


CONSERVATION SCIENCE IN MEXICO'S NORTHWEST

ECOSYSTEM STATUS AND TRENDS IN THE GULF OF CALIFORNIA




Elisabet V. Wehncke, José Rubén Lara-Lara,
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This book is dedicated to the memory of
Laura Arriaga Cabrera, Salvador Contreras-Balderas,
and Daniel Lluch Belda, caring colleagues,
great scientists, and exceptional human beings
to whom Baja California and the Gulf of California
owe so much.

Dedicamos este libro a la memoria
Laura Arriaga Cabrera, Salvador Contreras-Balderas y
Daniel Lluch Belda, colegas comprometidos,
grandes científicos, y seres humanos excepcionales,
a quienes Baja California y el Golfo de California
tanto les deben.

THE GEOLOGICAL FOUNDATIONS OF THE GULF OF CALIFORNIA REGION

Arturo Martín-Barajas*

To Gordon Gastil (1928-2012) for his major contribution to the geology of northwestern Mexico.

The geological evolution of northwestern Mexico is marked by two tectonic and magmatic events: 1. The development of an Andean type subduction zone and its volcanic arc, and 2. An extensional episode that culminated with the rupture of the continental lithosphere along the Gulf of California. During Late Mesozoic and Late Cenozoic time (120-12 Ma) a long-lived subduction zone created magmatic arcs with volcanic eruptions over large regions in northwestern Mexico and southwestern United States. The magma bodies intruded older (Paleozoic-Mesozoic) sedimentary deposits along the margins of the North America craton adding a significant volume of new continental crust. During Late Cretaceous and Tertiary time (74-12 Ma) the continental crust was uplifted and deeply eroded along the Pacific margin and more than 10 km of vertical crust was striped away. A period of continental extension and coeval arc-volcanism and extension in Tertiary time (32 My to 12 Ma) produced the distinctive physiographic relief of basins and ranges in Sonora and Arizona. This occured simultaneously with the waning stage of arc-volcanism in the Sierra Madre Occidental and later along the Baja California Peninsula. Since ~12 Ma subduction ceased and crustal extension focused in a narrow belt along the Gulf of California capturing rivers, and allowing the first marine incursion and producing intermittent volcanic eruptions. Since ~3-4 Ma the narrow continental rift evolved to a proto-oceanic rift. This rifting event may have influenced the evolution of species when a new seaway formed, and landmasses were separated from the continent due to tectonic activity. New islands and prominent landforms emerged due to volcanic eruptions and block faulting during the ongoing phase of rifting.

1. INTRODUCTION

The geological substratum that supports the rich marine and terrestrial biodiversity and distinctive ecological niches in the Gulf of California region is predominantly composed of granitic and volcanic rocks, and sediments derived from these igneous rocks of various ages. This chapter summarizes the main geologic events that produced the geological foundations of the Gulf of California Extensional Province and its geologically young rift system. This chapter makes reference principally to landmark studies and publications concerning key recent findings, and although the cited bibliography is not exhaustive, this chapter provides the reader with a general overview of a long process of continental accretion and subsequent crustal stretching and rifting apart of Baja California from mainland Mexico.

2. TWO LANDMARK GEOLOGIC EVENTS AS TIME-DIVIDES

The geologic evolution of northwestern Mexico is marked by two main tectonomagmatic events that constitute useful time-divides to reconstruct its geological history. The first event was the onset of two sub-parallel magmatic arcs, and the second was the rifting of the continental crust and the formation of the Gulf of California.

The first event started during Late Jurassic to Late Cretaceous (163-90 Ma). The older of the two sub-parallel magmatic arcs is an oceanic arc active during Mid-Late Jurassic and Early Cretaceous that was accreted against the continental margin in Middle Cretaceous (Wetmore *et al.* 2003). Subsequently in Late Cretaceous a continental, Andean-type, magmatic arc developed due to collision and subduction of the Farallon oceanic plate beneath the North America continent. This continental arc produced intense volcanism fed by large magmatic intrusions along the western margin of North America. Its roots are the granitic bodies that form the peninsular ranges batholith (PRB) and the coeval but somewhat younger Laramide batholith of Sonora and Sinaloa (McDowell *et al.* 2001, Henry *et al.* 2003, Ortega-Rivera 2003). The peninsular ranges batholith is continuously exposed from southern California to mid-Baja California, and further south where it is likely covered by 1-1.5 km-thick Tertiary volcanic and sedimentary deposits north of La Paz in southern Baja California (see Figure 1). This granitic belt crops out again in the Los Cabos block in southernmost Baja California and continues in mainland Mexico south of Puerto Vallarta and along the Pacific margin of southern Mexico (see Figure 1). The granitic intrusives are also exposed over Sonora and Sinaloa and lie beneath the volcanic cover of the Sierra Madre Occidental (McDowell *et al.* 2001, Henry *et al.* 2003).

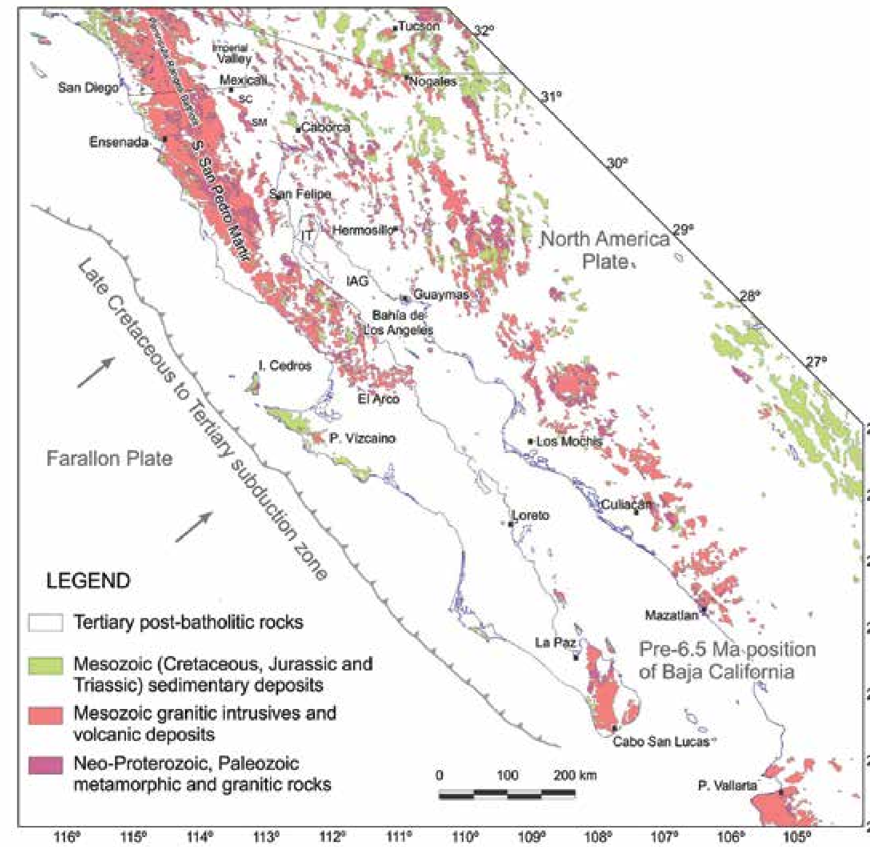

FIGURE 1. Simplified geological map of northwestern Mexico and southwestern United States. Only batholitic and prebatholitic rock units are shown for simplicity. Note the N-NW trending basin and range physiography in Sonora and Arizona that resulted from mid to late Tertiary extension. Baja California is ~250 km south of its present position prior to the onset of oblique rifting (*ca.* 7 Ma). Additional 250 to 300 km are required to close the mouth of the Gulf. Geological map adapted from INEGI 1:1000,000 geological maps and USGS 1:1,000,000 geological maps of Arizona and California.

