CONSERVATION SCIENCE IN MEXICO'S NORTHWEST

ECOSYSTEM STATUS AND TRENDS IN THE GULF OF CALIFORNIA

Elisabet V. Wehncke, José Rubén Lara-Lara,
Saúl Álvarez-Borrego, and Exequiel Ezcurra
EDITORS

NEOGENE SEDIMENTARY RECORD OF THE GULF OF CALIFORNIA: TOWARDS A HIGHLY BIODIVERSE SCENARIO

Javier Helenes[1] and Ana Luisa Carreño[2]

The biodiversity in Baja California and the Gulf of California is the result of biological processes related and influenced by the geological history of the region. Particularly important is the opening of the Gulf, since it represents the onset of one of the most diverse marine basins and an effective barrier to continental dispersion. Geologic models propose opening of the Gulf of California during Miocene times. Marine fossils indicate that at approximately 12 Ma, a marine basin formed in the northern part of the Gulf, and by 8 Ma, reached from southern California to Santa Rosalía in the south, forming two biotas, one in Sonora and another one in Baja California. This proto-Gulf could have been connected to the Pacific somewhere south of the Sierra San Pedro Mártir, while the southern part of the Peninsula was still connected to the continent. Then, from 6 to 3 Ma, a sea transgression connected all the depressions, reaching the modern configuration with the Peninsula completely separated from the continent. After this interval, opening of other seaways took place, one at 3 Ma, which isolated Los Cabos region, and another one at ~1-1.6 Ma, near central Baja, which separated the biotas into two groups.

1. INTRODUCTION

The great biodiversity of the region around the Gulf of California (hereafter referred to as the Gulf) is due to the diverse ecosystems in and around the region. These range from continental Sonoran Desert with terrestrial Neotropical and Neartic taxa, to marine fauna with Californian, Panamic, Caribbean, and even tropical West Pacific affinities. At the present time, the Baja California Peninsula (hereafter referred to as the Peninsula) constitutes an enormous barrier that separates the tropical-subtropical

FIGURE 1. Location map of main regional features and points of interest.

marine organisms inhabiting the Gulf from the temperate ones in the Pacific Ocean at the same latitude. Conversely, the Gulf acts as an effective barrier which, together with the Sonoran arid region, precludes mixing of most terrestrial organisms living in mainland Mexico and in the Peninsula (see Figure 1).

