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Bathymetry and active geological structures in the Upper Gulf of California

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Abstract

Bathymetric surveys made between 1994 and 1998 in the Upper Gulf of California revealed that the bottom relief is dominated by narrow, up to 50 km long, tidal ridges and intervening troughs. These sedimentary linear features are oriented NW-SE, and run across the shallow shelf to the edge of Wagner Basin. Shallow tidal ridges near the Colorado River mouth are proposed to be active, while segments in deeper water are considered as either moribund or in burial stage. Superposition of seismic swarm epicenters and a seismic reflection section on bathymetric features indicate that two major ridge-troughs structures may be related to tectonic activity in the region. Off the Sonora coast the alignment and gradient of the isobaths matches the extension of the Cerro Prieto Fault into the Gulf. A similar gradient can be seen over the west margin of the Wagner Basin, where in 1970 a seismic swarm took place (Thatcher and Brune, 1971) overlapping with a prominent ridge-trough structure in the middle of the Upper Gulf. It is believed that these major elongated features can be linked to active geological structures reflecting the geometry of the deep basement in the Wagner Basin.

Key words: Bathymetry, tidal ridges, seismicity, Gulf of California.

Resumen

Los sondeos batimétricos hechos entre 1994 y 1998 en el Alto Golfo de California revelaron que el relieve del fondo se caracteriza por angostas barras mareales, de hasta 50 km de largo, con depresiones intercaladas. Estas estructuras sedimentarias lineales están orientadas NW-SE, cruzando la plataforma somera hasta el borde de la Cuenca Wagner. Se propone que las partes someras de las barras mareales próximas a la desembocadura del Río Colorado son activas, mientras que las partes en aguas más profundas se consideran o bien moribundas, o enterradas.

La superposición de los epicentros de enjambres sísmicos y un perfil de reflexión sísmica sobre la batimetría muestra que dos estructuras barra-depresión pueden estar relacionadas con la actividad tectónica de la región. Frente a Sonora la alineación de las isobatas y el gradiente concuerda con la continuación de la Falla Cerro Prieto dentro del Golfo de California. Un gradiente similar puede observarse en la margen oeste de la Cuenca Wagner, donde se registró un enjambre sísmico en 1970 (Thatcher and Brune, 1971), coincidente con una prominente estructura barra-depresión en la parte central del Alto Golfo. Se cree que estos rasgos alargados principales están ligados a estructuras geológicas activas que reflejan la geometría del basamento profundo de la Cuenca Wagner.

Palabras clave: Batimetría, barras mareales, sismicidad, Golfo de California.

1. Introduction

The Gulf of California is a receiving basin characterized by a narrow structural trough into which the Colorado River supplied sediments at the closed end of the trough (Coleman and Wright, 1975). Tectonically, the Gulf is located at the boundary of the Pacific and North America plates. The boundary between the two plates is a transform fault system that extends from San Francisco, California, USA, to the mouth of the Gulf, and is known as the San Andreas-Gulf of

California fault system. The Upper Gulf of California (or Upper Gulf) is the semi-enclosed shallow northern end of the Gulf of California, northward of latitude 31° N (Figure 1). Interest in studying this shallow area is due to its unique oceanographic and tectonic character. It shows inverse estuary conditions and fast tidal currents due to large amplitude semidiurnal tides. Its sedimentary regime has undergone drastic changes after damming of the Colorado River and, since 1994, it has been a protected ecological reserve area. The Upper Gulf is surrounded by arid alluvial plains, piedmont deposits, and the Colorado River Delta and estuary to the north (Figure 2). Its seaward limit is roughly defined by the 40 m isobath, where the Gulf is ~70 km wide, near the edge of the 200 m deep Wagner Basin.

Morphologic and dynamic aspects such as continuity and stability of tidal ridges in the Upper Gulf of California, as well as their link to tectonic process, are still a matter of conjecture (Gorsline, 1967; Geehan, 1978; Huthnance, 1982; Carbajal and Montaño, 2001). The present work aims at advancing our knowledge of these topics based on a description of recent bathymetry, tidal dynamics and seismic records. Furthermore, a classification of the ridge-trough system of the Upper Gulf of California is proposed for the first time, based on recent sand bank taxonomy (Coleman and Wright, 1975; Belderson *et al*., 1982; Dyer and Huntley, 1999).