The second event that marks the geologic history of northwesten Mexico is the rifting process that culminated in the formation of the Gulf of California, which started about 12 million years ago, but was well established along its present length by ~6.5 ma (Oskin and Stock 2003). This phase of continental rifting developed along the ancient suture between an essentially Mesozoic magmatic arc-terrain to the west, and the Proterozoic-Paleozoic cratonic margin to the northeast.

Based on these two tectonomagmatic events, we refer to pre-batholitic rocks as the rock units formed prior to and metamorphosed by Late Jurassic to Late Cretaceous magmatic intrusions (see Figure 1). Post-batholitic rocks are subsequently divided into rocks units formed during latest Cretaceous and Tertiary times (65 to 25 Ma), and rock units formed during and after the Oligocene to Middle Miocene (25-12 Ma) extensional event that stretched the continental crust simultaneously with the waning stage of arc volcanism. Extension of the crust affected a broad region in Sonora and Sinaloa but subsequently (*ca.* ~12 Ma) the extension focused along a narrower region that rapidly subsided and conducted the first marine incursion in the Gulf of California. We thus subdivide the post-batholitic geologic record in two stages; pre-rift and syn-rift stages. Pre-rift rocks are principally arc-related volcanic and volcaniclastic deposits of the Sierra Madre Occidental and the Comondú arc in Baja California (23-12 Ma). Syn-rift rocks are mainly sedimentary and volcanic deposits formed during the current phase of active rifting. This rifting event resulted in the progressive capture of the Baja California Peninsula by the Pacific Plate and defined the modern transtensional boundary between the Pacific and North America plates along the Gulf of California and the San Andreas fault system.

A summary of the main characteristics of the rock units, and their tectonic settings before, during and after the two principal tectonomagmatic events is presented bellow.

2.1. Pre-Batholitic Geology

The evolution of the Proterozoic and Paleozoic continental margin of southwestern North America has been depicted from studies along discrete localities in Baja California (see compilation of papers in Gastil and Miller 1993), and more extensively in Sonora (Stewart *et al.* 1997, 2001, Gehrels and Stewart 1998, Iriondo *et al.* 2004) and Arizona, Nevada, and California (Gehrels 2000, Stewart *et al.* 2001) (see Figures 2a and 2b).

During Paleozoic time (570-245 Ma) the southwestern margin of the North America craton was located in present Arizona-Sonora and eastern California and Nevada (see Figure 2a). The continental crust that forms the contemporary Baja California Peninsula did not exist at that time. Shallow marine and deep marine sediments of Paleozoic and Mesozoic Era were deposited as recorded at several locations in eastern Baja California, Sonora and southern California (see Figures 2a, 2b and 3). These sedimentary deposits accumulated over a composite Proterozoic-Paleozoic continental shelf and slope (Gastil 1993, Stewart *et al.* 1997), and were metamorphosed principally during emplacement of Jurassic and Cretaceous plutonic rocks.

The oldest rocks in Baja California crops out near the town of San Felipe (see Figure 2). An Early Paleozoic age of a quartzite and mafic schist was established

FIGURES 2. Schematic distribution of Paleozoic and Mesozoic sedimentary facies in northwestern Mexico before rifting in the Gulf of California (adapted from Gastil 2003): (a) late Proterozoic-Early Paleozoic Miogeoclinal facies and reported localities. (b) Distribution of Triassic, Jurassic and Cretaceous sedimentary and volcanic deposits in northwestern Mexico. This figure shows the area of volcanic deposits of the Late Jurassic to Early Cretaceous Alisitos arc to the west and terrigenous sediments derived from continent to the east. FIGURE 2A (ABOVE)

from lithologic and stratigraphic correlations with well-dated Pre-Cambrian and Early Paleozoic rocks near Caborca in Sonora (Anderson 1993, Stewart and Pole 2002) and Death Valley region in California (Stewart *et al.* 2001). In the southern flank of Sierra San Pedro Martir similar metamorphic rocks are exposed and lie within a belt of Proterozoic and Paleozoic terrigenous and carbonate rocks extending from central Nevada to Sonora (see Figure 2a). Paleozoic deep-water facies are common in Baja California and quartzite and marble are more common in Sonora were shallower marine sedimentary environments developed over the cratonic

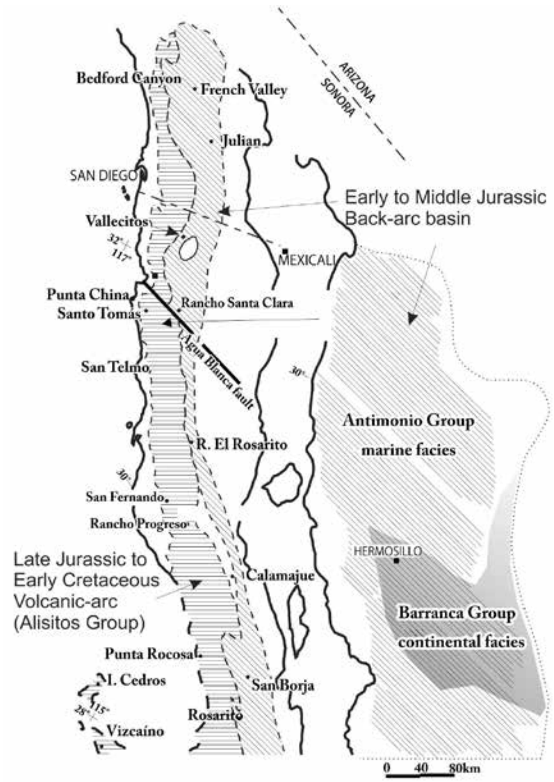

FIGURE 2B

continental shelf. These Late Precambrian and Paleozoic rocks correspond to continental shelf-slope deposits along the margins of the North American craton, and imply that central and northwestern Sonora contains a Proterozoic cratonic basement that accumulated Paleozoic marine deposits along its margins (Stewart *et al.* 2001, Valencia-Moreno *et al.* 2001).

