mexico that recorded several tectonic events associated with rifting, terrane accretion, large-scale lateral shearing, and regional thrust/fold deformation (Torres-Vargas *et al.*, 1993; Centeno-García *et al.*, 1993a; Jones *et al.*, 1995). This paper is focused on the Zacatecas/San Luis Potosí region, where the Sierra Madre and Guerrero terranes converge (Figure 1) (Campa and Coney, 1983; Coney and Campa, 1987). The Sierra Madre terrane is floored by a Precambrian basement that apparently was accreted to North America in late Paleozoic time by the collision between North and South America during the formation of Pangea (Yáñez *et al.*, 1991; Stewart *et al.*, 1993). The Guerrero terrane is made up of deformed ocean-floor and island-arc sequences of Triassic to Early Jurassic, and Late Jurassic to mid-Cretaceous age, respectively. Final accretion of the Guerrero terrane to its actual location might have occurred in Late Cretaceous time (Centeno-García, 1993a; Tardy *et al.*, 1991; Talavera-Mendoza *et al.*, 1995). How these two terranes relate to Pacific or to Atlantic tectonics will be discussed in this paper.

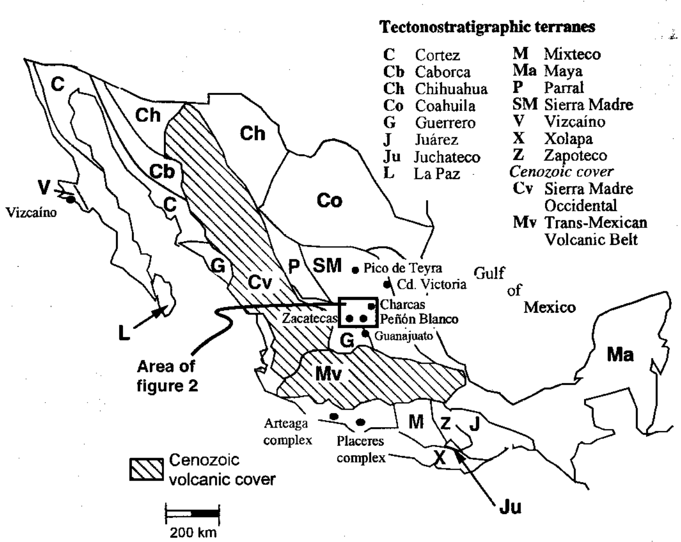

Figure 1. Terrane map of Mexico, location of the study area, and other geologic features mentioned in this paper (map modified from Coney and Campa, 1987).

Scarce exposures of pre-Cenozoic rocks in the Zacatecas-San Luis Potosí region make it difficult to reconstruct the tectonic evolution of central Mexico during early Mesozoic time. The purpose of this study is to characterize the tectonic affinity of the Triassic-Jurassic rocks of central Mexico, and to define approximately the limit between the Guerrero and Sierra Madre terranes. Regional mapping, sandstone modal composition, trace element geochemistry, and Samarium-Neodymium (Sm/Nd) isotopic analyses have been done on early Mesozoic sedimentary and volcanic rocks of this area. This paper summarizes the data obtained and focuses mainly on the tectonic setting of the Triassic-Jurassic sequences. Paleogeographic evolution of central Mexico is also discussed.

GEOLOGICAL SETTING

Most of the central part of Mexico is covered by Cenozoic volcanic rocks, making it difficult to determine the stratigraphy and the contact relationships among some of the Mesozoic units. Figure 2 shows the geographic distribution of the main pre-Cenozoic outcrops and the possible location of the boundary between the Sierra Madre and Guerrero terranes. The Peñón Blanco and Charcas areas (Figure 2) contain the most complete stratigraphic section of the Sierra Madre terrane in the studied region (Silva-Romo, 1993; Tristán-González and Torres-Hernández, 1994). The stratigraphy consists of Late Triassic siliciclastic strata, Middle(?) Jurassic volcanic and volcaniclastic rocks and late Mesozoic carbonate, sandstone, and shale.

The stratigraphy of the Guerrero terrane is well exposed in the El Saucito, Zacatecas, and Fresnillo areas (Figure 2). These areas show important differences in stratigraphy with respect to the Sierra Madre terrane, including: (a) presence of Triassic pillowed basalts interbedded with siliciclastics, (b) absence of Middle to Late Jurassic volcanic and carbonate rocks, and (c) presence of Lower to mid-Cretaceous ocean-arc sequences mostly composed of volcanic and volcaniclastic rocks (Figure 3).

SIERRA MADRE TERRANE

The Triassic to Cretaceous units of the Sierra Madre terrane that crop out in the Peñón Blanco and Charcas areas are La Ballena, Nazas, Zuloaga, La Caja, Taraises, Tamaulipas, Indidura and Caracol formations (Figures 2 and 3) (López-Infanzón, 1986; Silva-Romo, 1993; Tristán-González and Torres-Hernández, 1994).

The older clastic marine sequences of these areas were originally described as the Zacatecas Formation by Labarthe and collaborators (1982), and redefined as La Ballena formation by Silva-Romo (1993) based on major stratigraphic differences with respect to the type Zacatecas Formation. La Ballena formation consists almost exclusively of siliciclastic deposits, including black shale, quartz-rich sandstone and some conglomerate (Silva-Romo, 1993). Primary sedimentary structures indicate that La Ballena sediments were deposited by turbidity currents in a deep marine sedimentary environment. Middle and outer submarine-fan facies have been recognized in the

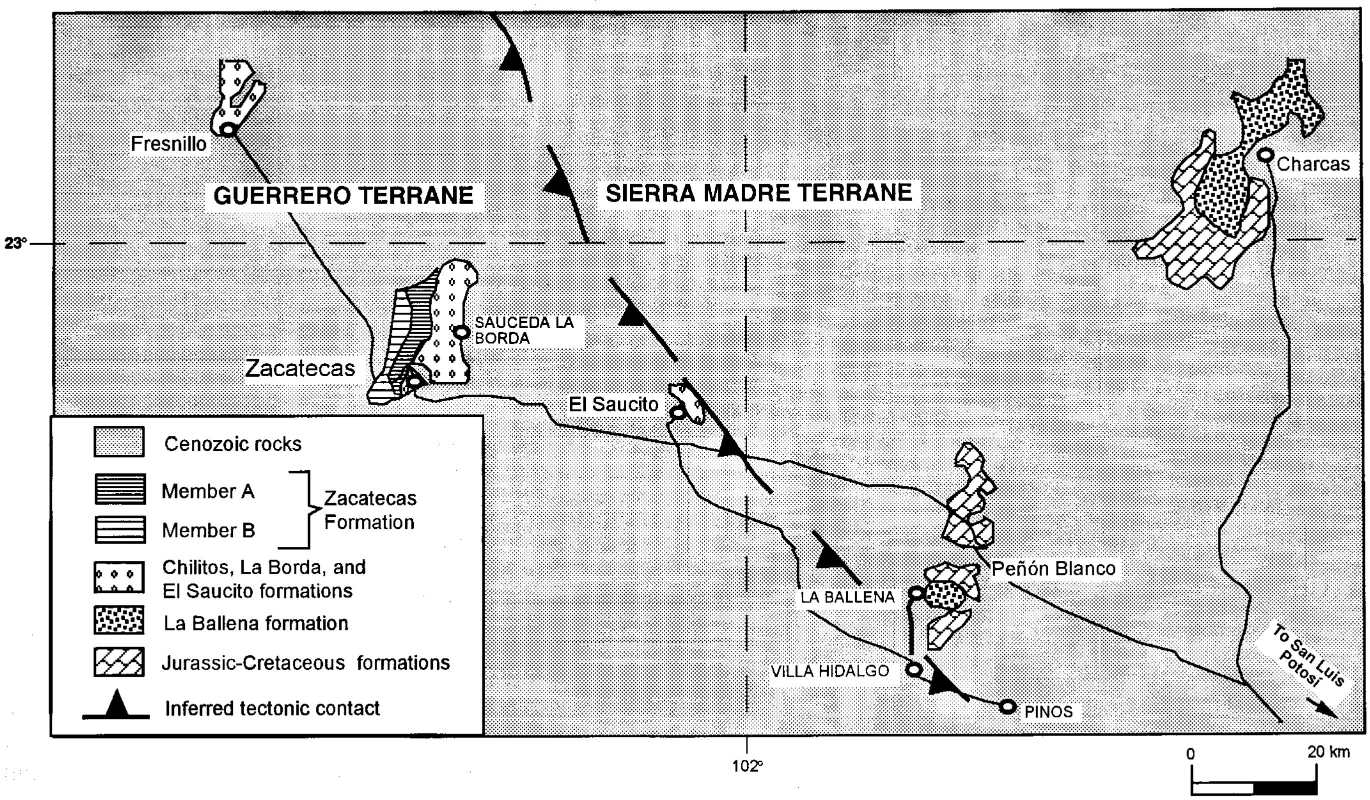

Figure 2. Generalized geologic map of the Zacatecas-San Luis Potosí region. Approximate boundary of the Guerrero and Sierra Madre terranes is shown in thick line.

Peñón Blanco area (Silva-Romo,1993). Gravitational folding and slump-brecciated sediments have been found in the Charcas area, and suggest a slope-like depositional environment. Ammonites and bivalves of Late Triassic (Carnian) age that are similar to those from the type Zacatecas Formation, have been reported from both Peñón Blanco and Charcas areas (Cantú-Chapa, 1969; Silva-Romo, 1993). The original thickness of La Ballena formation is uncertain because of its tight folding. A bore hole at Charcas drilled as much as 4,640 m of the unit without reaching the base of the sequence (López-Infanzón, 1986).