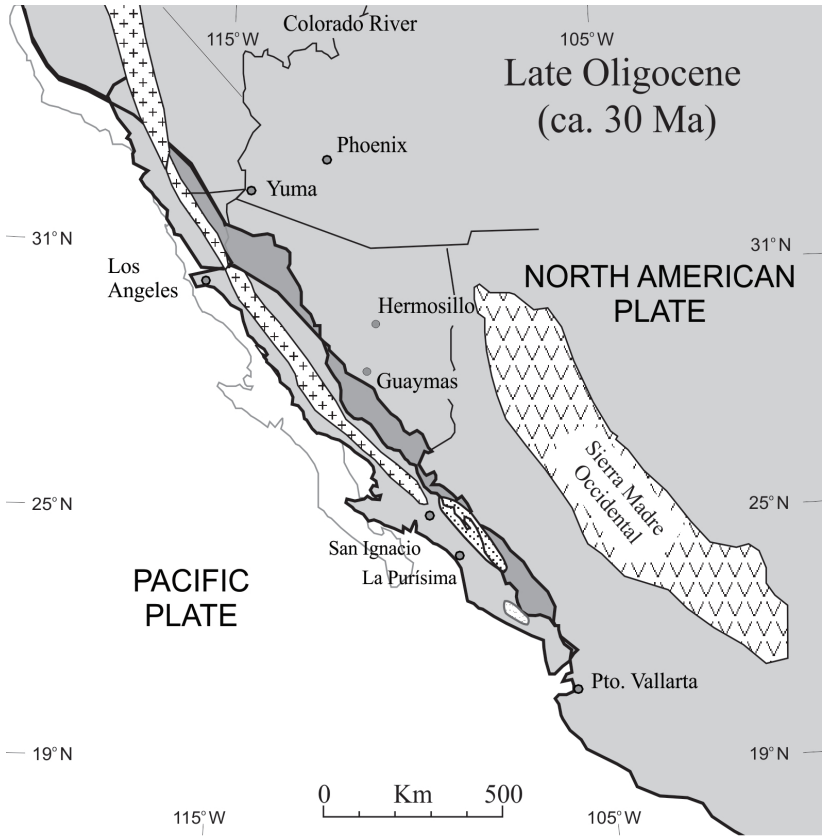

FIGURE 2. Location of the Baja California Peninsula next to mainland Mexico, during Oligocene times (30 Ma). Palinspastic reconstructions of figures 2 to 4 are based on models presented by Lonsdale (1991), Bohannon and Parsons (1995) and Helenes and Carreño (1999).

The Gulf and the surrounding coasts are the result of many geological events that determined the evolution and distribution of the organisms inhabiting the region. The complex geological history of this region allowed the formation of passages and barriers that enhanced or barred the dispersion of organisms at different times. According to our current knowledge of the geological characteristics of the Gulf, the separation of the Baja California Peninsula and the Gulf of California and therefore the configuration of the actual scenario took no less than 25 million years (see Figure 2).

It is difficult to establish with confidence the precise geological moment in which a marine or terrestrial basin begins to form, as well as its extent, structure

and shape through time. It is also complicated to determine the exact timing and intensity of the geological processes involved in the formation or disappearance of these basins. However, we can establish that in the Baja California region, from at least 90 Ma (Late Cretaceous) to approximately 37 Ma (late Eocene), the geologic framework was characterized mainly by a subduction (compressive) tectonic regime. This was caused by the subduction of the oceanic Farallon plate under the western margin of the continental North America plate (Atwater 1970, 1989). Sometime in the late Eocene, the Pacific-Farallon spreading ridge collided against the continent and caused several important changes in the adjoining areas. These changes can be related to three critical stages that permit to explain the evolution of a marine basin such as the Gulf. After the first contact of the Pacific plate with North America, the initial changes in the area, are related to signs of continental crust extension at ~27 Ma, when the normal faulting, characteristic of the Basin and Range extension, reached the eastern side of the actual Gulf (Gans 1997). In this stage, is noticeable a change in the style and composition of the volcanism, from subduction related to one caused by continental extension, at ~14 Ma. Also during this stage, the continental crust became thin enough to subside below sea level, developing the earliest marine basins in the region, over thinned continental crust at ~12 Ma (Helenes *et al.* 2009). Next, in an intermediate stage, there was a change from mainly normal faulting to strike-slip at ~6 Ma, which caused a great part of the displacement of Baja California (Oskin *et al.* 2001). And finally, the stage when new oceanic crust begins forming under the basin at ~3 Ma, in the southern part of the Gulf (Lonsdale 1991).

The initial stages of the regional geologic evolution are clearly described elsewhere in this volume (Martín-Barajas, this chapter). In this paper, we describe the geological and sedimentary record of the Gulf of California region during from the middle Miocene creation of a proto-Gulf, to the late Pliocene, when the region reached its modern configuration.

2. INITIAL STAGE

2.1. Middle Miocene Proto-Gulf

After 12 Ma, the strike-slip faulting migrated to the east of the batholith (Crowe 1978, Dokka and Merriam 1982, Barrash and Venkatakrishnan 1982, Stock and Hodges 1989). This change caused that by middle Miocene times, some areas in the northern part of the Gulf subsided below sea level (see Figure 3).