During the Mesozoic time shallower marine conditions existed in Sonora and Arizona while deeper marine conditions occurred in present Baja California and California (see Figure 3). Triassic and lower Jurassic continental and marine deposits in Sonora are grouped into de Barranca Group and Antimonio Group, respectively (González-León *et al.* 2009). The Antimonio Group includes chiefly shallow marine carbonate and terrigenous sequences located on the continental shelf that surrounded deltaic and fluvial sedimentary environments represented in the Barranca Group. The Antimonio and Barranca groups overlie the Paleozoic (Permian), dominantly calcareous deposits represented by the Monos Formation in Sierra El Alamo of northwestern Sonora (González-León *et al.* 2009). The slope facies and deep basin environments were located toward the west and southwest (*e.g.* San Marcos in

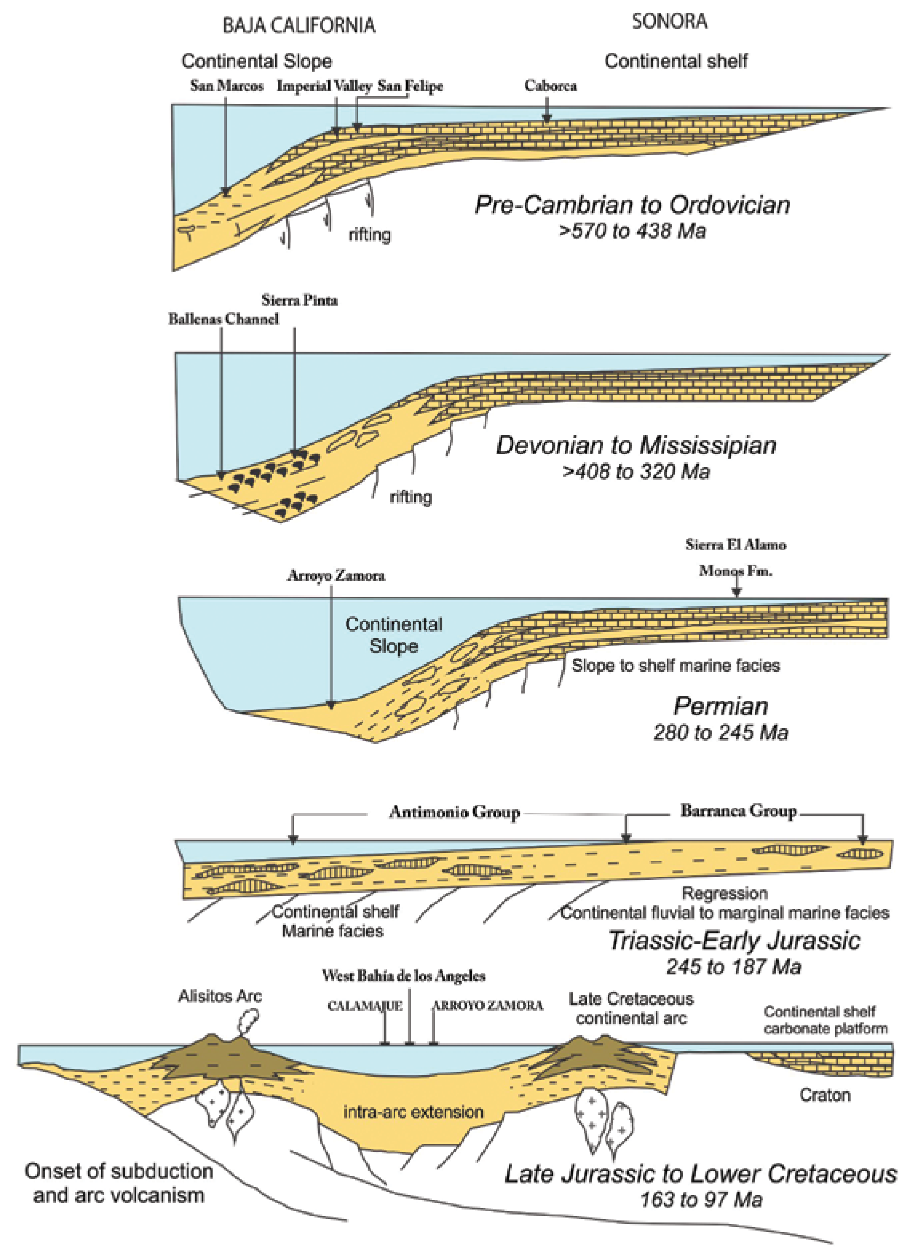

FIGURE 3. Schematic cross-sections of facies distribution across the southwestern margin of the North American craton. Note that carbonate and quartzose sediments dominate the eastern continental shelf in Sonora, whereas deep-water sedimentary facies dominate to the west (slope and basin sedimentary environments). In Late Jurassic and Early Cretaceous a volcanic arc developed as consequence of subduction of the Farallon Plate under North America (modified from Gastil and Miller, 1993).

northern Baja California and Bedford Formation of southern California) were the typical sandstone, siltstone, and mudstone, mostly turbidite deposits includes large exotic blocks (olistostrome) transported in mass flows deeper across the continental slope (c.f. Lothringer 1993).

The relevance of these medium to high-grade metasedimentary rocks is their contribution to reconstruct the paleo-geography of the southwestern continental margin. For the biosphere that supports the circum-Gulf region its relevance is probably their high-alumina content of phyllosilicates derived from dominantly pelitic, clay-rich mudstone deposits and were progressively buried several kilometers and metamorphosed during large igneous intrusions in the Cretaceous time.

2.2. Onset of subduction and arc volcanism

The southwestern margin of the North American continent contains the record of two parallel but diachronous episodes of subduction and arc-volcanism that were tectonically juxtaposed during Mid- to Late Cretaceous time (see lower schema in Figure 3). The westernmost and older volcanic arc is allochthonous and is of oceanic affinity. It is thought to have formed in an island arc setting (subduction involving two oceanic plates) west, but at an unknown distance from the continent (Gastil 1993, Wetmore *et al.* 2003, Umhoefer 2003). This Late Jurassic to Early Cretaceous volcanic arc has two episodes of volcanism: one crops out in the Cedros-Vizcaíno and El Arco areas (see Figures 1 and 2b); a second episode crops out along the Pacific margin past-north latitude 28°N in the Baja California Peninsula (the Alisitos arc) and southward in the Pacific margin of southern and central México (Centeno-García *et al.* 1993, Talavera-Mendoza *et al.* 2007, Escalona-Alcázar *et al.* 2009).

At the Vizcaíno Peninsula, and Cedros Island a sequence of Late Jurassic-Early Cretaceous sedimentary arc-related volcaniclastic rocks overlie a Triassic ophiolite (oceanic) basement intruded by Middle-Jurassic to Early Cretaceous granitic intrusives. The volcanosedimentary sequence and granitic intrusions constitutes the first evidence of oceanic arc - continent interaction in the Pacific margin of Baja California (Kimbrough and Moore 2003).