The La Ballena formation contains structures related to two phases of deformation. The older deformation produced tight folding and shearing, with some incipient foliation, mostly parallel to bedding. The general trend of the incipient foliation is N 40°-60° E. The second phase of deformation affected both La Ballena formation and the younger Jurassic-Cretaceous units. The second phase is related to the Laramide orogeny, which generated tight to open folds and a well developed axial cleavage. This second generation of folding shows an average N 50°-20° W trend.

The Nazas Formation (Figure 3) rests unconformably on La Ballena formation in both Peñón Blanco and Charcas areas (Silva-Romo, 1993; Tristán-González and Torres-Hernández, 1994). It is made up of volcanic and volcaniclastic rocks. Lavas and tuffs are mostly andesitic, and are interbedded with conglomerates composed mostly of volcanic and sandstone fragments. Sandstone clasts in the conglomerate have grain-modal compositions similar to those of sandstone beds of the underlying La Ballena formation, and suggest that La Ballena formation was deformed, uplifted and exposed to erosion before Late Jurassic time (pre-Oxfordian-Kimmeridgian) (Silva-Romo, 1993). The age of the Nazas Formation in this area is unknown, but similar volcanic sequences are exposed, although more deformed, in the Caopas-Pico de Teyra area (Figure 1), which have yielded Late Jurassic (Oxfordian) U/Pb ages (Jones *et al.*, 1995).

La Ballena and Nazas formations are unconformably overlain by calcareous sandstone, conglomerate and carbonates of the Zuloaga Formation. This unit was deposited in a "middle shelf" environment, and contains invertebrates of late Oxfordian-Kimmerigdian age (Figure 3) (Silva-Romo, 1993). The Zuloaga Formation changes transitionally upward to La Caja Formation, composed of interbedded calcareous mudstone, shale, sandstone, chert and phosphatic limestone. La Caja Formation may have accumulated in a shallow to moderately deep marine, open ocean environment (Silva-Romo, 1993). It contains abundant ammonoids of Kimmeridgian to Tithonian age.

La Caja Formation represents the initial deposits of an Upper Jurassic to lower Upper Cretaceous (Turonian) succession that records long-term continuous subsidence. La Caja Formation grades transitionally to overlying Cretaceous carbonates, including the Taraises (Berriasian-Hauterivian), Tamaulipas (Hauterivian-Aptian), Cuesta del Cura (Albian-Cenomanian), and Indidura (Cenomanian-Turonian) forma-

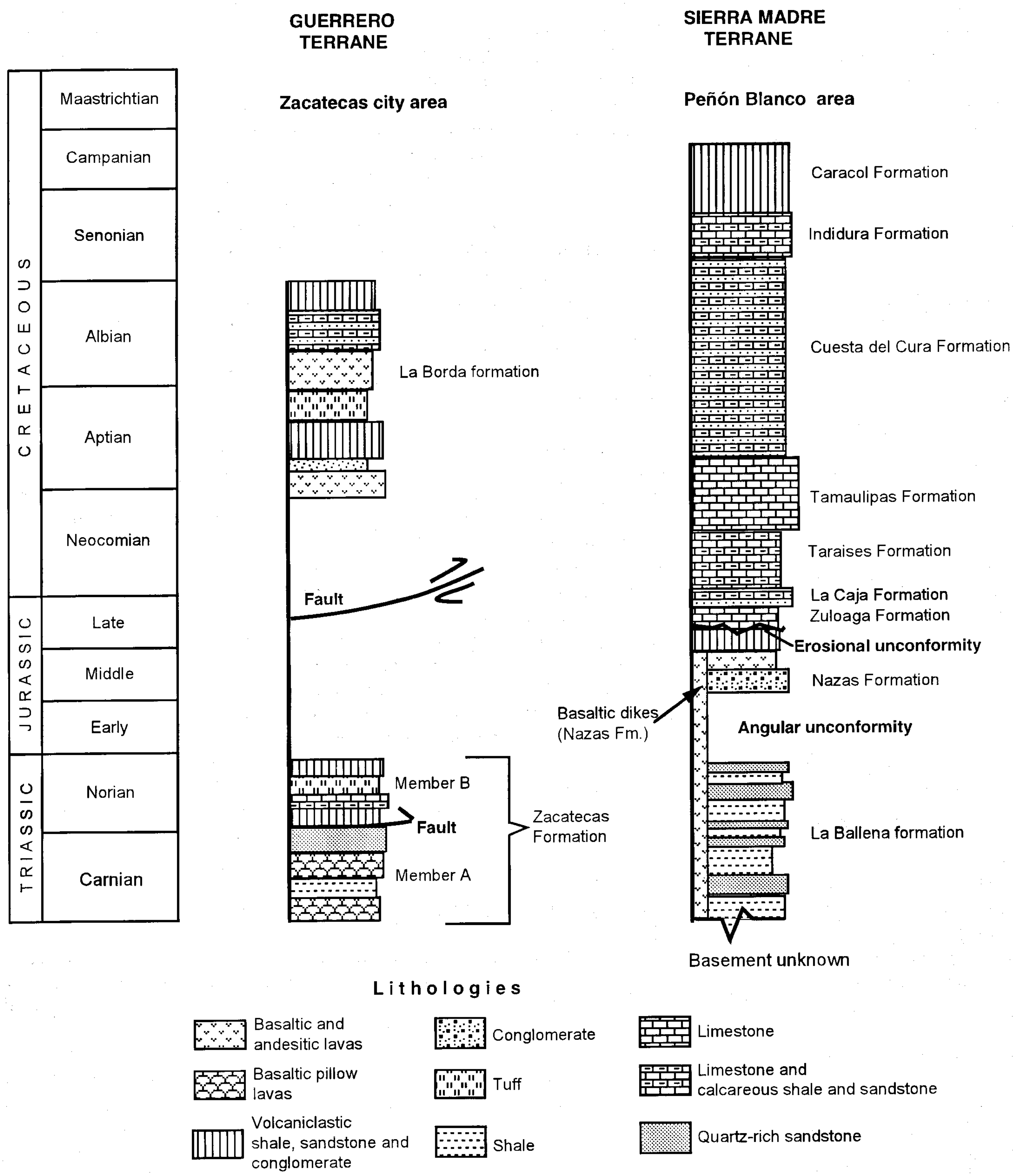

Figure 3. Stratigraphic columns of the Zacatecas and Peñón Blanco areas.

tions (Figure 3) (Silva-Romo, 1993; Tristán-González and Torres-Hernández, 1994). Those calcareous units were deposited in relatively deep open ocean, and in inner and outer shelf environments, and may represent the southwest margin of the carbonate platform of northeastern Mexico (Silva-Romo, 1993). A major change in lithology and depositional environment took place in Late Cretaceous (Turonian to Campanian?) time, when a succession of interbedded shale, sandstone and conglomerate mostly composed of volcanic, chert and quartz fragments was deposited (Silva-Romo, 1993). This is the Caracol Formation, and has been interpreted as deposit of a foreland basin created by the collision of the Guerrero terrane (Centeno-García, 1994).

GUERRERO TERRANE

Marine volcanic and associated sedimentary rocks interpreted as part of the Guerrero terrane crop out a few kilometers west of the Peñón Blanco area (Figure 2). Stratigraphy of the terrane is better exposed in south and western Mexico (Michoacán and Guerrero states). In contrast, the northeastern part of the terrane is characterized by isolated outcrops surrounded by large areas of Cenozoic volcanic-sedimentary rocks (Figure 1).

These northern exposures of the Guerrero terrane are mostly characterized by volcanic and volcaniclastic rocks, and some limestone of Lower Cretaceous age (de Cserna, 1976; Yta, 1992). Older sedimentary and volcanic rocks have been found in Zacatecas city, and belong to the Zacatecas Formation (Burckhardt and Scalia, 1906) (Figure 2). Whether the older rocks are part of the basement of the Guerrero terrane or not has not been determined, but are herein considered as part of the Guerrero terrane for descriptive purposes. Their origin and significance will be discussed at the end of this paper.

The Zacatecas Formation (Burckhardt and Scalia, 1906) is a low-grade metamorphosed clastic-volcaniclastic unit that crops out in a small tectonic window near Zacatecas city (Figures 2 and 3). In this study it was divided in two members. Member A is made up of alternating thick intervals of interbedded black shale, quartz-rich sandstone, and subordinate pillow lavas and thin bedded limestone (Figure 3) (Ranson *et al.*, 1982; Cuevas-Pérez, 1983; and Monod and Calvet, 1991). Member B is composed of thick units of fine-grained volcaniclastic rocks and volcanic breccias that are tectonically intercalated with member (A). Monod and Calvet (1991) suggest that pillow lavas of the member A were part of the Cretaceous arc. However, their stratigraphic relationships with the siliciclastic sedimentary rocks and major geochemical differences with the arc volcanics suggest that they form part of the Zacatecas Formation. Contacts among the two members are faulted, such that the original stratigraphic relationships are modified. It is not clear if the volcanic breccias and volcaniclastic rocks of member B were intercalated during deposition or by tectonic transport with the basaltic lavas and siliciclastics of member A. The Zacatecas Formation is Norian (Upper Triassic) in age, based on its fossil content of ammonoids (Burckhardt and Scalia, 1906). Few sheared lenses of limestone are exposed near the type section of the Zacatecas Formation, and were interpreted as part of the Cretaceous arc sequences by Monod and Calvet (1991). The Zacatecas Formation shows two generations of structures. The first phase of deformation created incipient to well developed foliation, tight folding, and some sheared zones with mylonitic textures. The second phase of deformation produced local thrust faulting and open to tight folding with local development of axial cleavage. The Zacatecas Formation is tectonically overlain by basaltic to andesitic lavas and volcaniclastic rocks of the La Borda formation (Figure 3). La Borda formation is best exposed in the eastern part of the Sierra de Zacatecas, between Sauceda de La Borda and Zacatecas city. This succession is made up of andesitic to basaltic lava flows interbedded with thick packages of fine-grained volcanic sandstone, tuff, green chert, and thin layers of cherty black shale. This succession contains radiolarians of Cretaceous age (Miriam Yta, personal communication, 1993), and shows structures related to one phase of shortening. The contact between the La Borda and the Zacatecas formations is thrust faulted.

