A gap in the Pliocene invasion of seawater to the Gulf of California

Jorge Ledesma-Vázquez

Facultad de Ciencias Marinas, UABC, A.P. 453
Ensenada 22800, Baja California, México
e-mail: ledesma@faro.ens.uabc.mx

ABSTRACT

The Proto-Gulf extensional province was formed during the Miocene, from 14 to 12 Ma. During the main extensional period, within the Baja California central domain, several depocenters were formed including the El Boleo basin, followed to the south by the Bahía Concepción basin, and to the southeast, the San Nicolás basin. The San Nicolás basin is associated with the transfer zone coupled to the Bahía Concepción accommodation zone. The Miocene extensional process resulted in the uplift and exhumation of the regional Cretaceous granodiorite basement in the Concepción peninsula, Punta San Antonio, and San Juan Londó valley. The episode of extension is responsible for the tilting of volcanic blocks of Miocene age. The late Pliocene San Nicolás Formation is a lithostratigraphic unit with three sedimentary members. Most of the sedimentary units in the San Nicolás Formation reflect a post-extensional episode that involved rapid initial subsidence, reactivation associated with low rates of sedimentation, followed by periods of shallow water deposition dominated by storm activity, and the presence of large scale sand wave deposits which delineate extreme tidal conditions. The maximum age assigned to the San Nicolás Formation is 3.3 ± 0.5 Ma.

In contrast, at Punta Chivato, and in the Bahía Concepción area, all the marine units are assigned to the lower Pliocene San Marcos Formation, and upper Pliocene Marquer Formation. Here, the marine strata reflect a post-extensional episode that involved low rates of subsidence, associated with moderate rates of sedimentation followed by periods of shallow water deposition dominated by very low energy. These relationships suggest that during the late Pliocene, the inter-connection between the Proto-Gulf and the Gulf of California was not completed, and the head of the developing modern Gulf of California was near the San Nicolás basin during the late Pliocene, clearly associated with the transtensional regime responsible for the present tectonic configuration in the Gulf of California

Keywords: Gulf of California, Pliocene, extensional basins, half graben.

RESUMEN

El Proto-Golfo se formó durante el Mioceno, entre 14 y 12 Ma. Como resultado directo del episodio extensional principal, dentro del dominio central de Baja California, se formaron múltiples depocentros, incluyendo la cuenca El Boleo, seguida al sur por la cuenca Bahía Concepción y al sureste la cuenca San Nicolás. Esta última se asocia a una zona de transferencia de tipo sintética múltiple, relacionada con la zona de acomodamiento de Bahía Concepción. El proceso extensional del Mioceno exhuma al basamento regional de granodiorita cretácica, haciéndolo aflorar en Punta San Antonio, península Concepción y el Valle San Juan Londó. La misma extensión genera el arreglo de bloques basculados de material volcánico del Mioceno. La Formación San Nicolás del Plioceno tardío se presenta con tres miembros sedimentarios. Los estratos reflejan en general un episodio post-extensional con alta tasa de subsidencia inicial, reactivación asociada con bajas tasas de sedimentación, seguida por periodos de depositación somera asociados con eventos de tormenta, *y la presencia de depósitos de ondas de arena de gran escala que reflejan condiciones extremas de marea. La máxima edad determinada en las unidades depositadas al interior de la cuenca es de 3.3. ± 0.5 Ma. En contraste, en Punta Chivato y en Bahía Concepción, se presentan capas de origen marino asignadas a la Formación San Marcos del Plioceno inferior y a la Formación Marquer del Plioceno superior. Estas unidades sedimentarias reflejan en general un episodio post-extensional con tasas de subsidencia bajas, asociadas a tasas moderadas de sedimentación, seguidas por períodos de depositación somera en condiciones de baja energía. Estas relaciones sugieren que durante el Plioceno tardío no se había alcanzado la conexión entre las aguas del proto-golfo y el actual Golfo de California y que la cabeza del actual Golfo de California se encontraba cerca de la cuenca de San Nicolás durante el Plioceno tardío, en una clara asociación con el régimen transtensional responsable de la configuración tectónica del actual Golfo de California.*

Palabras clave: Golfo de California, Plioceno, cuencas extensionales, semi-graben.