Microfossil data from oil exploratory wells in the northern part of the Gulf indicate marine deposition during middle Miocene times in Tiburón, Consag and Wagner

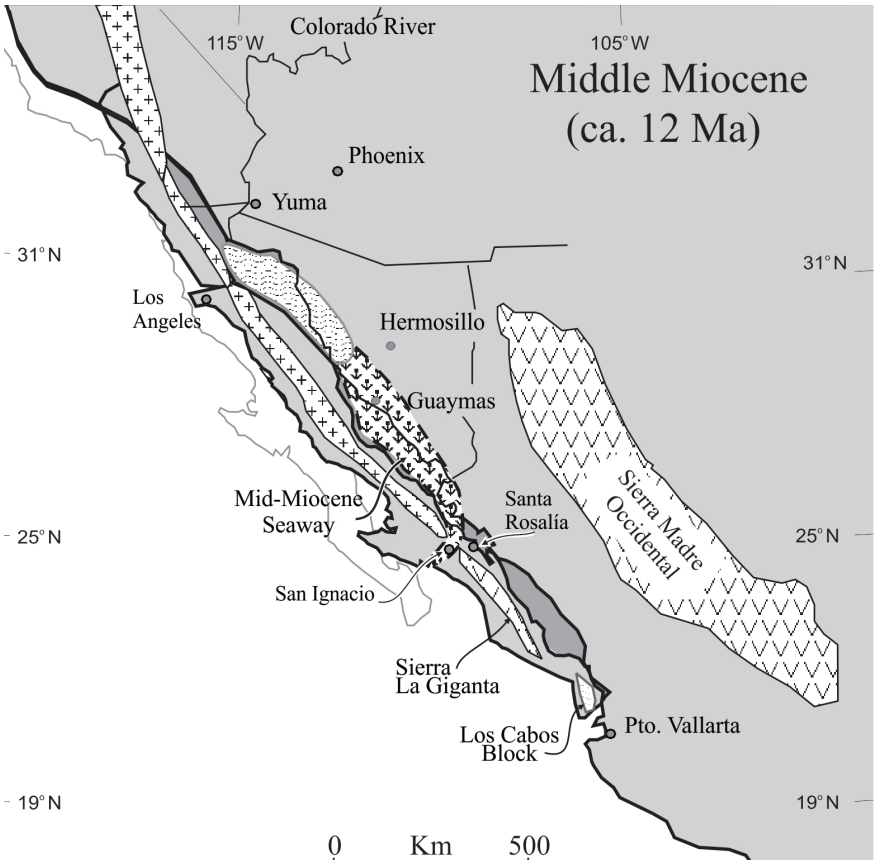

FIGURE 3. Approximate location and extent of the proto-Gulf and the approximate location of the Mid-Miocene seaway near San Ignacio, during the latter part of the middle Miocene (12 Ma).

basins (Helenes *et al.* 2009). These late middle Miocene microfossil assemblages represent the earliest marine sediments in the proto-Gulf area, which was formed in the eastern part of the Gulf, probably related to Basin and Range extension. A middle Miocene age for the earliest marine sediments in the area is controversial because it does not fit with some tectonic models which suggest the beginning of marine sedimentation in late Miocene times (Oskin *et al.* 2001, Oskin and Stock 2003).

The possibility for reworking these middle Miocene microfossils in samples from the exploration wells exists, but the microfossils must come from *in situ* stratigraphic sections yet undiscovered around the Gulf of California. In the areas surrounding

the Gulf of California, the nearest middle Miocene marine sedimentary rocks crop out near San Ignacio, approximately 300 km southwest of Isla Tiburón, so it is unlikely that the reworking came from that area. Those outcrops belong to the San Ignacio Formation, which contains abundant marine megafossils, representing inner neritic facies, but to date, no planktonic foraminifera, calcareous nannofossils or dinoflagellates have been described from this unit (Carreño and Smith 2007). It is more probable that the reworking of the mentioned assemblages originated from within the proto-Gulf area.