The nearest well dated exposures of Lower Cretaceous volcanic-sedimentary rocks of the Guerrero terrane arc assemblage are found in Fresnillo (60 km WNW of Zacatecas) and El Saucito (45 km east of Zacatecas) areas (Figure 2) (de Cserna, 1976; Yta *et al.*, 1990) and they are similar to the La Borda succession. The rocks at El Saucito are made up of basaltic pillow lavas and massive flows interbedded with radiolarian cherts and pelagic limestone (Yta, 1992). This succession is thrust over undated metamorphosed limestones. The chert layers contain radiolarians of Early Cretaceous age, similar to radiolarians reported in the Fresnillo region (Dávila-Alcocer, 1981; Yta *et al.*, 1990). The present authors consider the exposed thrust at this locality as the most suitable outcrop of the limit between the Guerrero and Sierra Madre terranes. The volcanic-sedimentary succession in the Fresnillo area is very similar to that at the El Saucito, and is mostly composed of basaltic lavas interbedded with volcaniclastic rocks and radiolarian-bearing chert assigned to the Chilitos Formation (de Cserna, 1976; Dávila-Alcocer, 1981).

SANDSTONE PETROGRAPHY

Point counting was carried out on sandstone samples collected from clastic units of the Sierra Madre and Guerrero terranes. Sand grains were assigned to categories used by Dickinson (1985). Results from the Peñón Blanco and Charcas areas of the Sierra Madre terrane are shown on Figure 4, and include the following: (a) sandstones from La Ballena formation; (b) sandstone clasts from the conglomeratic beds of the Nazas Formation; and (c) sandstone from the Caracol Formation. The data of the Guerrero terrane include the following: (a) sandstone from the Zacatecas Formation, and (b) sandstone from El Saucito Cretaceous succession.

Triassic sandstones (La Ballena and Zacatecas formations) from both terranes show no differences in composition (Figure 4*a*). Fragments are angular to subrounded, and moderately to well sorted. Both units show high percentages of quart-

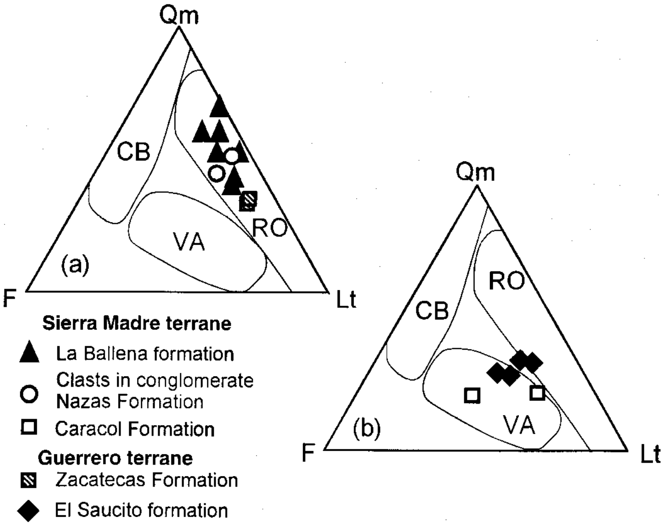

Figure 4. Tertiary diagrams comparing mean detrital modes of sandstones from the Guerrero and Sierra Madre terrane. *a*, Triassic sediments of member A of the Zacatecas Formation and La Ballena formation, as well as sandstone boulders from the conglomerates of the Nazas Formation. *b*, Cretaceous arc-related sandstones from El Saucito area of the Guerrero terrane and sandstones from Caracol Formation of the Sierra Madre terrane. Sandstones show remarkable difference in grain composition between the Triassic and Cretaceous units. Fields correspond to Dickinson (1985): Qm, monocrystalline quartz; F, feldspar; Lt, total lithics; CB, continental block; RO, recycled orogen; VA, volcanic arc.

zose fragments (Qt=88, F=10, L=2), and equal percentages of monocrystalline and polycrystalline quartz grains (39Qm, 49Qpt). All the samples plot in the recycled orogen provenance field on the Qm/F/Lt diagrams (Dickinson *et al.*, 1983) (Figure 4*a*). The composition suggests that the sediments were derived from either an uplifted fold-thrust belt, a collision suture belt and/or continental uplifted cratonic areas. The low percentage of volcanic lithics in both units indicates that there was no active arc system in the source area. Point counting carried out on sandstone clasts that form the conglomeratic beds of the Nazas Formation has similar compositions to those analyzed from the Zacatecas and La Ballena formations (Figure 4*a*). This suggests that the Triassic rocks, at least those of the La Ballena formation were uplifted and eroded before or during the deposition of the Nazas Formation.

Sandstones from El Saucito Cretaceous succession of the Guerrero terrane are made up of quartz and volcanic grains (Qt=54, F=18, L=28). Some samples plot within the volcanic arc field of the Qm-F-Lt diagram (Dickinson *et al.*, 1983), suggesting that they were derived from the erosion of the volcanic arc that characterizes the Guerrero terrane (Figure 4*b*). Other samples contain minor well rounded fragments of granite, quartz-muscovite schist and quartz-arenite grains, and plot within the recycled orogen field, suggesting that some continent-derived material also was supplied to the succession.

Sandstone modal composition of Caracol Formation (Late Cretaceous) records an important change in the sedimentary patterns of the Sierra Madre terrane. It is the first unit deposited on the Sierra Madre terrane that shows clear sedimentary links with the Guerrero terrane. Sandstones from this unit are composed of volcanic and feldspar grains (Qt=20, F=30, L=50), and plot in the magmatic arc provenance field of the Qm-F-Lt diagram (Dickinson *et al.*, 1983) (Figure 4*b*). The high abundance of volcanic and sedimentary fragments (mostly limestone) indicates that sediments of the Caracol Formation were derived from the erosion of the Guerrero terrane arc assemblage.

TRACE ELEMENT GEOCHEMISTRY

Whole-rock analyses to determine rare earth elements (REE) and other incompatible trace element concentrations (Table 1) were performed by ICP-MS (inductively coupled plasma mass spectrometry), at the Department of Geosciences of the University of Arizona, following procedures described in Roberts and Ruiz (1989). The REE data were chondrite-normalized using Evensen and collaborators (1978) values. Concentrations of other incompatible trace elements, such as Y, Zr, Nb, Hf, Ta, Pb, Th, and U were normalized to MORB, using concentrations proposed by Pearce (1982).

There is a significant difference in composition among basaltic lavas from the Zacatecas Formation, overlying Cretaceous volcanics in the Guerrero terrane, and Jurassic volcanics of the Nazas Formation from the Sierra Madre terrane (Table 1).

Volcanic rocks of the Zacatecas Formation are characterized by low REE abundances (REE= 26.82-32.33). Chondrite-normalized REE patterns are slightly depleted in light rare earth elements (LREE), with flat heavy rare earth element curve (HREE) and lack of significant Eu depletion (Table 1, Figure 5). These REE patterns are similar to those shown by N-MORB or primitive island arc basalts (Hess, 1989). The Pearce trace element variation diagrams show nearly flat patterns that are close to MORB values, and indicate that trace element abundances of the Zacatecas basalts are very similar to those of ocean-rift magmatism.

Samples from the Cretaceous arc sequences of the Guerrero terrane were not analyzed in this study. However some data from El Saucito, Fresnillo and Zacatecas have been published by Lapierre and collaborators (1992) and Tardy and collaborators (1991). Their data from El Saucito and Fresnillo show patterns similar to those obtained in other areas of Cretaceous rocks in the Guerrero terrane (Centeno-García *et al.*, 1993a; Talavera-Mendoza *et al.*, 1995) (dashed area, Figure 5*a*), and are more enriched in total REE and in LREE than our results from the Triassic rocks. These patterns are characteristic of oceanic island arc volcanic rocks. Other trace elements show enrichment in mobile elements in Pearce trace element variation diagrams (dashed area, Figure 5*b*; Table 1), suggesting an ocean arc origin as well. Samples collected by the same authors from Zacatecas city (Figure 5*a* and *b*, dotted area) are more similar to the data obtained in this study from the Triassic rocks of the Zacatecas Formation. It might be due

Table 1. Whole-rock trace element analyses from different lithologies of the Zacatecas Formation (Guerrero terrane), La Ballena, and Nazas formations (Sierra Madre terrane).