The easternmost evidence of this early oceanic arc has been found in east-central Baja California. Mafic intrusives at El Arco-Calmalli (see Figure 1), and mafic to intermediate lava flows at Arroyo Calamajue (see Figure 2b) are likely related to this phase of island-arc volcanism (Griffith and Hobbs 1993). At Calamajue the lava flows unconformably overlie quartz-rich sedimentary rocks derived from the North American craton to the east and constitute additional important evidence of the interaction between the island-arc and a basin that received quartzose detritus from the continent to the west. At El Arco a mafic intrusive dated at ~165 Ma (Weber and López-Martínez 2006) contains the geochemical and isotopic signature of an oceanic island-arc intrusive. This mafic dioritic rock is probably one of the oldest magmatic intrusions related to an early stage of the Alisitos volcanic arc, and clearly predates subsequent emplacement of the tonalitic plutons that dominated the continental arc thereafter.

In Baja California, the Early Cretaceous volcanic arc with oceanic affinity is the Alisitos arc. This volcanic arc accumulated >6 km of volcanic and sedimentary deposits at the type locality of the Alisitos Formation in Santo Tomas 20 km south of Ensenada (Allison 1974). This Early Cretaceous volcanic and sedimentary succession crops out continuously along the western side of the Peninsula (see Figure 2b), where it also includes intermittent reefal carbonates and volcanogenic sedimentary deposits, which likely developed during periods of volcanic quiescence (Suárez-Vidal 1987).

The Alisitos arc and its somewhat northern equivalent the Santiago Peak Volcanics of southern California both represent an island arc tectonically accreted to the western margin of the North America continent during Late Jurassic to Mid-Cretaceous time (see summary in Wetmore *et al.* 2003). Syn-batholitic crustal shortening occurred between 115 and 108 Ma in the Sierra San Pedro Martir region (Johnson *et al.* 1999). A change in the mineralogical and geochemical composition of the intrusive rocks of Late Cretaceous age indicates a change to continental arc magmatism (Andean type). This compositional change is well defined from west to east and has alternatively been explained in terms of a volcanic arc crossing a pre-existing Late Jurassic to Early Cretaceous oceanic-continental boundary (Thomson and Girty 1994, Todd *et al.* 2003). The suture of these two volcanic arcs follows the axis of the Baja California Peninsula and is defined by a distinctive contrast of two types of plutonic bodies. To the west, plutons are commonly zoned and composed of gabro, diorite and tonalite all containing magnetite as the principal iron oxide phase. In contrast, the eastern plutonic belt is characterized by tonalite and granite intrusives with ilmenite (Fe-Ti oxide) as a distinctive mineral phase. The boundary between these two suites of plutonic belts defines the magnetite-ilmenite boundary, which is a distinctive magnetic feature along the peninsular ranges batholith (Gastil *et al.* 1990). This lineament crudely defines the boundary between the Alisitos arc and its oceanic lithosphere to the west and the tonalitic plutonic belt with a continental lithosphere to the east.

The continental arc developed in Late Cretaceous along the edge of continental margin and magmatism progressively migrated eastward during Late Cretaceous and Early Tertiary time (Ortega-Rivera 2003, Todd *et al.* 2003) (see Figure 4a). In Sonora and Sinaloa Late Cretaceous-Paleogene volcanic and plutonic rocks were

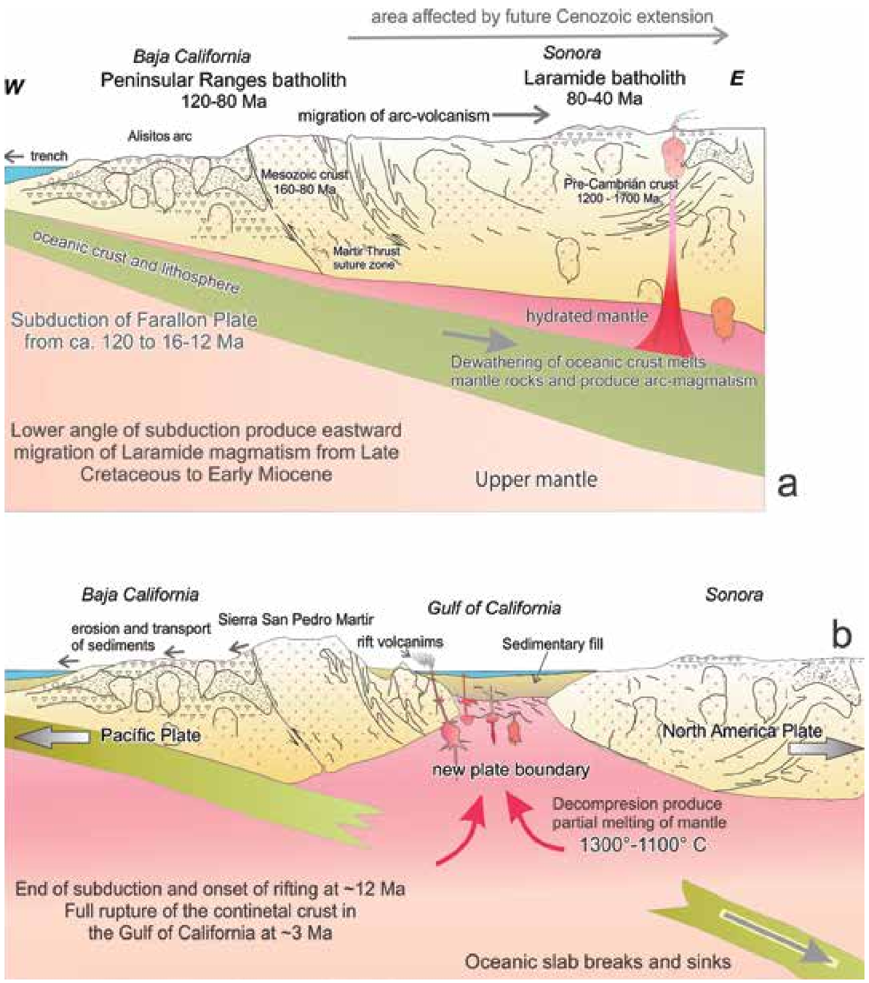

FIGURE 4. Schematic West to East cross section of the continental crust of northwestern Mexico (a) during subduction of Farallon Plate (above), and (b) during rifting and rupturing of the continental crust in the Gulf of California within the last three to four million years.

emplaced as part of the cordilleran magmatism temporally associated with the Laramide contractional deformation in the western United States and Canada (see Figure 4a). Significant magmatic activity in the coastal region of Sonora and Sinaloa is coeval with the peninsular ranges batholiths and indicates that the early stage of the continental arc occupied both Baja California and coastal Sonora and Sinaloa regions (Henry *et al.* 2003, Ramos-Velázquez *et al.* 2008). However, plutonic rocks tend to be progressively younger eastward across Sonora; varying from 90-70 ma

in the coastal region to predominantly ~55-75 Ma beneath the western flank of the Sierra Madre Occidental (Coney and Reynolds 1977, Damond *et al.* 1983, Roldán *et al.* 2009). In contrast radiometric ages in granitic rocks in Baja California are older and range from 80 to 110 Ma (Ortega-Rivera 2003).