INTRODUCTION

The peninsula of Baja California and the adjacent Gulf of California off the Mexican mainland evolved through three phases of development in Miocene to Recent times. The first phase is represented by a subduction regime active from 24 to about 12 Ma on the Pacific coast of Baja California (Hausback 1984). The second phase is associated with a major episode of crustal extension related to the opening of the Proto-Gulf (10 to 3.5 Ma) and distally associated with robust patterns of Basin and Range development in western North America (Karig and Jensky 1972; Stock and Hodges 1989). The final stage or phase is the transtensional regime responsible for the present tectonic configuration in the Gulf of California (Zanchi 1994; Mayer and Vincent 1999) and the total transfer of Baja California to the Pacific Plate from the North American Plate. This study focuses geographically on the Bahía Concepción region that accounts for approximately a third of the Baja California Central Domain (BCCD) (Umhoefer and Dorsey 1997) located between Bahía de Los Angeles and Loreto on the Gulf of California. Earlier studies from this district emphasize the latter stage of rift history by linkage of spreading zones and transform faults in the present Gulf of California with structural elements preserved in shallow basins on the gulf coast (Ortlieb 1978; Umhoefer *et al.*, 1994; Bigioggero *et al.*, 1995; Umhoefer and Dorsey 1997).

The basic structural element of a continental rift is now considered the half graben (Ingersoll and Busby 1995). During early basin development, sedimentation is controlled by strain rates, throw rates on border faults, the length of border faults, local climate, sediment influx rates, and basin outlet levels (Bond *et al.*, 1995). The structural asymmetry of many rift basins also exerts an overall control on the distribution of sedimentary deposition. This is particularly so along basin margins where drainage systems evolve on the footwall scarp to feed alluvial fans or fan deltas that spill across the hanging wall (*e.g.*, Zanchi 1994). Thus, the half graben may be envisaged as a sink for introduced clastic sediments or for biogenic and chemical sediments that form in place (Leeder 1995).

The Pliocene stratigraphy and paleontology of the Bahía Concepción region was previously summarized with particular attention to coastal development (Ashby and Minch 1987; Johnson *et al.,* 1997; Ledesma-Vázquez *et al.,* 1997; Simian and Johnson, 1997; Ledesma-Vázquez, 2000). Recent work by Helenes-Escamilla and Carreño (1999), and by Holt *et al.* (1997), described in a splendid way the evolution of the marine incursion of seawater to the Proto-gulf, and Gulf regions, especially in the northern areas.

The main objective of this report is to describe and contrast the styles of sedimentary deposition of the basin fill, manifested along the marginal basins of the expanding Proto-Gulf during and soon after the pivotal phase of crustal-extension, the transtensional regime and the presence of marine waters within the BCCD area.