FORMATION	Zacatecas	Zacatecas	Zacatecas	La Ballena	Nazas
Rock type	Sandstone	Basalt	Basalt	Sandstone	Andesitic dike
Sample no.	Z-7	Z-12a	Z-16	Z-40	Z-31
La	9.46	2.36	2.92	26.85	14.35
Ce	18.63	7.08	8.36	55.77	34.87
Nd	8.28	5.61	6.78	25.86	20.09
Sm	1.88	2.03	2.42	5.14	5.01
Eu	0.44	0.72	0.91	1.1	1.64
Gd	1.42	2.01	3.05	4.22	5.01
Tb	0.37	0.54	0.61	0.75	0.81
Er	1.41	2.22	2.94	2.72	2.67
Tm	0.18	0.38	0.43	0.49	0.42
Yb	1.74	2.24	2.38	2.89	2.62
Lu	0.44	0.37	0.47	0.52	0.42
∑REE	45.51	26.82	32.33	127.67	88.96
La/Yb	5.44	1.03	1.22	9.29	5.47
LaN/YbN+	3.68	0.71	0.83	6.27	3.7
LaN/SmN	3.17	0.73	0.77	2.29	1.8
GdN/YbN	1.25	1.18	1.4	1.56	1.87
Eu/Eu*	0.6	—	—	0.63	—
Y	11.28	19.9	37.25	26.75	26.69
Zr	349.4	55.96	80.81	275.36	203.41
Nb	6.42	1.45	0	11.56	13.21
Hf	13.18	1.65	1.29	7.61	5.05
Ta	0.85	0.3	0.27	0.92	1.04
Pb	6.41	0.66	1.76	8.01	1.75
Th	4.86	0.26	0.24	7.28	3.14
U	1.63	0.1	0.13	1.95	0.89
Zr/Hf	26.51	33.89	62.43	36.17	40.29
Th/U	2.98	2.73	1.88	3.74	3.52
La/Th	1.95	9.09	12.15	3.69	4.57
Yb/Hf	0.13	1.36	1.84	0.38	0.52

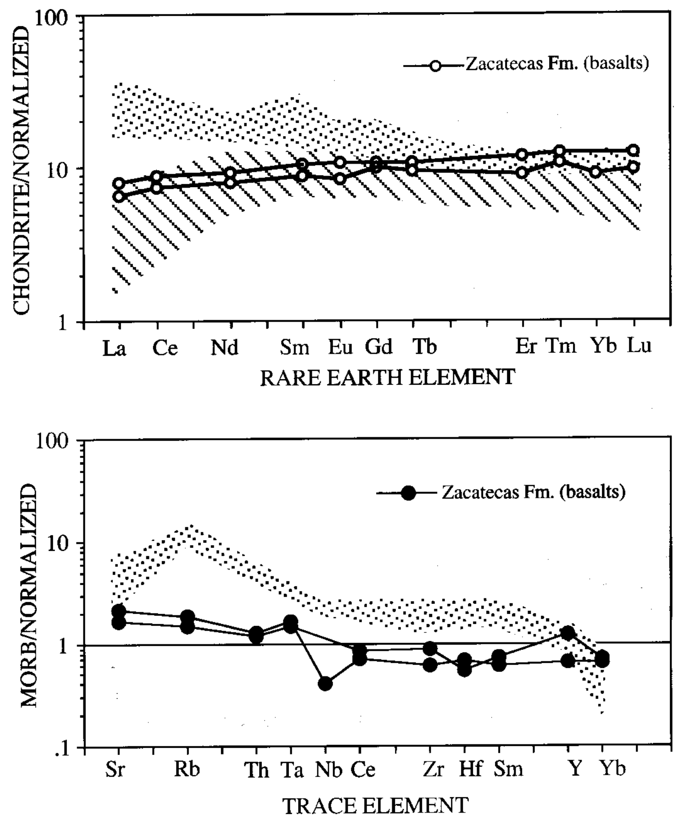

Figure 5. *a*, Chondrite normalized rare earth element abundances, and *b*, MORB-normalized trace element variation diagrams of basalts from the member A of the Zacatecas Formation. The low trace element abundances and flat patterns indicate a MORB affinity. Dotted areas correspond to data obtained by Lapierre and collaborators (1992) from El Saucito area. Dashed area corresponds to data obtained by the same authors in Zacatecas city that they considered to be part of the Cretaceous arc. The similarities with our data suggest that they might have been sampled from the Triassic sequences.

to the fact that Lapierre and collaborators (1992) and Tardy and collaborators (1991) considered all the rocks of the area as Cretaceous in age, and they did not differentiate the Zacatecas Formation from the younger units.

Overall, the volcanic rocks of the Zacatecas Formation as well as those of younger units that are exposed in the Guerrero terrane do not show major old crustal contamination and are of oceanic affinity (Table 1). In contrast, a sample collected from volcanic rocks of the Upper Jurassic Nazas Formation in the Sierra Madre terrane has relatively high total REE abundances (REE= 88.96 to 105.38), and it is enriched in LREE. It has MORB-normalized trace element patterns enriched in Th, Ta, Nb and Ce, similar to those from arc-related lavas (Pearce, 1982) (Table 1, Figure 6). The pattern suggests that the magma was contaminated by more evolved crust and/or it was associated with subduction.

ISOTOPE GEOCHEMISTRY

Whole-rock Sm-Nd isotopic analyses were performed on a VG-354 mass spectrometer at the University of Arizona, and following procedures described in Patchett and Ruiz (1987). Blanks were Nd<300 pg and duplicates are less than +0.2 ε_{Nd} units. Samples were collected from lavas and sedimentary rocks of the Zacatecas Formation (Guerrero terrane), sedimentary rocks from La Ballena formation, and volcanic rocks of the Nazas Formation (Sierra Madre terrane).

The results of the Sm-Nd isotopic analyses are given in Table 2 and Figure 7. Pillowed basalts from the Zacatecas Formation have initial ε_{Nd} values of +7.2 and +6.4 and are similar to ratios measured from present MORB from different ocean basins (Staudigel *et al.*, 1984; Ito *et al.*, 1987; and Hamelin *et al.*, 1985). They plot close to the depleted mantle array (DM), suggesting little or no crustal contamination. These data are compatible with the results obtained from the trace element analyses, which indicate that the Zacatecas pillow lavas were derived from the mantle.

Initial ε_{Nd} ratios from sandstone samples of the Zacatecas (Guerrero terrane) and La Ballena formations (Sierra Madre terrane) are -5.5 and -5.2 respectively. Neodymium model ages are 1.3 to 1.6 Ga. and indicate that the sedimentary samples collected from both units were derived from old continental

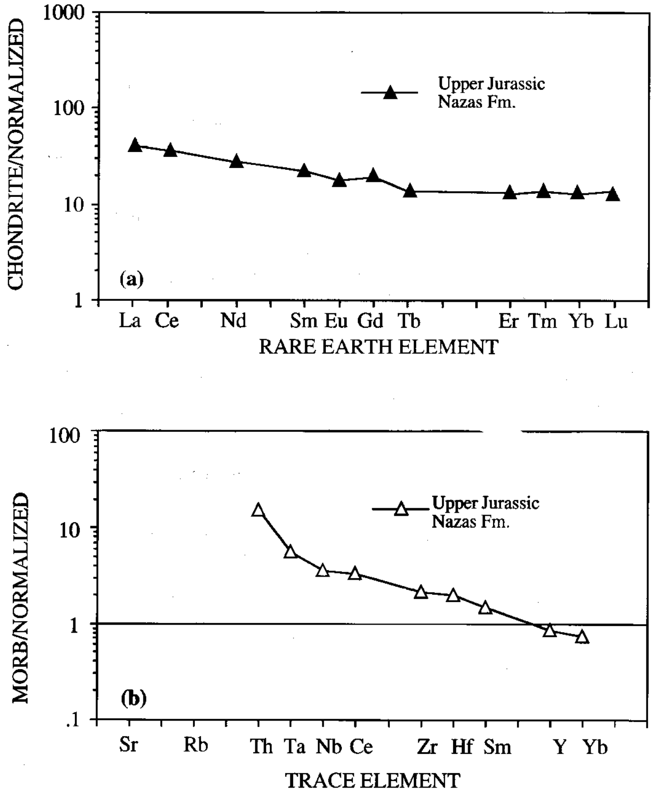

Figure 6. *a*, Chondrite normalized rare earth element graph, and *b*, MORB normalized trace element variation diagram of a basaltic dike related to the Nazas Formation (Sierra Madre terrane). The patterns suggest a volcanic-arc affinity.

sources of the same composition, which is compatible with results obtained from sandstone modal analyses. These isotopic ratios and model ages are also similar to values obtained from the Precambrian complexes of the Sierra Madre and Zapoteco terranes (Patchett and Ruiz, 1987; Ruiz *et al.*, 1988).

Neodymium isotopic signatures from igneous rocks of the Zacatecas Formation, as well as from quartz-rich sandstones of the Zacatecas and La Ballena formations are similar to those obtained from basement assemblages (Placeres and Arteaga complexes) that crop out in southern Guerrero terrane (Figure 1) (Centeno-García *et al.*, 1993a and 1993b; Centeno-García, 1994). Initial ε_{Nd} values of the upper Mesozoic arc assemblage of the Guerrero terrane (Figure 7) (Lapierre *et al.*, 1992; Centeno-García *et al.*, 1993; Centeno-García, 1994) are close to values observed in recent island arc volcanics (Wilson, 1989), and indicate that Precambrian crust was for the most part not involved in magma generation.