Reports in the area of fossils older than late Miocene include nannofossils in the Salton Sea area (McDougall *et al.* 1999); foraminifera in Cerro Prieto (Cotton and Vonder Haar 1979) and dinoflagellates from Laguna Salada (Helenes-Escamilla 1999, Martín-Barajas *et al.* 2001). There are other reports of older Miocene diatoms from the Wagner basin (Rueda-Gaxiola *et al.* 1982), and planktonic foraminifera in south Sonora (Gómez-Ponce 1971). These reports of middle Miocene fossils in the area have been interpreted as reworking, because they are combined with younger fossils or in stratigraphic positions that indicate their reworked nature.

Paleogeographic models based on geophysical information (Lonsdale 1991, Bohannon and Parsons 1995), propose that the passage of seawater from the Pacific from the north or west was obstructed by the presence of the plutonic belt. Additionally, the paleoclimatic characteristics of the diatom assemblages from San Felipe (Boehm 1984) indicate tropical affinities (Esparza-Álvarez 1997, Esparza-Álvarez *et al.* 1998). This climatic affinity indicates that in the middle Miocene, the sea water must have entered from the south, similar to today's Gulf of California. Considering the extent of the main outcrops of the peninsular batholith, the mid-Miocene seaway was probably located between the Sierra San Pedro Mártir and the Sierra La Giganta (see Figure 3).

2.2. Late Miocene Oblique Extension

During the last part of the late Miocene (*ca.* 6 Ma) intensive volcanism took place at the Gulf, particularly along the eastern side of the Peninsula and in some Gulf islands (Martín-Barajas 2000). From the sedimentary point of view, by late Miocene to early Pliocene times, the proto-Gulf extended extensively toward the northern part of the area (see Figure 4).

To the north, the late Miocene marine basin reached into the Salton Sea area (McDougall *et al.* 1999), Laguna Salada (Martín-Barajas *et al.* 2001) and Altar Basin (Pacheco *et al.* 2006), and to the northeast near Yuma (Eberly and Stanley 1978). To the west it reached from the northern San Felipe-Puertecitos platform (Boehm

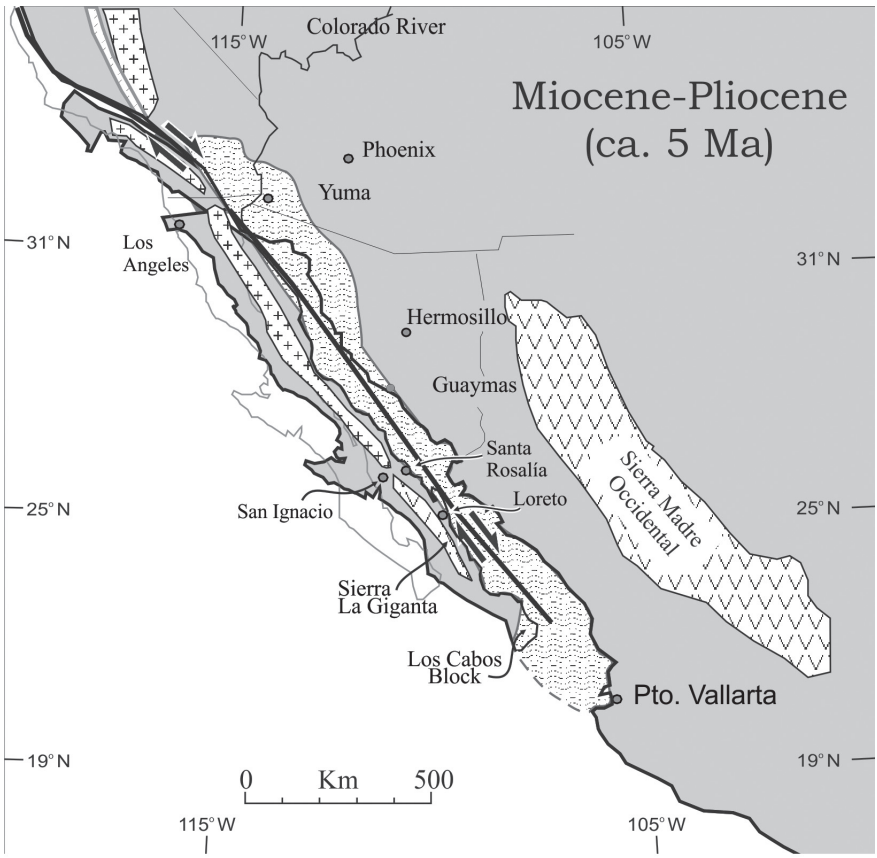

FIGURE 4. Location and extent of the Gulf of California at the beginning of the Pliocene (5 Ma).