GEOGRAPHIC AND GEOLOGIC SETTING

Having an area of 270 km^2, Bahía Concepción is the largest fault-bounded bay in the BCCD (Figure 1). Bounded by Punta Chivato to the northwest and Punta San Antonio below to the southeast, the greater Bahía Concepción region comprises approximately a third of the coastal BCCD. Bahía Concepción is 40-km long, and extends from an open mouth facing Punta Chivato on the northwest to a narrow enclosed bay in the southeast. The bay ranges from 5 to 10 km in width (González-Yajimovich and Pérez-Soto, 1998). The first general geological exploration of the area was carried out by Beal (1948). McFall (1968) realized a more comprehensive geological survey of the area immediately surrounding the entire bay. Ashby and Minch (1987) described the Pliocene and Pleistocene stratigraphy and paleoecology of marine units associated with the Mulegé estuary at the northern end of the bay. More recently, Johnson *et al.* (1997) and Ledesma-Vázquez *et al.* (1997) described some of the Miocene and Pliocene units present along the margin of Bahía Concepción. The Concepción Peninsula forms the eastern margin of Bahía Concepción, which is 8 to 17 km wide, 40-km long, and up to 600 m in height. As described by McFall (1968), most of the peninsula is composed of stratiform volcanic rocks of the Oligocene-Miocene Comondú Group, but some basement granodiorite of Cretaceous age is also exposed (Figure 2). The western side of the peninsula accommodates the Bahía Concepción fault (Figure 2), originated during Miocene times, and reactivated in more recent times. It is geomorphologically expressed as a distinctive fault zone from which well-developed alluvial fans extend westward into the bay. The eastern side of the peninsula is delineated by the Bahía Concepción escarpment (Nava-Sánchez *et al.,* 1998) (Figure 2). Rocks of the Bahía Concepción region consist of a basement complex of Cretaceous schistose and granitic rocks (K-Ar date on granite of 78.4 ± 2.9 Ma; McFall, 1968) overlain unconformably by more than 1,500 m of tilted Oligocene and Miocene volcanics of the Comondú Group. In Punta San Antonio to the south, a 99 ± 2 Ma granodiortite is exposed (Ledesma-Vázquez, 2000). Alluvial and marine sediments form a thin veneer over the Comondú Group and include alluvial conglomerates, marine conglomerates, calcarenites, siltstones, and coquinas of the lower Pliocene San Marcos Formation, upper Pliocene Marquer Formation, the late Pliocene Infierno Formation, and the late Pliocene San Nicolás Formation (Simian and Johnson, 1997; Johnson *et al.*, 1997; Ledesma-Vázquez *et al.*, 1997; Ledesma-Vázquez, 2000). In all areas these latter sedimentary units are flat-lying or form low-angle ramps. The Infierno, the San Marcos, and San Nicolás formations rest with an angular unconformity on the tilted volcanics of the Comondú Group.

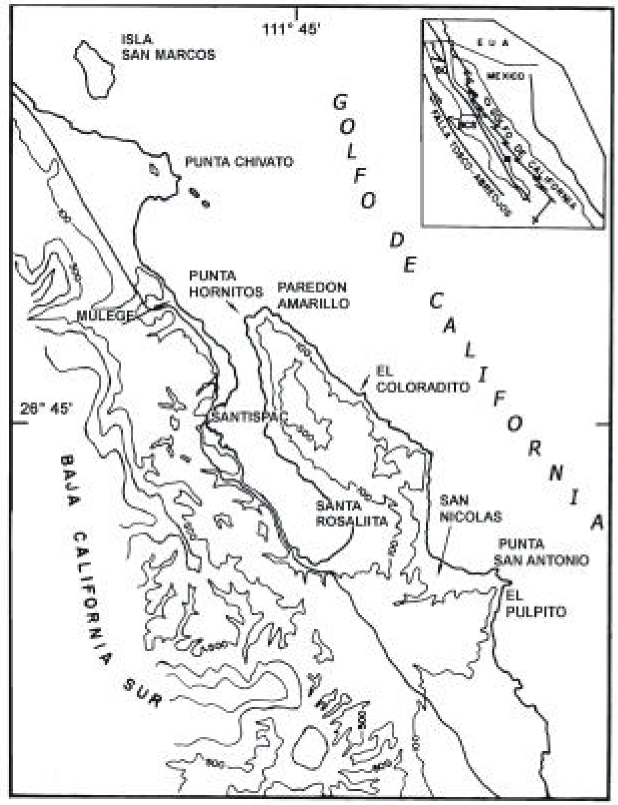

Figure 1. Location map of the study area extending from Punta Chivato to Punta San Antonio, Baja California Sur, Mexico.

STRUCTURAL SETTING

Bahía Concepción occupies a major northwest-southeast-trending half graben. A pre-Pliocene age for this structure is based on the occurrence of flat-lying marls on the northern tip of Peninsula Concepción that are dated as late Miocene to early Pliocene age on the basis of the foraminifers *Globigerinoides obliquus obliquus* and *G. extremus extremus* (Carreño, 1999, personal communication). These beds are very similar to the Tirabuzón Formation at Santa Rosalía (Carreño, 1983). The main structural features of the Bahía Concepción region are northwest-southeast trending faults. The most prominent of these make up the Bahía Concepción fault zone (McFall, 1968), which runs along the bajada on the eastern side of the bay. Exposures of Cretaceous granitoids on the peninsula, and offset of Comondú units were interpreted by McFall (1968) as indicative of large vertical displacements along this fault zone.