The plutonic and volcanic rocks produced in Sonora and Chihuahua expands from Late Cretaceous to Paleogene during the Laramide contractional event (see Figure 4a). The Paleogene plutonic and volcanic are rocks are collectively grouped into the Lower Volcanic Complex of the Sierra Madre Occidental by McDowell and Keizer (1977). Exposures of the Lower Volcanic Complex coeval with Laramide plutonic rocks are widespread over considerably wider areas in the north compared to southern Sonora and Sinaloa. This difference is likely related to a larger amount of Oligocene to Miocene extension in north-central Sonora that in southern Sonora and Sinaloa (see Figure 4).

The Laramide magmatic event and the rocks it formed in Sonora is also important because of the mineralization of Cu, Mo and Au that accompanied the associated hydrothermal circulation and cooling history of intrusive rocks (Damon *et al.* 1981, Clark *et al.* 1982, Pérez-Segura *et al.* 2009).

In summary, during Cretaceous and Tertiary time plutonic bodies metamorphosed and amalgamated Paleozoic and Mesozoic sedimentary deposits previously deposited over the continental shelf across western Sonora, Sinaloa, Baja California and southwestern United States (Figure 4a). This cretaceous magmatic arc represents a significant volume addition to the continental crust along the southwestern margin of the North America continent.

3. POST BATHOLITIC GEOLOGIC HISTORY PRIOR TO RIFTING (50-25 MA)

The sub-aereal volcanic rocks genetically linked to the dominantly tonalitic plutons were deeply eroded during the latest Cretaceous, Paleogene and Neogene times due to uplift of the continental crust; more than 10 km of vertical crust in both southern California and Baja California was eroded during progressive exhumation (Ortega-Rivera 2003, Symons *et al.* 2003, Grove *et al.* 2003). The resultant detritus of this vast erosion was transported to the Pacific continental shelf and slope-trench system where these sediments subducted beneath the continental crust or remained stored at the accretionnary prism above the subduction zone. This sedimentary wedge also widened the continental shelf of western North America.

During Oligocene and Early Miocene time the volcanic arc stalled along the Sierra Madre Occidental and accumulated >2 km of rhyolite to dacite pyroclastic

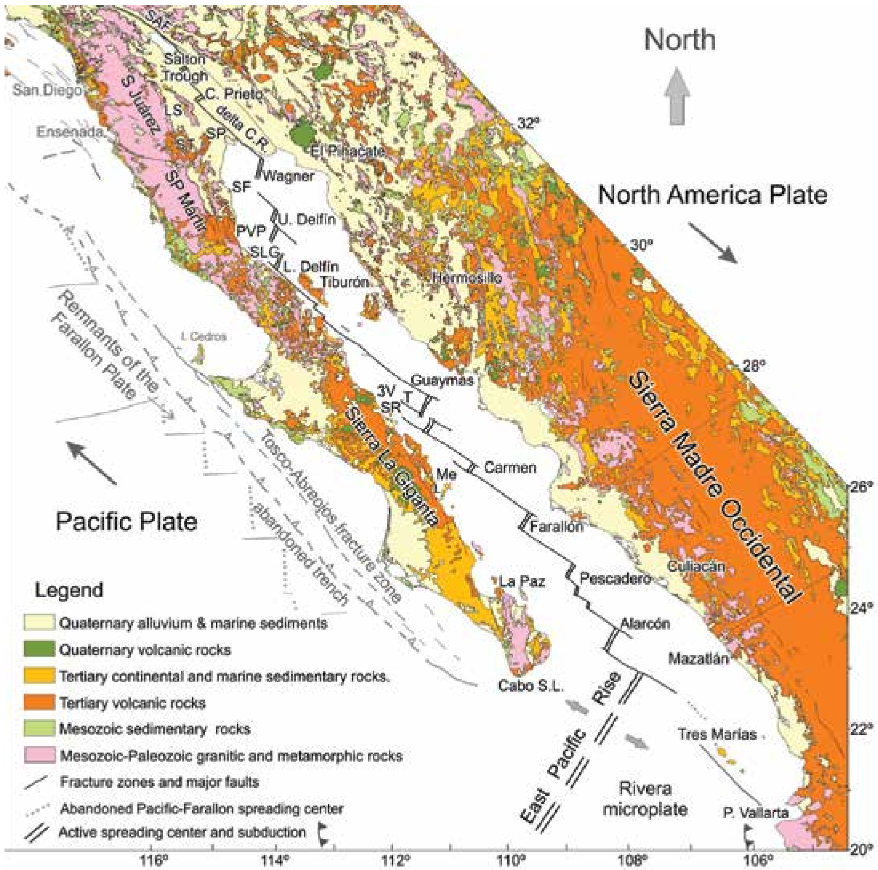

FIGURE 5. Geologic and tectonic map of northwestern Mexico. The granitic and metamorphic rocks form the continental crust. The Sierra Madre Occidental and a large area in Baja California (Sierra La Giganta) contain most of Miocene arc volcanism in northwestern Mexico. Several synrift volcanic fields overly arc-related volcanic deposits and basement rocks. Tectonic features offshore the Pacific Ocean are abandoned spreading ridges, fracture zones and remnants of the Farallon Plate that failed subduction beneath the North American Plate. The West Baja Shear zone is the Tosco-Abreojos fault zone, interpreted to accommodate part of the Pacific-North America plate motion during the opening of the Gulf of California. SAF San Andreas fault, C.R. Colorado River, LS Laguna Salada, LT Sierra Las Tinajas, PVP Puertecitos Volcanic Province, SLG San Luis Gonzaga, 3V Tres Vírgenes, SR Santa Rosalía, T Isla Tortugas, Me Mencenares volcanic field.

deposits (ignimbrites) and lava domes forming what is known as one of the largest rhyolitic volcanic provinces on Earth (McDowell and Clabaugh 1979, McDowell *et al.* 2001, Ferrari *et al.* 2002).

During Middle Miocene most of the Farallon oceanic plate was nearly consumed, and the Pacific-Farallon ridge progressively encountered the subduction zone along the Pacific margin (see Figures 4a and 4b). This plate reconfiguration was accompanied by two major geological events: 1. The progressive ending of arc volcanism in northwestern Mexico and southwestern United States, and 2. A process of intra-arc extension of the continental crust. This last event progressively conducted to rifting along the Gulf of California corridor.