Volcanic rocks from the Nazas Formation (Sierra Madre terrane) show present ε_{Nd} of -2.7 and possible initial ε_{Nd} values of -1.5, as calculated for Middle Jurassic time (Table 2), based on the relative stratigraphic position of this sequence. The low Nd isotopic ratios obtained from a volcanic rock of the Nazas Formation plot outside the fields defined by the Triassic Zacatecas Formation and the Cretaceous arc assemblages of the Guerrero terrane, and close to the bulk-earth evolution curve (CHUR) (Figure 7). This suggests that these rocks incorporated some older crustal material during their genesis, and could indicate that the Precambrian basement of the Sierra Madre terrane (exposed in the eastern parts of the terrane) might extend as far as the Peñón Blanco area.

INTERPRETATION

The lithological associations, geochemical and isotopic affinities of the Triassic rocks from the Sierra Madre and Guerrero terranes show some important differences, but also some similarities. The lithologic characteristics, fossil content, depositional environments and thickness of the siliciclastic rocks of La Ballena formation (Sierra Madre terrane) suggest that it was deposited on a continental shelf-slope environment. The absence of volcanic or volcaniclastic rocks in La Ballena formation favors a passive margin and/or rift over a subduction-related forearc/shelf tectonic environment. Although clastic sediments and fossil faunas are similar in both Zacatecas and La Ballena formations, they have some important differences, such as the basaltic pillow lavas, which are interbeded with the siliciclastic sediments of member A of the Zacatecas Formation, and are absent in La Ballena formation. The MORB geochemical and isotopic affinity of the basaltic lavas suggests that the member A of the Zacatecas Formation probably represents a deformed ocean-floor assemblage. However, its original relationship with the member B was not constrained because the high shearing along the contact between the members. This leads to several possible interpretations that will be discussed later.

Table 2. Sm/Nd and Rb/Sr isotopic data from different lithologies of the Zacatecas Formation (Guerrero terrane), La Ballena, and Nazas formations (Sierra Madre terrane).

Unit/Rock type	Sample	Sm	Nd	Rb	Sr	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	T DM	ε_{Nd}	ε_{Ndi}	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$^{87}Sr/^{86}Sri$
Zacatecas Fm.													
Sandstone	Z-7	1.96	8.49			0.1396	0.512275	1.57	-7.08	-5.45			
Basalts	Z-12	1.9	5.45	3.67	257.93	0.2106	0.512987		6.81	6.42	0.041105	0.705582	0.705453
Basalts	Z-16	2.1	6.16	3.02	195.97	0.2042	0.51302	0.55	7.45	7.24	0.045	0.704292	0.704151
La Ballena													
Sandstone	Z-40	4.95	24.75			0.1208	0.512261	1.28	-7.35	-5.18			
Nazas Fm.													
Dike (basalt)	Z-31	4.56	18.99			0.1451	0.512502	1.2	-2.65	-1.5			

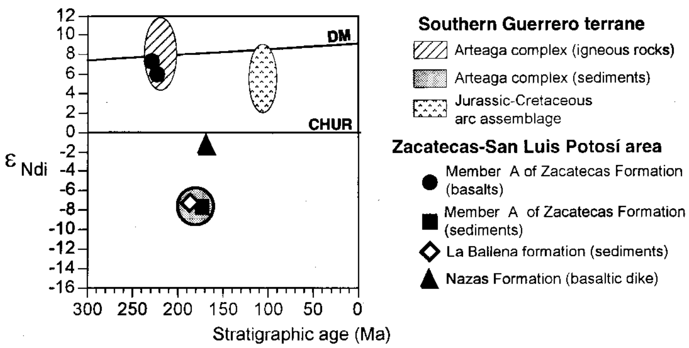

Figure 7. Initial epsilon neodymium values *vs.* stratigraphic ages for all the igneous and sedimentary rocks analyzed in this project. Data from the Zacatecas Formation basalts (Member A) plot closed to the depleted mantle array (DM). In contrast, the sample from and Nazas Formation plots close to CHUR, indicating that some old continental material might have participated in the magma generation. The sediment samples from the La Ballena and Zacatecas formations show the same value. Their negative ε_{Nd} data suggest that they are continent-derived material. These sediments have similar compositions as those obtained from the sediments of the Arteaga complex (Centeno-García *et al.*, 1993a), as suggested by the similarity in isotopic ratios. Cretaceous arc-related volcanics of the Guerrero terrane plot between depleted mantle and bulk-earth evolution curve (CHUR) (Centeno-García *et al.*, 1993a).

Other Triassic-Jurassic? units with lithological associations similar to Zacatecas Formation are exposed about 400 km to the south. These units are the Arteaga and Placeres complexes (Figure 1) of southern Guerrero terrane (Centeno-García *et al.*, 1993b; Centeno-García, 1994). Although the original stratigraphic relationships among the three units are unknown, their trace element concentrations and Nd-isotopic ratios suggest major similarities in the composition of their sources. A possible interpretation is that all those units might have been deposited in interrelated basins. The most likely primary source for all those sediments is the Grenville belt that extends from central Chihuahua to Oaxaca. Cratonic rocks of Sonora, northern Chihuahua and western United States are not suitable as primary sources for the sediments of the Triassic rocks of central-southern Mexico, since they have much older Nd model ages (1.7–2.3 Ga) (dePaolo, 1981; Ruiz *et al.*, 1988; Nelson and Bentz, 1990).

The exact age and mechanisms of compressional deformation of the Zacatecas Formation in the Guerrero terrane and La Ballena formation in the Sierra Madre terrane are still uncertain. Regional pre-Cretaceous deformation has been reported by de Cserna (1971) and Jones (1995). In the study area, the Zacatecas and La Ballena formations were deformed and partially metamorphosed prior to development of the Cretaceous arc assemblage of the Guerrero terrane, and before deposition of the Nazas Formation of the Sierra Madre terrane.

The authors suggest that La Ballena formation was accreted to the Sierra Madre terrane during Early-Middle Jurassic based on: (a) La Ballena formation is covered by Late Jurassic to Late Cretaceous units that belong to the Sierra Madre terrane, and (b) the Nazas magmatism, of Late Jurassic age, shows a significant component of ancient crust involved in the magma generation, which means that the La Ballena formation might be underlain by Proterozoic basement of the Sierra Madre terrane. Whether or not the deformation of the Zacatecas Formation was related to its accretion to the continental margin has not been well constrained.

The tectonic setting of the Nazas Formation has been under debate. Some authors consider this unit as part of a Jurassic continental arc that extended along western Mexico (*e.g.*, Grajales-Nishimura *et al.*, 1992; Jones *et al.*, 1995); however, similar formations in eastern Mexico also have been interpreted as graben fill deposits associated with the opening of the Gulf of Mexico (Carrillo-Bravo, 1961). Trace element and isotopic signatures obtained in this study suggest a subduction-related tectonic setting for the Nazas Formation and support continental-arc interpretations of similar rocks in northern Zacatecas, Durango, and Sonora (Anderson and Silver,1969; Grajales-Nishimura *et al.*, 1992; Jones *et al.*, 1995).

The Zuloaga Formation is the first unit of a subsiding carbonate platform of a passive margin that persisted until mid-Cretaceous (Campa and Coney, 1984). This unit marks an important change in the tectonic setting of the Sierra Madre terrane.

The Guerrero terrane shows a different tectonic history from Late Jurassic to mid-Cretaceous time than does the Sierra Madre terrane. The relatively deep-water depositional environment of the Lower Cretaceous rocks of the La Borda, Chilitos and El Saucito formations suggests that they might have formed in an intra-arc or back arc setting. The fact that the magmatism of the Jurassic-Cretaceous arc assemblage does not show large amounts of older crust contamination suggests that it was not constructed on continental crust. The Caracol Formation of the Sierra Madre terrane probably formed as a foreland basin, associated with the accretion of the Guerrero terrane against eastern Mexico during the Laramide Orogeny.

TECTONIC EVOLUTION OF CENTRAL MEXICO

Several models have been proposed for the tectonic evolution of the western margin of Mexico during early Mesozoic time (Coney, 1978, 1983; Dickinson and Coney, 1980; Damon *et al.*, 1981; Pindell and Dewey, 1982; Cuevas-Pérez, 1983; Sedlock *et al.*, 1993; Ortega-Gutiérrez *et al.*, 1994; Lapierre *et al.*, 1992; Tardy *et al.*, 1991, 1994; Jones *et al.*, 1995, etc.). Damon and collaborators (1981) proposed that subduction-related magmatism in western Mexico has been continuous in time but discontinuous in space throughout the Mesozoic and Cenozoic. They interpreted Late Permian batholiths as associated with the collision between Laurentia and Gondwana. They also suggested that an Andean-type volcanic arc developed in northern Mexico, and extended throughout the Pacific coast by Middle Jurassic time. However, this model does not consider a separate history for the Guerrero terrane. Dickinson and Coney (1980), and Coney (1981) suggest continuous subduction from

Triassic to Jurassic time, and associated strike-slip motion during Early to Middle Jurassic (Mojave-Sonora megashear). Coney's (1983) model is similar, but placing the continental margin along the eastern limit of the Guerrero terrane. Cuevas-Pérez (1983) interpreted the Zacatecas Formation as part of a transgression over a Paleozoic continent in a basin controlled by horst and graben. However, evidence of Paleozoic continental basement has not been found in the Zacatecas region. Quintero-Legorreta (1992) proposed an arc/back arc system for central Mexico in Permo-Triassic time. This model suggests that Nazas-Caopas volcanic units formed an island arc located west of the Zacatecas Formation, but new data indicate that they are of continental affinity and of Jurassic age (Jones *et al.*, 1995). Jones and collaborators (1995) suggest the development of a Middle Jurassic continental arc that extended from the western margin of North America to central Mexico, across the Coahuila and Sierra Madre terranes. This arc was displaced by the Mohave-Sonora Megashear by the Oxfordian. Models proposed by Sedlock and collaborators (1993) and Ortega-Gutiérrez and collaborators (1994) are more complex. They proposed the following evolution: (1) strike-slip/subduction collision of the Sierra Madre (Guachichil terrane) and northern parts of the Guerrero terrane (Tepehuano terrane) to a continental margin by Late Triassic time; (2) development of a continental arc on the Sierra Madre and northern Guerrero terrane (Tepehuano terrane) during early Middle Jurassic; (3) collision of the southern Guerrero (Náhuatl terrane of Sedlock and collaborators [1993]) and Zapoteco terranes via strike-slip faults during late Middle Jurassic; (4) formation of a continental arc toward the west of southern Guerrero terrane (Náhuatl terrane) with unnamed basement by the end of the Jurassic; and (5) displacement of this continental arc and development of a new continental arc on the Guerrero (Náhuatl and Tahue terranes of Sedlock *et al.*, 1993) by mid-Cretaceous time. In contrast, Lapierre and collaborators (1992) and Tardy and collaborators (1994) proposed that the Guerrero terrane be an intra-oceanic arc that remained isolated from the continent until the Late Cretaceous, when it collided to the continental margin.