The prominent steep escarpment occurring along much of the bay's western shore suggests that this side is also bounded by a northwest-southeast-trending fault zone (Figure 2). However, McFall (1968) does not recognize major offset in the bedrock units on the west side, suggesting such a fault zone experienced less vertical throw than the Bahía Concepción fault zone.

SEDIMENTARY MODELS

To the north of the study area at Punta Chivato, the local basement is composed of resistant tilted Miocene volcanic blocks of the Comondú Group, interpreted by Simian and Johnson (1997) as Pliocene islands. The island blocks are skirted by carbonate ramps sloping at angles averaging 6º from present sea level, The carbonated deposits are present at elevations up to 80 m, suggesting that relative sea level at the time of deposition of these units was 100 m above modern sea level. The lithofacies represented in these units range from intertidal conglomerates at the bottom of the section, to offshore limestone and siltstone. These sediments are assigned to the lower Pliocene San Marcos and upper Pliocene Marquer Formations (Simian and Johnson,

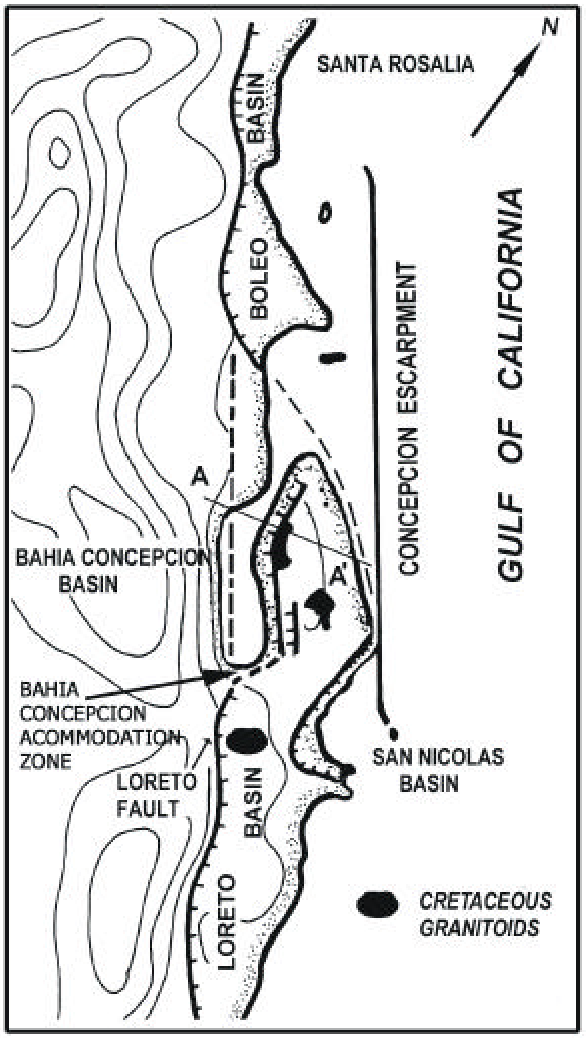

Figure 2. Simplified map of the major tectonic features in the study area. Black areas represent the presence of Cretaceous granodiorites located east of the main scarp of the western limit of the Extensional Province.