1984, Martín-Barajas *et al.* 1997), to Santa Rosalía (Holt *et al.* 2000, Miranda-Avilés *et al.* 2005) in the central part of the Gulf. The eastern side of the Gulf also contains evidence of this late Miocene basin in Isla Tiburón (Smith 1991a, Gastil *et al.* 1999). In southern Sonora, there have been reports of marine sediments related to late Miocene basaltic flows in the vicinity of Hermosillo (Montijo-González 2000), in the Empalme Graben to the east of Guaymas (Roldán-Quintana *et al.* 2004, Marcos-Girón 2011).

The Miocene marine sedimentary units reported at the Los Cabos block (McCloy *et al.* 1988, Carreño 1992) and in the Islas Marias (Carreño 1985, McCloy *et al.* 1988) are more probably related to the Oligocene-Miocene marine units present in the Pacific side of Baja California Sur (Carreño and Smith 2007).

3. PRESENT STAGE

3.1. Late Pliocene Sea-Floor Spreading

Marine deposition on oceanic crust in the southern part of the Gulf itself began in late Pliocene time. Magnetic anomalies along the Tamayo Transform Fault have been dated at 3 Ma (Lonsdale 1991). Therefore, the southern mouth of the Gulf opened at that time, completely separating the Los Cabos block from mainland Mexico. For most of the Pliocene, the circum-Gulf region contains marine sedimentary rocks which represent essentially the actual Gulf of California. From the middle Pliocene (3 Ma) on, the present configuration of the region started and oblique extension occurred along strike slip faults and oceanic spreading in the Gulf itself.

The central part of the Gulf received marine sediments until early Pliocene times (Carreño 1982, Smith 1989, Dorsey *et al.* 1997), when a marine basin formed and reached its present extent by the late Pliocene. Marine outer neritic sediments are found near Santa Rosalía (Wilson 1948, Applegate and Espinosa-Arrubarena 1981, Carreño 1982, Smith 1989). In the vicinity of the Concepción Peninsula (Wilson 1948, Smith 1991a, b, Johnson *et al.* 1997, Ledesma-Vázquez *et al.* 1997), the Pliocene is represented by clastic alluvial to neritic deposits, with chert and limestones with mollusks and mangrove roots in the upper portions (Johnson *et al.* 1997). Near Loreto, the Pliocene is represented by deltaic to shallow marine sediments (McLean 1988, 1989, Umhoefer *et al.* 1994, Zanchi *et al.* 1992, Piazza and Robba1994, Dorsey *et al.* 1997).

Middle to late Pliocene marine deposits are found in Punta Chivato and on the islands between Santa Rosalía and Loreto, referred to as San Lorenzo, del Carmen, Montserrat and probably also on Coronado island (Durham 1950).

4. BIOGEOGRAPHIC DISCUSSION

Nowadays, the Peninsula and the Gulf of California contain a great marine and terrestrial biodiversity that is the result of biological process, particularly those related with the dispersion, isolation, origin and loss of species, all of them influenced by the geological history of the Baja California region. Most researchers involved in the regional evolution of southwestern North America accept that during late Miocene times a marine transgression coincident with a generalized rise in the sea level and the elevation of the isotherm formed a shallow embayment in NW Mexico, while the real Gulf started forming in the Pliocene. In the other side most part of biologists agree in consider this two mega geological events as responsible of two mega vicariate events.