Figure 8 shows a modified paleogeographic reconstruction of Pangea of Late Triassic time (modified from Rowley and Pindell, 1989). Isotopic ratios obtained in this study and others (*e.g.*, Yáñez *et al.*, 1991; Ruiz *et al.*, 1988; Torres-Vargas *et al.*, 1993) suggest that the pre-Mesozoic basement, that approximately defines the continental margin of eastern and northern Mexico, extended up to the western boundary of the Sierra Madre terrane before thrusting of the Guerrero terrane. This margin might have been developed as an active subduction zone at different times in its evolution. The oldest stage of subduction seems to have occurred from Permian to Early Triassic time, according to isotopic and geochemical signatures of a granitoid belt that runs from north to south along the eastern part of Mexico (Torres-Vargas *et al.*, 1993). Figure 8 shows the reconstructed position of this belt prior to the movement of the Mojave/Sonora megashear (Silver and Anderson, 1974) and Figure 9 shows the K/Ar age range of the granitoids. This belt suggests that the Sierra Madre terrane was already accreted to the North America margin, and did not collide by Late Triassic as proposed by Sedlock and collaborators (1993) and Ortega-Gutiérrez and collaborators (1994). Apparently, subduction ended before Late Triassic, as suggested by the lack of igneous rocks of this age, as well as the composition of the sandstones of La Ballena and Zacatecas formations. In this reconstruction, La Ballena formation might have formed as distal parts of a submarine fan in a continental-slope setting. Stratigraphy of the northeastern margin of the present Gulf of Mexico suggests that graben-related basins, like South Georgia and Ridleville (Figure 8), started to form by Late Triassic time (McBride *et al.*, 1987). These basins trend NNW-SSE and were associated to active normal faulting from Triassic to Jurassic time (McBride *et al.*, 1987). In this scenario, the Sierra Madre terrane might have received large quantities of terrigenous sediment shed by rivers associated with some of these grabens (Figure 8).

The Zacatecas Formation probably formed in an ocean basin located relatively close to the continent, since it also received continental derived sediments. Whether or not the ocean-floor assemblages of the Zacatecas Formation were part of the same basin where the Arteaga and Placeres complexes formed is not well constrained. All these sequences might represent a marginal back-arc basin or an accreted fragment of open ocean floor (eugeoclinal deposits). Rocks of Triassic ocean floor and Jurassic arc magmatism found in the Vizcaíno Peninsula (Kimbrough, 1985) may represent displaced fragments of an oceanic arc that might had been located west of the Guerrero terrane during Late Triassic-Early Jurassic time.

Deformation in the La Ballena and Zacatecas formations suggests that a major tectonic event occurred between Late Triassic and Late Jurassic (pre-Oxfordian–Kimmeridgian) time, and apparently involved a considerable amount of shortening. This event caused the thrusting of the continental-slope sediments of the La Ballena formation over the continental margin in Peñón Blanco and Charcas areas of the Sierra Madre terrane. Their exhumation must have occurred prior to deposition of the continental Nazas Formation. The thrusting and deformation of the La Ballena formation are contemporaneous with deformation of the Zacatecas, Arteaga and Placeres units of the Guerrero terrane, suggesting that they probably were interconnected and deformed originally under the same tectonic event. The exact age of this tectonic event is unknown. It might be Middle to Late Jurassic in age (Bajocian to Oxfordian), based on K/Ar ages from the Arteaga complex in the Guerrero terrane and the fact that subduction resumed along this margin by that time (Grajales-Nishimura *et al.*, 1992; Jones *et al.*, 1996) (Figure 8). Middle Jurassic volcanic rocks have not been found in the Guerrero terrane.

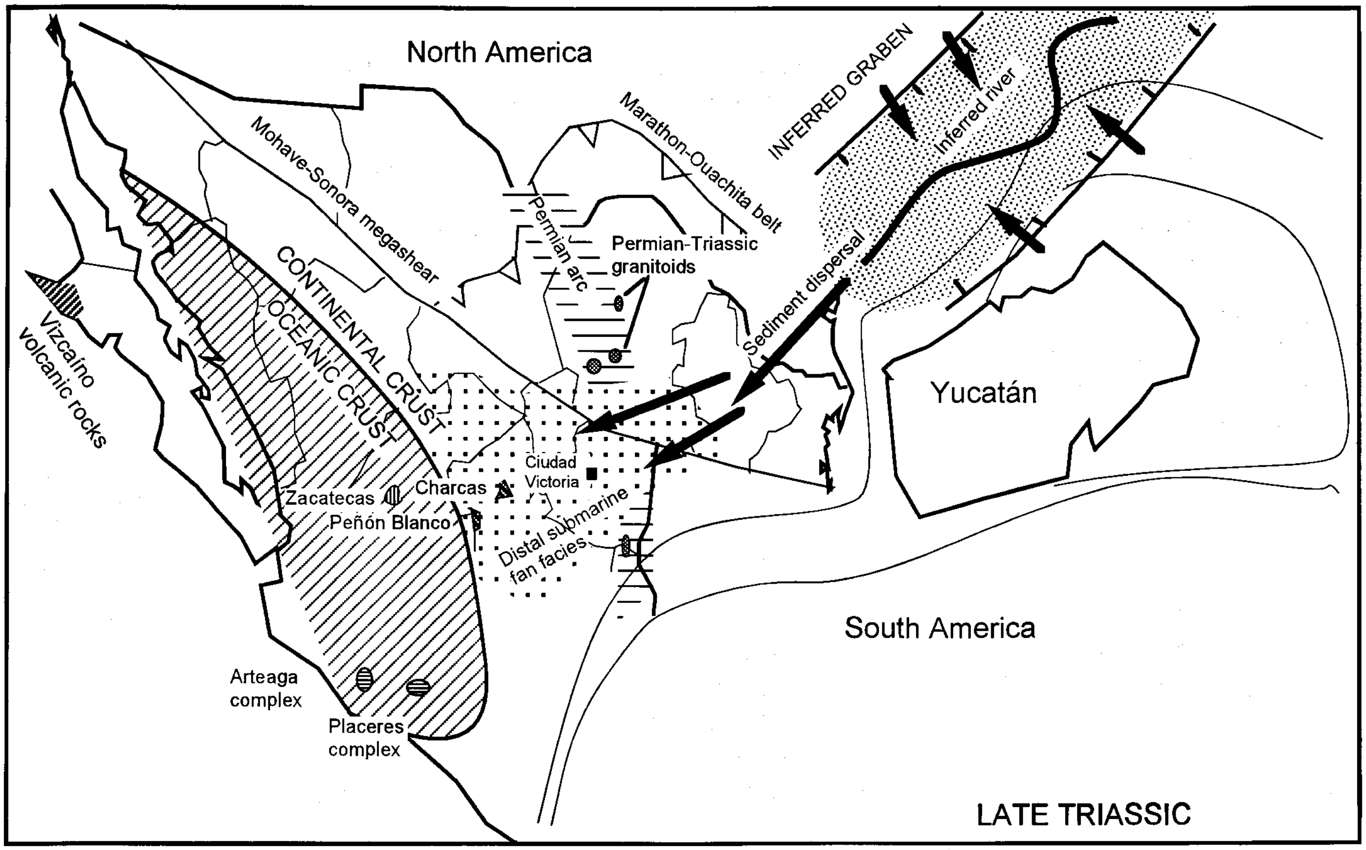

Figure 8. Proposed paleogeographic reconstruction of central Mexico for Late Triassic time. Coarsed-dotted area represents continental deposits associated to inferred grabens. Small-dots are the submarine fan deposits where La Ballena formation may have formed. Dashed area is possible oceanic-crust, where the Zacatecas Formation was formed. Displacement along the Mojave-Sonora megashear has been restored. Reconstruction modified from Pindell and Dewey (1982).

The authors of the present paper proposed two models for the evolution of central Mexico from Middle Jurassic to Late Cretaceous time, based on the data obtained from the Zacatecas and Peñón Blanco areas (Figures 10 and 11). They were generated because there is no strong evidence to relate the evolution of the Zacatecas Formation either to the Sierra Madre terrane (model 1) or to the Guerrero terrane (model 2).