1997; Johnson *et al.*, 1997) (Figure 3). The islands were exposed to ocean waves, and any shelter from the energy associated with the waves was minimum, for the deposition of the sedimentary units. Alternatively, inside the paleo Bahía Concepción at Santa Rosalita, upper Pliocene units assigned to the Infierno Formation, were deposited in well-sheltered conditions. The Santa Rosaliita sediments were deposited under the same stratigraphic arrangement of tilted volcanic blocks of Comondú skirted by sedimentary units and includes rocky shoreline deposits and flat lying limestones interbeded with siltstones derived from alluvial fan deposits. The limestones were sequentially deposited within four interconnected basins of very shallow depth, one at a time, and relative sea-level rise is interpreted to have been on the order of 100 m above present sea level in order to fill the basins (Johnson *et al.*, 1997). Tectonic-eustatic factors are invoked to maintain the shallowness of the basins (Ledesma-Vázquez and Johnson, 1993; Johnson *et al.*, 1997). At Mulegé, inside Bahía Concepción, equivalent Pliocene deposits are very narrow, but the general conditions of deposition were similar to those at Punta Chivato and Santa Rosaliita. In the Mulegé area, there is an unconformity between volcanic units belonging to the tilted Miocene Comondú Group, and sedimentary strata of the Infierno Formation (Ashby and Minch, 1987). The stratigraphy of this area includes marine conglomerates at the bottom of the section, underlain by silty units and lithic arkose arranged as ramps that surround the mouth of a paleo-estuary dipping into the bay to the east. Generally, the sediments are moderately sorted, poorly indurated, and moderate to well bedded. The thickest section is 40 m thick and was measured on the northern side of the estuary. Dip angles commonly range between 5^o and 9^o. Average ramp dip is 6^o to the east. Post-Pliocene tilting of the region by tectonic processes is excluded on the basis of consistent dip values from opposite sides of the estuary, and in other Pliocene units. Fossils indicate an upper Pliocene position within the Infierno Formation. All the units were deposited under low energy protected conditions.

The San Nicolás Basin, a half-graben structure, was formed within a major episode of crustal extension related to the opening of the Proto-Gulf. It was formed during the main extensional period as one of the multiple synthetic basins associated with transfer zones, at this area coupled to the Bahía Concepción accommodation zone (Figure 2). The extensional process resulted in the uplift and exhumation of the regional Cretaceous granodiorite basement (99 ± 2 Ma; in Ledesma-Vázquez, 2000; Ledezma Vázquez and Johnson, 2001). The oldest sedimentary units are lithic tuffs, draped around the volcanic and plutonic blocks like an apron and exhibiting high dip angles. The San Nicolás Formation is a lithostratigraphic unit with four members as follow: 1) the lowermost Tobas San Antonio member, 2) the alluvial fan Los Volcanes Member, 3) the transitional Lodolita Arroyo Amarillo Member, and 4) the marine La Ballena Member (Figure 4). Most of the sedimentary units in the San Nicolás Formation are flat lying, and reflect low rates of sedimentation characterized by shell beds, followed by periods of shallow water deposition with evidence of storm activity in the form of reworked marine conglomerates which are interpreted as lag deposits within a storm related sequence (Ledesma-Vázquez, 2000). The maximum age assigned to the Toba San Antonio unit, is 3.3 ± 0.5 Ma (Bigioggero *et al.*, 1995). San Nicolás sediments also include large-scale sand wave deposits, 18 m thick, at top of the whole 100-m San Nicolás sequence, which delineate extreme tidal conditions up to 65 cm s^{-1} (Berné *et al.*, 1988) within the San Nicolás basin. Individual beds within the sand wave facies dip from 13º to 20º. These types of sedimentary structures have being interpreted by Allen (1980) as produced by strong unidirectional currents, related to