4. THE RIFTING STAGE AND THE PROTO-GULF OF CALIFORNIA

The Cenozoic extensional event in southwestern United States and northwestern Mexico that preceded rifting in the Gulf of California has been attributed to various causes; *e.g.* gravitational collapse of over-thickened crust, mantle upwelling due to slab-free window, and relaxation of confining stresses due to plate reconfiguration in the Pacific margin. These processes are not mutually exclusive and probably all played a role in producing large amounts of extension of the continental crust over a vast region in southwestern United States and northwestern Mexico. This extensional event originated the Basin and Range Extensional Province, which also comprises the region of northwestern Mexico surrounding the Sierra Madre Occidental (see Henry and Aranda-Gómez 1992), and includes the Gulf of California Extensional Province (see Figure 5).

The Gulf Extensional Province is the southwestern part the Basin and Range Province, and for practical purposes its eastern boundary is the topographic escarpment of the Sierra Madre Occidental. The western boundary is the topographic escarpment along the eastern side of the Peninsula, which is also known as the Main Gulf Escarpment along the Sierra Juárez and Sierra San Pedro Mártir (see Figure 5). The Gulf Extensional Province in turn surrounds the Gulf of California, which represents the narrower and younger stage of the ongoing proto-oceanic stage of rifting. Most pre-rift volcanic and sedimentary deposits that once covered the crystalline basement were severely faulted and eroded during the Miocene extensional event that produced the distinctive basin and range topography in Sonora and Arizona (see Figures 4 and 5). This province is characterized by a series of northwest to north-south trending mountain ranges composed of igneous and metamorphic rocks separated by broad elongated valleys filled with alluvial deposits derived from erosion of uplifted blocks (see Figure 5). There, the ranges are bounded by normal faults oriented along the range fronts. Many of these faults dip shallow (<30°) and typically accommodated large-magnitude of extension during the Middle Miocene. This early period of extension overlaps in time with the waning stage of arc volcanism in the Sierra Madre Occidental (32-19 Ma), and along the Baja California Peninsula between 20 and 12 Ma (Martín-Barajas 2000, Ferrari *et al.* 2007).

A peak of extension in central Sonora occurred in Late Oligocene to Middle Miocene time (Nourse *et al.* 1994, Gans 1997), and extreme crustal extension produced significant footwall uplift in detachment faults. The resultant metamorphic core complexes in central Sonora expose middle to lower crustal levels due to uplift during the 25 to 12 Ma time spans (Nourse *et al.* 1994). This time constraint is also consistent with age dating in continental basins in Sonora with mid-Miocene interbedded basaltic lava flows (McDowell *et al.* 1997).

In northwestern Sonora and southwestern Arizona a pulse of extension named "Late Miocene block faulting episode" by Eberly and Stanley (1978), produced basin and range structures and thick continental and lacustrine deposits in the Yuma basin between ~13 and >10.5 Ma. This is also consistent with the post-17 Ma age for widespread normal faulting in the Yuma area proposed by Spencer *et al.* (1995).

In the Salton Trough of southern California and northern Baja California Miocene sedimentary and volcanic deposits dated between 22 and 12 Ma record a first phase of weak extension and high-angle normal faulting (Winker and Kidwell 2002). This early period of weak extension predated the Late Miocene to Pliocene phase of high-magnitude extension and rift-basin development (Winker and Kidwell 1996, Axen and Fletcher 1998). In the southwestern Salton Trough and the Laguna Salada area (see Figure 5) the Late Miocene phase of high-magnitude extension occurred along detachment fault systems (Axen and Fletcher 1998, Winker and Kidwell 2002). The Laguna Salada detachment system is likely to be active and kinematically linked with strike-slip faults of the northern Gulf of California (Axen *et al.* 1999, Fletcher and Spelz 2008).

In northern Baja California the onset of Miocene extension is constrained by faults that cut arc-related volcanic rocks dated at approximately 16 Ma in the range front of southern Sierra Juárez (Lee *et al.* 1996) and lava flows and tuffs from Sierra Las Tinajas dated 10.5 and 12 Ma, respectively (Mendoza-Borunda *et al.* 1998). These crosscutting relationships provide a maximum age of 12 Ma for the onset of extension along the Main Gulf Escarpment in northern Baja California. Additionally, cooling ages of crystalline rocks on Sierra El Mayor at the western edge of the delta-plain of the Colorado River and on Sierra San Felipe constrain the early uplift and exhumation of this intra-rift crystalline block between 10 and 7 Ma (Axen *et al.* 2000, Seiler *et al.* 2010).

5. THE PROTO GULF OF CALIFORNIA

During Late Miocene (<12 Ma) the broadly distributed extension that affected most of Sonora and southern California and Arizona became localized towards the west in a narrow zone that rapidly subsided and promoted the first marine incursion in the Gulf of California (see Figure 4b). Current field studies look for evidence of the timing of the first marine incursion, and for when and how strike-slip motion was fully transferred from the Pacific margin into the Gulf of California corridor (c.f. Stock and Hodges 1989, Fletcher *et al.* 2007). This event progressively occurred between 12 and 6 Ma when the Pacific margin also acted as a plate boundary along the Baja California shear zone (also named the Tosco-Abreojos fracture zone). The southward "jump" of the Rivera triple junction and subsequent propagation of the East Pacific Rice (EPR) northward into the mouth of the Gulf defined the new plate boundary (Curry and Moore 1984, Lonsdale 1991). An important implication is that mantle upwelling and thermal expansion of the lithosphere focused along the old boundary between the Late Cretaceous volcanic arc and the North American craton, which had been previously heated and weakened during the waning stage of arc-magmatism in the late Middle Miocene. These conditions may have controlled the definition of the new plate boundary, thus transferring the Baja California Peninsula to the Pacific plate.

The concept of the proto Gulf of California was first introduced by Karig and Jensky (1972) to refer to the early period of extension in the Gulf of California as an analog to other "volcano-tectonic rift zones associated with an active trench-arc system". This concept is analogous to the concept of intra-arc and/or back-arc basins. Subsequently, the term proto-Gulf was used as a synonym of the early marine basins and to name the early period of orthogonal extension and basin development (Gastil *et al.* 1975, Stock and Hodges 1989). However, the main discussion among scientists has centered on when this process of back-arc extension of the crust conduced the inflow of marine waters during the early stage of the Gulf of California or proto-Gulf stage. The proto-Gulf of California was considered to be older than 12 Ma (Middle Miocene) because volcanic deposits overlying a marine sequence at Isla Tiburón yielded that age (see Gastil *et al.* 1979). However, Oskin and colleagues (2001) proved that previous stratigraphic relationships were wrong and a younger age for the same marine section at Isla Tiburón (<6.2 Ma) was obtained. Age constraints at other sites with marine deposits around the Gulf margins are consistent with the <6.5 Ma age for the Isla Tiburón marine sequence and hence the first marine incursion in the northern Gulf of California may have occurred after 7 Ma, when the boundary between the Pacific and North American plates shifted into the Gulf region (Oskin and Stock 2003).