Model 1

Model 1 (Figure 10) presents a possible scenario, if the Zacatecas Formation was linked to the Sierra Madre terrane throughout the Mesozoic. Because of similarities in age, composition of sediments and fossil fauna content between La Ballena and Zacatecas formations, the latter might have been a distal facies of the same submarine fan, represented by the first, but deposited on oceanic crust (Figure 10*a*) that might have been part of a marginal back-arc basin or an open ocean floor. If the continental margin initiated subduction activity by Middle to Late Jurassic time, the Zacatecas Formation could represent pieces of ocean-floor, overlain by the sediments of the submarine fan, accreted to the continental margin. In this scenario, the Nazas Formation and member B of the Zacatecas Formation could have formed in a forearc basin environment (Figure 10*b*). The Sierra Madre terrane has no evidence of magmatism from Late Jurassic to Late Cretaceous time. During this time carbonate sedimentation evolved in a relatively deep marine continental platform, perhaps on a passive margin setting, with continuous subsidence (Figure 10*c*). In contrast, thick volcanic and volcaniclastic sequences of ocean-arc affinity developed in the Guerrero terrane during the same time (Figure 10*c*).

The major differences in the stratigraphy, structural style, and geochemical composition between the Jurassic-Cretaceous assemblages of the Sierra Madre and Guerrero terranes suggest that they evolved separately. Therefore, a considerable amount of tectonic transport probably occurred during their accretion in Late Cretaceous time (Laramide orogeny) (Figure 10*d*). During this phase of deformation, Jurassic-Cretaceous arc related succesions of the Guerrero terrane may have been thrust over the Zacatecas Formation (if this unit was part of the Sierra Madre terrane). Then, sediments of the Caracol Formation, rich in volcanic fragments, were derived from the erosion of the Guerrero terrane and recorded the final amalgamation of the Guerrero terrane (Figure 10*d*).

Model 2

Model 2 (Figure 11) is based on the possibility that the Zacatecas Formation might be the basement of the Guerrero terrane. In this scenario, the Zacatecas Formation was deposit-

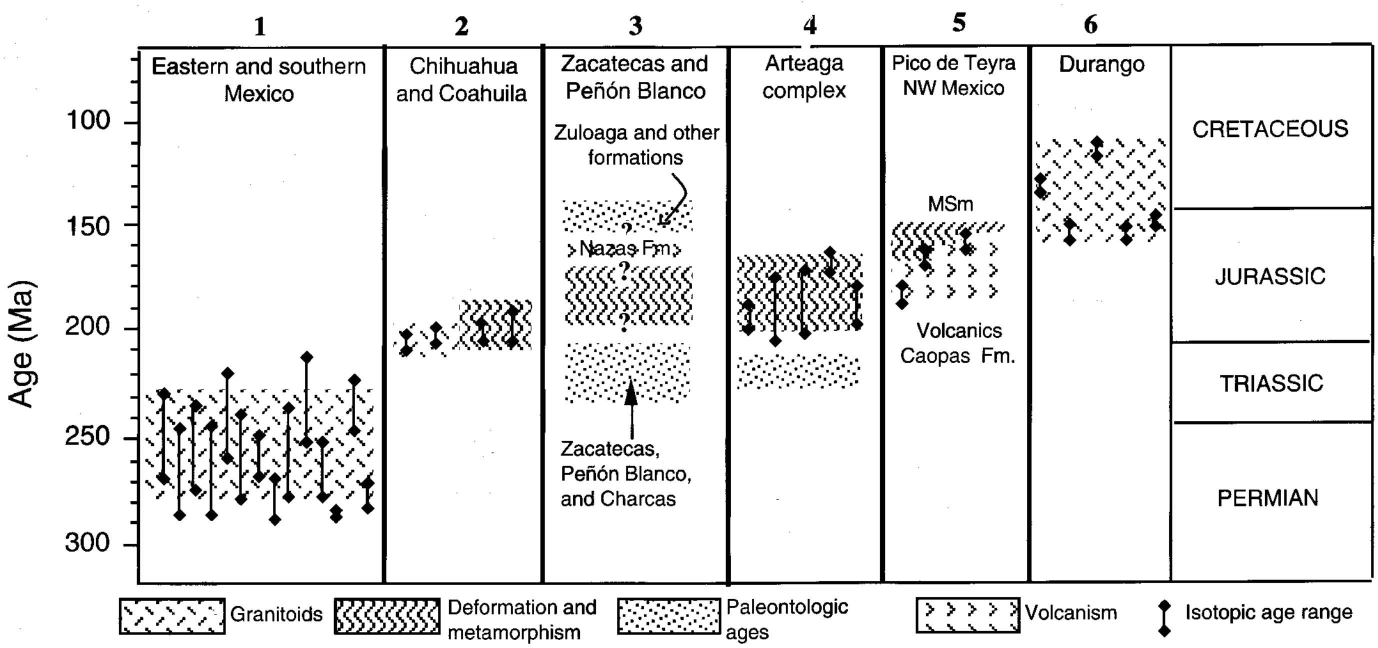

Figure 9. Table showing compilation of isotopic (K/Ar and U/Pb) and paleontologic ages of key units on the reconstruction of the evolution of central Mexico during the Mesozoic. Age distribution suggests a gap in the magmatic activity from Middle Triassic to Late Jurassic time. A major 180–160 Ma tectonic event has been recorded in the study area, as well as in the Arteaga complex of western Mexico, and the Pico de Teyra area. Compiled from Jones and collaborators (1995) and Grajales-Nishimura and collaborators (1992).

ed on the same marginal back-arc basin or open ocean floor as the Arteaga and Placeres complexes of southern Guerrero terrane (Figures 7 and 11a). The sequence was deformed, partially metamorphosed and exposed prior to the development of the Cretaceous arc assemblage of the Guerrero terrane (Figure 11b). Whether this deformation was related or not to its accretion to the continental margin of Mexico is unknown. Afterward, arc-related sequences could have covered unconformably the Zacatecas Formation (Figure 11*c*). Then the Zacatecas Formation and the arc assemblages approached the Sierra Madre terrane until accretion of the Guerrero terrane in Late Cretaceous time (Figure 11*d*).

Evidence of development of a Late Jurassic continental arc toward the west of the Guerrero terrane has not been found to support Sedlock and collaborators' (1993) models. In model two, the Guerrero terrane has a pre-Cretaceous history of collision. Then, it could not evolve as an isolated oceanic island arc as proposed by Lapierre and collaborators (1992) and Tardy and collaborators (1994).

The data obtained suggest that the tectonic scenario of the studied area in central Mexico has not been related solely to the evolution of one of the continental margins of North America during the Mesozoic. It was sometimes related to the eastern margin, and sometimes to Cordilleran tectonics of the western margin. During Late Triassic the western margin of North America was active (Busby-Spera, 1988; Saleeby and Busby-Spera, 1992). Accreted eugeoclinal sediments and continental arc magmatism suggest that most of the margin might have been defined by subduction zones. Contemporaneous subduction is found only in the Vizcaíno Peninsula. In contrast, the results obtained from the area suggest that the evolution of central Mexico during Late Triassic apparently was associated with the rifting of the eastern margin of North America. During Middle to Late Jurassic time, the tectonic evolution of central Mexico has more affinities with the Cordilleran tectonics. Similar phases of deformation occurred in the western United States (Saleeby and Busby-Spera, 1992), although stratigraphic and isotopic ages indicate that the deformation in Mexico is slightly older. The deformation event in the southwestern parts of the North American Cordillera has been attributed to the accretion of island arcs which formed either well offshore within the Paleo-Pacific Ocean, or as fringing arcs bounding marginal seas lying just offshore (Dickinson, 1992; Seleeby and Busby-Spera, 1992). The same process might have occurred in western Mexico, where (as mentioned before) the Triassic Zacatecas Formation might represent a deformed marginal back arc basin, and the Triassic-Jurassic volcanic rocks of the Vizcaíno Peninsula might be related to the deformed oceanic island arc.

Therefore the development of the Nazas Formation might have been associated with the Cordilleran continental arc of Late Jurassic age (Jones *et al.*, 1996). Magmatism ceased by Kimmeridgian time, with a major change in the tectonic scenario. Cretaceous evolution of the Sierra Madre terrane seems to have been controlled in part by eustatic sea level changes and the rifting in the Atlantic, as indicated by the facies distribution of the carbonate platforms. In contrast, the magmatic activity of the Guerrero terrane suggests that during the Cretaceous it was associated to the Cordilleran tectonics of North America.