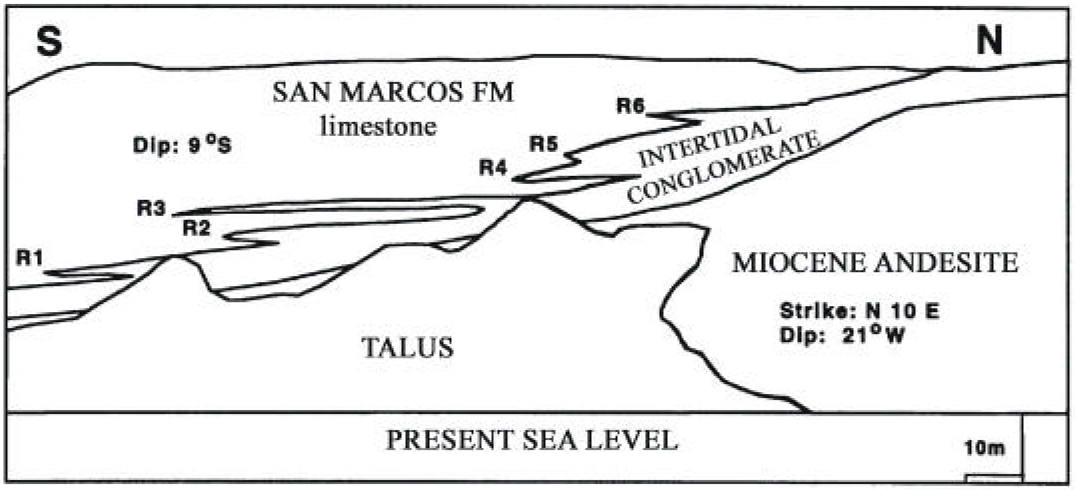

Figure 3. Pliocene-Miocene unconformity exposed in the high cliff face on the east side of the Punta Chivato promontory. Designations R1 through R6 denote regressive conglomeratic wedges (after Simian and Johnson, 1997). The pattern exhibited is the sawtooth pattern of the post-rift strata predicted by Bosence (1998).

either storm waves or extreme tides. The La Ballena member consists of biocalcarenite, coquinas and marine conglomeratic units and is clearly associated with extreme storm activity. Both the coquinas and the marine conglomeratic units are a direct result of storm conditions prevailing during their deposition as evidenced by multiple erosional contacts between layers, and the chaotic arrangement of the broken shells. The coquinas are interpreted as storm lag deposits and are very frequent within the stratigraphic section at San Nicolás basin.

A NEW MODEL FOR THE PLIOCENE GULF EVOLUTION

The Pliocene stratigraphic sequence at Punta Chivato, Mulegé and Santa Rosaliita (Ashby and Minch 1987; Simian and Johnson, 1997; Johnson *et al.*, 1997) are similar and reflect low to moderate energy conditions controlling the deposition of the marine units. In contrast, most sedimentary units in the San Nicolás basin reflect extreme or high-energy events (Ledesma-Vázquez, 2000). In particular, the Punta Chivato and San Nicolás areas were completely exposed to the ocean, as reflected by their sedimentary records (Figures 3 and 4). Nevertheless, each of these areas exhibits a distinct and separated evolution. For example at San Nicolás, two major subsidence episodes can be interpreted from the progradation of alluvial fan conglomeratic units, representing events related to the transtensional regime responsible for the present tectonic configuration in the Gulf of California. Whereas at Punta Chivato, the tectono-sedimentary evolution is clearly post-rift (Bosence, 1998) and associated with an episode of crustal extension related to the opening of the Proto-gulf.

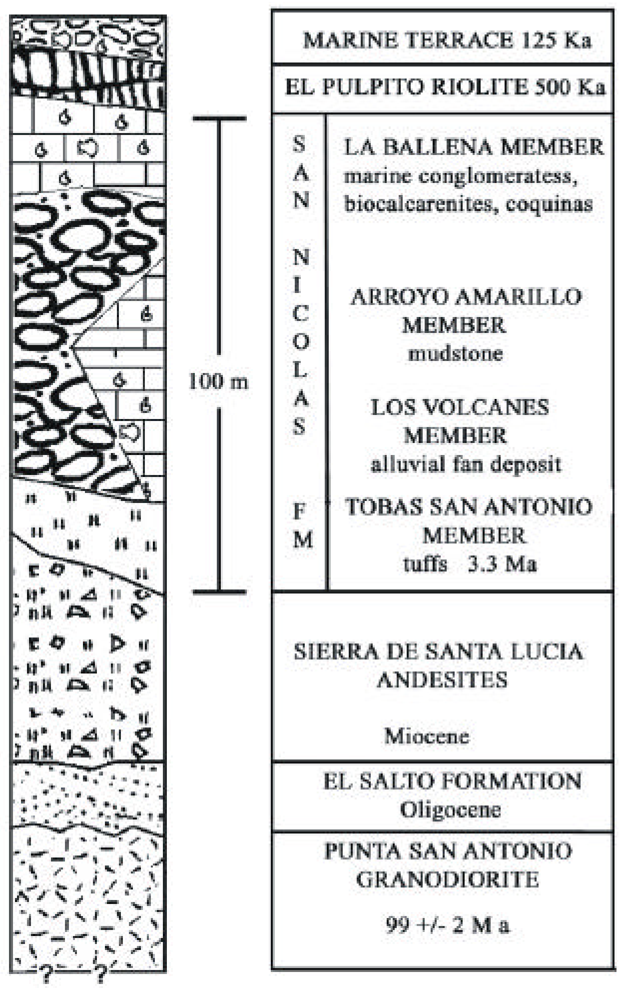

Figure 4. Composite stratotype of the upper Pliocene San Nicolás Formation, and regional relationships within the San Nicolás Basin, Baja California Sur, Mexico. See the text for detailed discussion.