According to the Neogene geologic evolution described above, in northwestern Mexico there were two main events which affected the existing biotas in different parts of the region. The first one took place between 12 and 6 Ma and is related to the formation of the proto-Gulf basin (see Figure 3). The second event took place from 6 to 3 Ma, when the sea transgression connected all the depressions and finally reached the modern configuration (see Figure 4).

This proto-Gulf basin was composed by a series of shallow, elongated depressions formed in mid-Miocene (12-11 Ma) times, from south-western Sonora to the central part of the actual Gulf, north of the midriff islands (Tiburón, Ángel de la Guarda, San Esteban). By late Miocene times (>10 Ma), the basins reached from southwestern Arizona to northeastern Baja California in the north, and to Santa Rosalía to the south. We believe that these basins were connected to the Pacific through a marine passage located somewhere south of the Sierra San Pedro Mártir. In the meantime, the southern part of the Peninsula was connected to mainland Mexico. The basins themselves starting to form two different biotas, one on Sonora to the east and another in Baja to the west.

Regardless of the age of the first marine sediments in the proto-Gulf, the phylogeographic signature of continental and shallow marine faunas in the modern Peninsula and around the Gulf indicates isolation of biotas during different periods and locations. This condition suggests the presence of barriers which effectively precluded migration of organisms during enough time so that they could diverge. Although there is no direct geologic evidence to define their precise location, the presence of marine transpeninsular passage ways is the most parsimonious and plausible way to isolate terrestrial and intertidal faunas (Hurtado *et al.* 2010).

A west to east seaway to connect the Pacific Ocean with the proto-Gulf (see Figure 3) has been proposed to have occurred during middle Miocene times in the center of the Peninsula near San Ignacio area (Helenes and Carreño 1999, Carreño and Helenes 2002). Some workers (Escalona-Alcázar *et al.* 2001, Oskin and Stock 2003) argue that no evidence has been found in the area, to support the presence of this seaway. However, no one has presented any evidence against it either.

Other researchers (Murphy and Aguirre-León 2002) have proposed that at 10 Ma the proto-Gulf was separated from the Pacific Ocean by a short peninsula, more or less equivalent to the state of Baja California or the northern half of the actual Peninsula. At the same time, the southern half was an archipelago and the Los Cabos region was still integrated to the continent. Then at ~7 Ma, a marine transgression invaded the Los Angeles Basin while the rest of the Peninsula was converted into an archipelago.

During the second event (6-3 Ma), the Peninsula separated completely from the continent (see Figure 4) giving rise to a second vicariant event. During this interval, at ~5 Ma, the Los Angeles Basin Sea receded and the Peninsula almost reached its actual configuration, except for the Los Cabos region where, they propose isolate land- mass very close to the continent. The existence of other, younger seaways have been proposed. One at 3 Ma to isolate the Los Cabos region from the rest of the Peninsula, and another one at ~1-1.6 Ma near the center of the Peninsula, which separated the biotas into two groups (Grismer 1994, Riddle *et al.* 2000).

The second event took place from 6 to 3 Ma, when the sea transgression connected all the depressions and finally reached the modern configuration (see Figure 4). To establish with any accuracy the precise timing of formation of the numerous islands forming the archipelagos, as well as the duration and extension of each step in this process has not been possible. Additionally, proposing the existence of seaways and islands or archipelagos is controversial because they do not seem to conform to current tectonic models, and because there is no direct geologic evidence to support their presence. Nevertheless, the phylogeographic characteristics of several groups from terrestrial and/or intertidal habitats clearly indicate that a separation of the populations took place following one of the geographic proposals mentioned before. So, to explain the origin and evolution of their actual diversity in the Gulf region, it is necessary to improve our understanding of the geological processes that produced the present landscapes, including the setting which fits with the actual biogeographic patterns.

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[1] Departmento de Geología, CICESE, Ensenada, BC, México, jhelenes@cicese.mx

[2] Instituto de Geología, UNAM, Cd. de México, México, anacar@geología.unam.mx

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.

Elisabet V. Wehncke

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