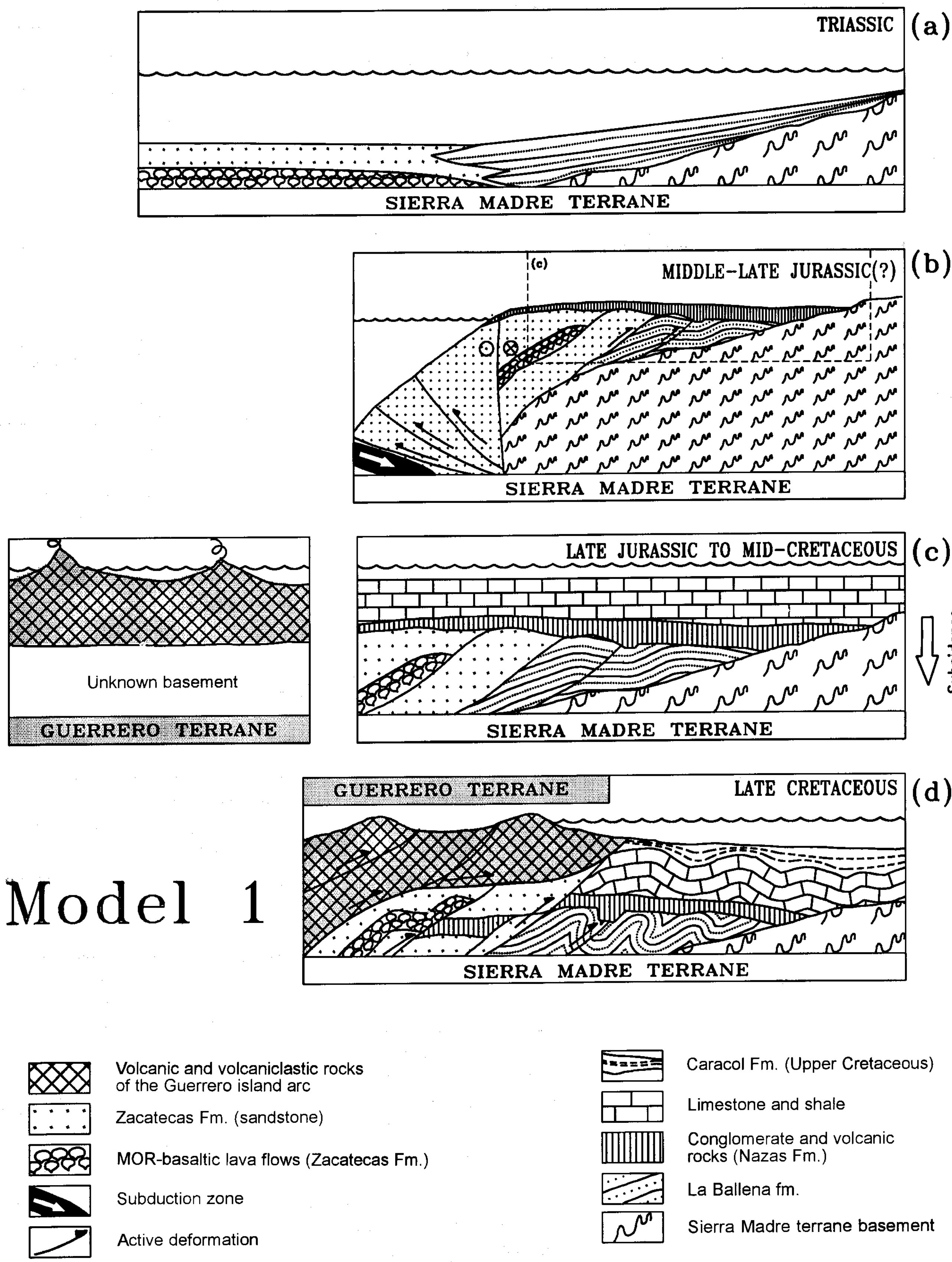

Figure 10. Model 1 to explain the tectonic evolution of the study area. Early Mesozoic evolution of the Zacatecas Formation is linked to the Sierra Madre terrane in this model.

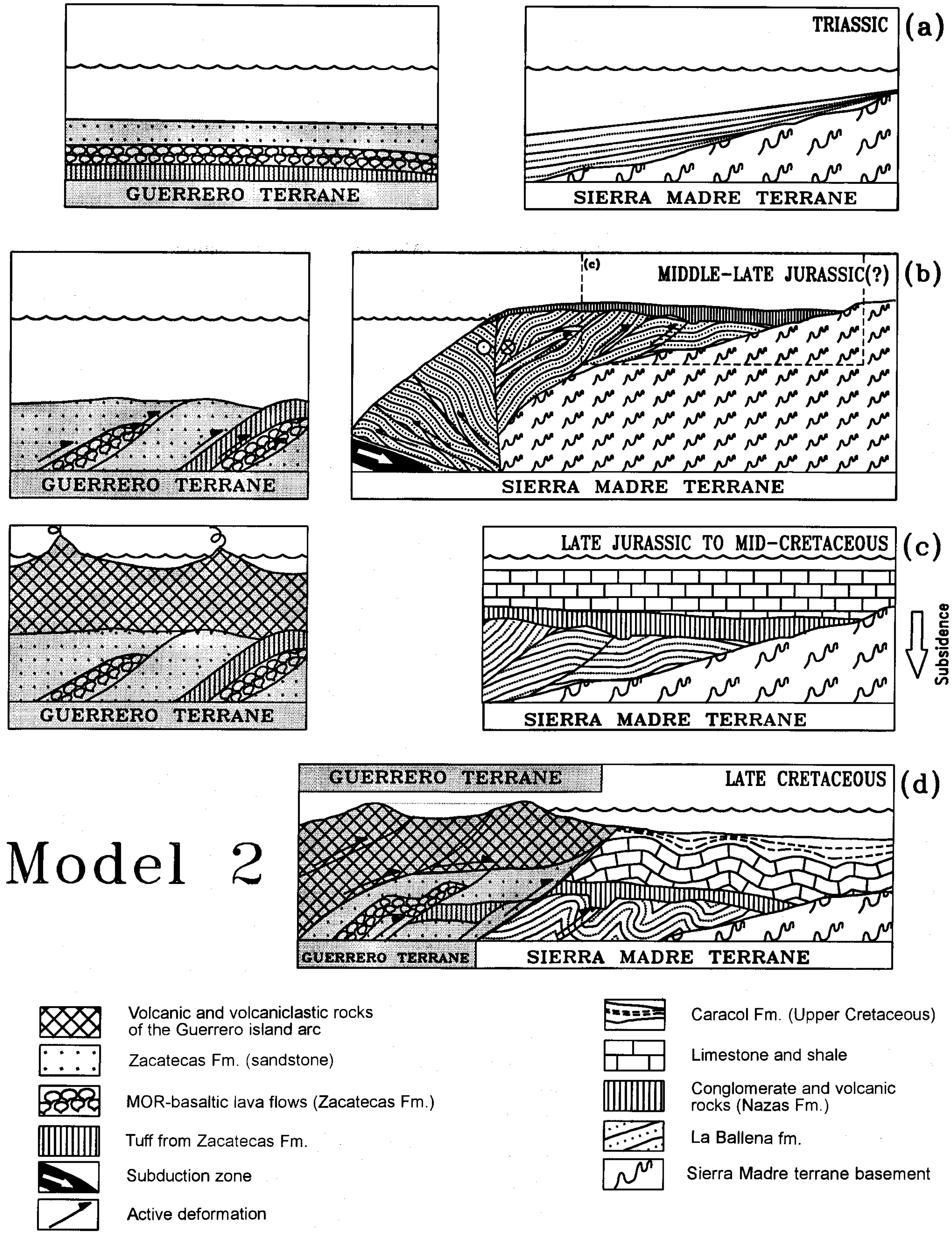

Figure 11. Model 2 to explain the evolution of the area if the Zacatecas Formation was associated with the Guerrero terrane from early Mesozoic time until Late Cretaceous.

SUMMARY

Conclusions derived from this study include:

- Exposures of Triassic rocks west of Zacatecas city (Zacatecas Formation) are stratigraphicly different from those in Peñón Blanco and Charcas (La Ballena), which have previously been described as the Zacatecas Formation.
- Geochemical signatures and lithological associations suggest that the Zacatecas Formation represents a deformed and partially metamorphosed ocean-floor assemblage. However the mechanisms of its emplacement (via subduction, thrusting or strike-slip faulting) are still unknown.
- Sedimentology and petrography of the sediments of La Ballena formation indicate that they were deposited on a continental-slope setting. Its primary structures suggest middle to outer submarine-fan depositional environment.
- Evidence of a pre-Late Jurassic-Cretaceous major deformational event is found in both the Zacatecas and La Ballena formations. Stratigraphic relationships indicate that this event is pre-Oxfordian-Kimmeridgian in the Peñón Blanco area.
- Whether the Zacatecas Formation constitutes the basement of northeastern Guerrero terrane or not is still under debate. Petrological similarities with the Arteaga complex of southwestern Guerrero terrane strongly support their correlation. However the contact between the arc assemblage of the Guerrero terrane and the Zacatecas Formation was sheared off during the Late Cretaceous deformational event (Laramide Orogeny).
- The data obtained in this study suggest that the western continental margin of Mexico was located along central Mexico by Triassic to Middle Jurassic time. This margin might approximately trend along the western limit of the Sierra Madre terrane prior to thrusting of the Guerrero terrane.
- The La Ballena formation is unconformably overlain by the Nazas and Zuloaga Formations. The La Ballena formation was deposited on the continental slope of the Sierra Madre terrane, subsequently thrust over and exhumated prior to deposition of the Nazas Formation.
- Two models are proposed for the evolution of the Zacatecas and La Ballena formations: (1) The Zacatecas Formation might have formed and deformed geographically distant from the La Ballena formation during early Mesozoic time. Thus, it was accreted to the Sierra Madre terrane, along with the Cretaceous arc of the Guerrero terrane by Late Cretaceous time. (2) The Zacatecas Formation might represent distal facies of the La Ballena formation. In this case both units were accreted to the Sierra Madre terrane by pre-Late Jurassic time. Thus, Cretaceous rocks of the Guerrero terrane arc-assemblage would be allochthonous with respect to the Zacatecas Formation.
- More research needs to be done to determine the age and mechanisms of accretion of the Guerrero terrane. However, it is clear from this study that an important tectonic discontinuity is presently placed along central Mexico.

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