The Late Miocene age for the first marine incursion in the Gulf (*ca.* 7 Ma) is widely accepted because it is also consistent with tectonic reconstructions of the Baja California Peninsula prior to 6.5 Ma. The correlation of pyroclastic deposits (ignimbrite) dated 12.5 and 6.5 Ma, respectively, and distinctive fluvial conglomerates require the Sonora margin being adjacent to the Baja California Peninsula prior to 7 Ma (Gastil *et al.* 1975, Oskin *et al.* 2001, Oskin and Stock 2003). Outcrops of these tuffs are found in both margins across Upper Delfin and Tiburón basins, and represent ~260 km of northwestward tectonic transport of Baja California to account for the opening of the Gulf of California during the current phase of oblique rifting. However, there are more than 250 km of oblique extension to account for in order to fully close the mouth of the Gulf (see Figures 1 and 5). This extension probably occurred along the margin of Sonora and Sinaloa and in a lesser amount along the coastal region of Baja California Sur sometime prior to ~7 Ma.

Recent paleontological studies in cutting samples of exploration wells from PEMEX indicate the presence of microfossils of Middle Miocene age in Tiburón, Upper Delfin and Wagner basins (Helenes *et al.* 2009, Helenes and Carreño, this volume). These findings raise again the controversy about the age of the proto-Gulf and maintain the likelihood of an older mid-Miocene age for the first marine incursion. The possibility for reworking these Middle Miocene microfossils in exploration wells exists, but the microfossils must come from *in situ* stratigraphic sections yet undiscovered around the Gulf of California.

The corollary of these new findings is that mid-Miocene marine deposits (*e.g.* Helenes *et al.*, 2009; Helenes and Carreño, this volume) contradict the <6.5 Ma age for the onset of oblique extension based on the correlation of volcanic and sedimentary units across the Gulf of California (Oskin *et al.* 2001) and from age-compilation of marine deposits around the Gulf margins, which is consistent with a <6.5 Ma age for the first marine incursion in the Gulf (Oskin and Stock 2003). Deciphering when Baja California started to move northwestwards and when it was fully detached from North America has important implications to understand the rheological behavior of the lithosphere under different rates of strain. Based on the ~6.5 onset of oblique extension we can conclude that the Gulf of California is a young and fast rift system, which currently records ~51 mm/yr of relative plate motion across the Pacific and North America (Plattner *et al.* 2007).

6. THE DELTA OF THE COLORADO RIVER

A major event in the history of the Gulf of California region is the capture of drainage discharge of the Colorado River in the Salton Trough and the northern Gulf of California by the end of the Miocene time. Field studies in the western Salton Trough and NE Baja California indicate that Pliocene fluvio-deltaic deposits from the Colorado River prograded over Late Miocene marine basins (Dibblee 1984, Winker and Kidwell 1996, Pacheco *et al.* 2006). The change from marine to fluvio-deltaic environments in the Salton Trough is well documented to have occurred by ~5.5 Ma (Dorsey *et al.* 2011); however, what is still a matter of debate is the establishment of an integrated course of the Colorado River that may have occurred either by headward erosion or by lake overflow near Lake Mead. Whatever the mechanism of integration of fluvial drainage, field studies indicate that the course of the Colorado River below Grand Wash and the site of the Hoover Dam established post 6 Ma and pre 4.3 to 4.8 Ma. This age interval marks the time when the upper Colorado River integrated its course with the lower Colorado and drainage from the Rocky Mountains reached the Gulf of California. This process dramatically increased the sediment supply and the growth-rate of the delta of the Colorado River.

7. THE TRANSITION FROM ARC TO RIFT VOLCANISM

The end of arc volcanism in the Sierra Madre Occidental is ~19 Ma ago (Ferrari *et al.* 2002) and thus overlaps in time with the onset of extension of the continental crust in central Sonora recorded between 27-12 Ma (Nourse *et al.* 1994, Gans 1997). During this time the volcanic arc retreated to eastern Baja California and remained active from 20 to 16 Ma in both northern and southern Baja California. The volcanic record in coastal Sonora and Sinaloa is also this age although less well preserved. Progressively the volcanic arc ended during a waning stage in southern Baja California from 16 to ~12 Ma (Hausback 1984, Sawlan 1991, Martín-Barajas *et al.* 2000, Umhoefer *et al.* 2001).

The transition from subduction to rifting is accompanied by a change in the type of volcanic eruptions and composition of magmas. Pre-rift mid-Miocene arc volcanism in Baja California is characterized by composite strato-volcanoes of dacite to andesite lavas that produced large volcano-sedimentary aprons due to their high relief and explosive events (Gastil *et al.* 1979, Hausback1984, Martín-Barajas *et al.* 1995, 2000, Umhoefer *et al.* 2001). Several of these pre-rift volcanic deposits are still preserved in northern Baja California beneath syn-rift volcanic and sedimentary deposits (*e.g.* Puertecitos volcanic province, San Luis Gonzaga, and Isla Ángel de la Guarda (see Figure 5). In contrast arc volcanism formed a continuous volcanosedimentary sequence in Baja California Sur, where the volcanic succession is the Comondú arc, which is more that 1000 m-thick in southern Baja California and forms the abrupt relief in Sierra La Giganta (see Figure 5). The Comondú arc represents the waning stage and end of subduction along the Pacific margin offshore Baja California (Hausback 1984, Umhoefer *et al.* 2001).

After subduction ceased, syn-rift volcanism changed dominantly to bi-modal rhyolitic-basaltic in composition. Volcanic eruptions chiefly produced rhyolite ignimbrite deposits and lava domes in Late Miocene and Pliocene volcanic fields in the margins of the Gulf of California (*e.g.* Sierra Las Pintas, Puertecitos, Isla San Esteban; Mencenares; see Figure 5). Also andesitic to dacitic composite volcanoes and calderas (*e.g.* Tres Vírgenes volcanic field) are local distinctive syn-rift magmatic events. This silicic to intermediate volcanism was accompanied with basaltic and andesitic lava flows and small scoria cones mostly in areas west of the zone of extension beyond the main Gulf escarpment from 10 M.a. to Recent in central and southern Baja California. Late Miocene to Quaternary basaltic lavas also emplaced along the coast of Sonora and Sinaloa (Mora-Álvarez and McDowell 1995, Henry and Aranda-Gómez 2000, Paz-Moreno *et al.* 2003).

Subaereal volcanic eruptions have intermittently occurred in the margins of the Gulf in Pleistocene time (<1.6 Ma), and some volcanoes emerged from underwater or throughout the sediments on both the submerged continental margins (*e.g.* Isla San Luis; Isla Coronado) or on the axial deep troughs (Isla Tortuga, Roca Consag; Cerro Prieto, Salton Buttes; see Figure 5).