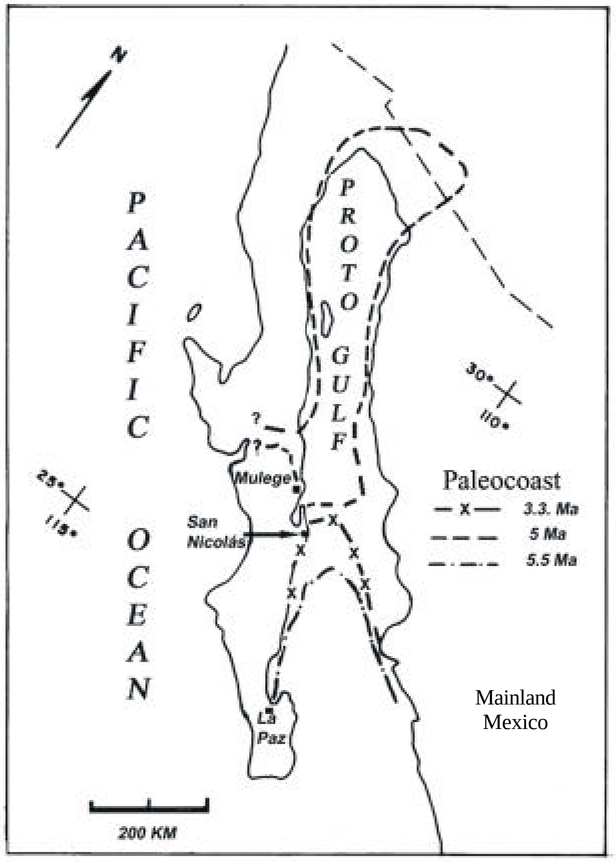

Figure 5. Proposed position of the paleocoast for the Gulf of California region in the late Miocene (5.5 and 5.0 Ma) and late Pliocene (3.3 Ma). Modified from Helenes-Escamilla. and Carreño (1999) and Molina-Cruz (1994).

Based on the evidence presented above, it is proposed here that the two marine bodies representing the Pliocene Proto Gulf of California (Figure 5) were near to each other, but not connected during the late Pliocene. One to the north of Bahía Concepción, designated as the Proto-Gulf, and a second one to the south, as the onset of the modern Gulf of California. Furthermore, the evidence suggests that the two gulf areas were at least partially separated by the Peninsula Concepción, a major rock mass, which was uplifted in post-late Miocene time (Ledezma Vázquez and Johnson, 2001).

In January of 1998, fieldwork was conducted on the eastern side of Peninsula Concepción, along more than 50 km on the gulf coast. Only a single locality was discovered containing evaporitic deposits of probable Pliocene age, but no fossils were found, nor any other evidence that could bring light to determine the age of the unit (Johnson and Ledesma-Vázquez, 2001). Furthermore, this outcrop is very thin compared with the Pliocene units in all other nearby areas. The apparent absence of Pliocene marine strata on the eastern margin of the Peninsula Concepción offers additional support for the proposed separation of a northern and southern Proto-Gulf in late Pliocene time.

The earlier evolution of the marine waters for the Gulf of California proposed by (Helenes-Escamilla y Carreño, 1999), is very accurate up to the final connection during Pliocene time (Figure 11; Helenes-Escamilla y Carreño, 1999), when the transtensional regime finally connected the southern and northern basins of the Proto-Gulf (Figure 5). The interpretation presented here follows the original work by Molina-Cruz (1994) for the southern end of the Proto-Gulf.

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