Offshore the most recent volcanic eruptions have occurred mostly within tectonically active rift basins and its margins. Basaltic lava dominates the volcanic activity in deep basins in the southern Gulf of California. These basins are nascent spreading centers floored with both basaltic lava-flows fed through dikes and lava flows from a central vents. Other vents have formed submarine shield volcanoes emerging from the ocean (e.g Isla Tortuga, c.f. Batiza *et al.* 1979).

North of the mid-drift islands the inflow of Pliocene to Pleistocene terrigenous sediments from the Colorado River has been very high and sedimentary deposits reach several kilometers-thick (Pacheco *et al.* 2006, Aragón-Arreola and Martín-Barajas 2007). The less dense sedimentary rocks cap the new crust and prevent dense basaltic magmas from reaching the surface and forcing them to differentiate at depth. This has produced lower density magmas that overcome the sediment lithostatic load and may ascent to shallower levels, and eventually erupt andesite dacite and rhyolite lavas. Geochemical and Sr-Nd and U-Th and U-Pb isotopic data indicates that magmatic differentiation from basalt to andesite and rhyolite may take place either by partial melting of gabbroic (basaltic) magmas (Schmitt and Hulen 2008, Schmitt *et al.* 2013), or by crystal fractionation with minor contamination of continental crust and sediments (Herzig and Jacobs 1994, Paz Moreno and Demant 1999, Martín-Barajas *et al.* 2008).

The Tres Vírgenes volcanic complex north of Santa Rosalía, Baja California Sur is a Quaternary volcanic field that includes three synrift stratovolcanoes and two caldera structures (see Figure 5 for location). The geochemistry and the style of volcanic eruptions in stratovolcanoes and calderas mimic the activity of the extinct arc volcanism around the Gulf of California. The highest volcano is La Virgen (~1900 m high) whose last eruption occurred less than 34 ky (Schmitt *et al.* 2006). The two large calderas (La Reforma and Aguajito) predate the activity of Las Virgenes volcanoes, but erupted less than one million year ago (Garduño-Monroy *et al.* 1993). This young volcanic complex is potentially hazardous although in recent years it also provides geothermal energy to the town of Santa Rosalía. Other Late Pliocene and Pleistocene volcanic eruptions have occurred in Mencenares north of Loreto, Puertecitos and coastal Sinaloa north of Mazatlán, but the largest and more distinctive Pleistocene volcanic field around the Gulf of California is El Pinacate in northwestern Sonora (see Figure 5).

El Pinacate Volcanic field has a long geological history of volcanic activity. This area contains remnants of two old arc-related volcanic episodes, which occurred in Early Miocene and Middle Miocene (23-12 Ma), respectively (Vidal-Solano *et al.* 2008). However, the most dramatic landform at El Pinacate was produced during Pleistocene time when a first episode of basaltic volcanism known as Santa Clara formed a basaltic shield volcano that progressively changed to produce felsic lavas (trachyte) from the same parent magma (Lynch *et al.* 1993). Subsequently hundreds of basaltic cinder cones, spatter cones and maar craters have formed over the last million year. Radiometric ages reported by Lynch (1981) and Slate *et al.* (1991) of several cinder cones indicates that they are probably all less than about 400,000 years old. Due to its low-K these lavas are challenging to date; nevertheless, using improved radiometric methods Gutmann *et al.* (2000) dated Crater Elegante at 32,000 ± 6,000 years. This maar-type eruption resulted from interaction of groundwater and magma. Recently Turrin *et al.* (2008) reported some of the youngest lavas flows of Pinacate at ~13 thousand years.

The source of magma for El Pinacate volcanic field is beneath the continental crust in the mantle. The geochemical and isotopic studies demonstrate that magma originated from partial melting of the peridotitic mantle beneath a thinned continental crust (Lynch *et al.* 1993) with almost no assimilation of continental material during the magma ascent, a process that is clearly related to the current phase of oblique rifting in the Gulf of California.

8. FINAL REMARKS

A large portion of the continental crust serving as substratum that supports biocycles was generated prior to the Late Cenozoic rifting episode, but most of the topographic relief over the Gulf Extensional Province was produced by Cenozoic extension of the continental crust that culminated with the rupture of the continental lithosphere along the Gulf of California in the last four million years. However, both marine and terrestrial Late Pleistocene to Holocene ecological systems around the Gulf of California developed over an active rift system that records more than 12 Ma of tectonic, sedimentary and magmatic history. The new seaway was formed, and large land-masses like Ángel de la Guarda and Tiburón islands were separated from the Peninsula and the continent, respectively, due to tectonic activity mostly along major strike-slip faults. Other islands were formed during volcanic eruptions related to the same rifting process. All these geological events have influenced the evolution of species and created unique conditions to promote local endemism.

In a geologically short time, the ecological niches within the rift system were chiefly controlled by cyclic climatic changes at the millennium scale. These changes are now widely recognized in natural archives (*e.g.* lake and marine sediments, corals, tree rings, among other geological archives). However, effects of global glacial-interglacial periods over specific regions around and within the Gulf of California are still poorly understood. For instance, during the last glacial stage (~20-30 ky ago) sea level was ~120 m lower than now (c.f. Miller *et al.* 2005) and a much larger delta plain in the northern Gulf existed due to the very shallow submerged part of the delta. This scenario implies smaller marine basins and broader coastal plains, and probably smaller fluvial discharges into the Gulf of California during glacial periods.

Another important aspect is the magnitude of displacement of climatic belts southward during the last glacial stage, and the likely increase of aridity of the circum Gulf region. Nevertheless details of how different regions onshore and offshore respond to climatic cycles are needed to understand how species and ecological niches respond to this climatic stress, and what regions received less moisture during colder conditions under expanded ice sheets at mid latitudes. High-resolution geologic archives may help to understand how species adapted to these climatic changes and what species were forced to migrate elsewhere or even disappear. The geological foundations of the Gulf of California region may explain the physiographic and lithological characteristics that support the biota, but current research in high-resolution archives will provide critical information about climatic conditions of specific regions and the ways that climatic cycles affect both the rich marine and terrestrial communities in the Gulf of California region.

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Exploring Mexico's northwest, the Baja California Peninsula, its surrounding oceans, its islands, its rugged mountains, and rich seamounds, one feels diminished by the vastness and the greatness of the landscape while consumed by a sense of curiosity and awe. In a great natural paradox, we see the region's harsh arid nature molded by water through deep time, and we feel that its unique lifeforms have been linked to this desert and sea for thousands of years, as they are now.

These landscapes of fantasy and adventure, this territory of surprising, often bizarre growth-forms and of immense natural beauty, has inspired a wide array of research for over two centuries and continues to inspire the search for a deeper knowledge on the functioning, trends, and conservation status of these ecosystems in both land and ocean.

This book offers a compilation of research efforts aimed at understanding this extraordinary region and preserving its complex richness. It is a synthesis of work done by some exceptional researchers, mostly from Mexico, who indefatigably explore, record, and analyze these deserts and these seas to understand their ecological processes and the role of humans in their ever-changing dynamics.

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