1.1. Sediments and seabed morphology

Until 1935 the Colorado River was the main source of terrigenous sediments that formed extensive delta deposits which are now in a destructive stage by hydrodynamic forces (Thompson, 1969; Carriquiry and Sánchez, 1999). The bathymetric relief of the Upper Gulf was first described by Thompson (1968), based on a limited number of sounding lines made mostly on the western side. Two morphologically distinct zones were described: (a) a uniform gentle sloping plain on the western side, off Baja California, in 4–12 m water depths, with slopes averaging ~0.05° (~10^{-3}) to the east-southeast, and (b) an eastern section characterized by irregular morphology dominated by low tidal ridges separated by flat-bottomed troughs. In the central part of the Upper Gulf the ridges average 8–9 m in vertical relief and are separated ~6 km. Some ridges are roughly symmetrical in profile while others are asymmetrical, with their steepest side facing westward, up to 2°–3° (Meckel, 1975). The broadly spaced sounding lines were insufficient for establishing continuity of the ridges, some of which were though to extend for at least 30 km, and aligned NW-SE, parallel to the along-gulf direction. The ridges appear to have shifted laterally in response to changes in the river mouth and seaward progradation of coastal deposits. The lateral migration has not been well documented in modern times (Meckel, 1975).

The ridges compare closely with the tidal current sand banks described by Off (1963), also referred to as linear sand banks (Huthnance, 1982), tidal current ridges (Stride, 1982), or linear tidal ridges (Coleman and Wright, 1975). These quasi-periodic bed forms occur in shallow seas with adequate supply of sandy sediments and intense tidal currents, between 0.5 and 2 m s^{-1}. In a theoretical study, Carbajal and Montaño (1999, 2001) have proposed that the sand banks of the Colorado River Delta are formed by interaction of the sea bed with tidal currents and the earth's rotation. The calculated sand bank wavelengths were 2 – 7 km, oriented 20° counter-clockwise from the modeled tidal current axis, in agreement with the sand bank morphology described by Thompson (1968).

A gross distribution pattern of surface sediments shows a sandy eastern side (83.4% fine to medium sand, 10.1% silt and 6.2% clay) off Sonora, in contrast with a muddy western side (7% fine sand, 39% silt and 54% clay) off Baja California. Such distribution reflects different dispersal paths of the fine and coarse fractions supplied early by the Colorado River. Fine sand with shell fragments have been found on higher ridges; whereas, finer silts and clays have been found on lower ridges, ridge slopes and flat intervening troughs. Recent mud accretion is restricted to the inter-tidal and sub-tidal flats (depocenter) in the western gulf and to the deeper Wagner Basin (Thompson, 1968; Carriquiry and Sánchez 1999).

1.2. Structural framework of the Upper Gulf of California

The most obvious characteristic of the Gulf of California is its linearity expressed by features of various scales. These features form straight steep escarpments of different lengths and are bound by deep depressions or basins distributed along the Gulf from the latitude of the East Pacific Rise to the Colorado River Delta (Figure 1). The Upper Gulf of California is bordered by the Colorado River Delta, resting on the floor of the Sonora Desert province and forming a barrier which restricts the free circulation of oceanic water over the Salton trough and Mexicali Valley depression. The structural framework of this area is very simple to the east, over the Sonora desert and coast; nevertheless, to the west along the margin of the Baja California peninsula the framework is more complex, and consists of folded blocks bounded by detachment, strike slip and normal faults of complex origin (Rusnak *et al.,* 1964; Axen and Fletcher, 1998) (Figure 2).

In the Upper Gulf the Pacific-North American plate boundary is located within the Colorado River Delta and includes the Wagner Basin and the Consag Rock, which are bounded by active transform faults that are part of the plate boundary (Biehler *et al*., 1964; Thatcher and Brune, 1971; Suárez-Vidal *et al*., 1991; Axen and Fletcher, 1998; Aragón-Arreola and Martín-Barajas, 2007).

According to Rusnak *et al*. (1964), in the northern gulf, the shallow floor dips gently offshore and southward with no obvious shelf-break, and with only three evident small elongated depressions evident on the floor. Two of these depressions are aligned off the Colorado River Delta and probably mark the old river course during the last Pleistocene low stand of sea level. Dauphin and Ness (1991) believed that these depressions could be an expression of an active tectonic feature, such as a closed basin oriented roughly NE that is presumed to be a spreading center, and the elongate NW trending bathymetric lines which apparently connect the

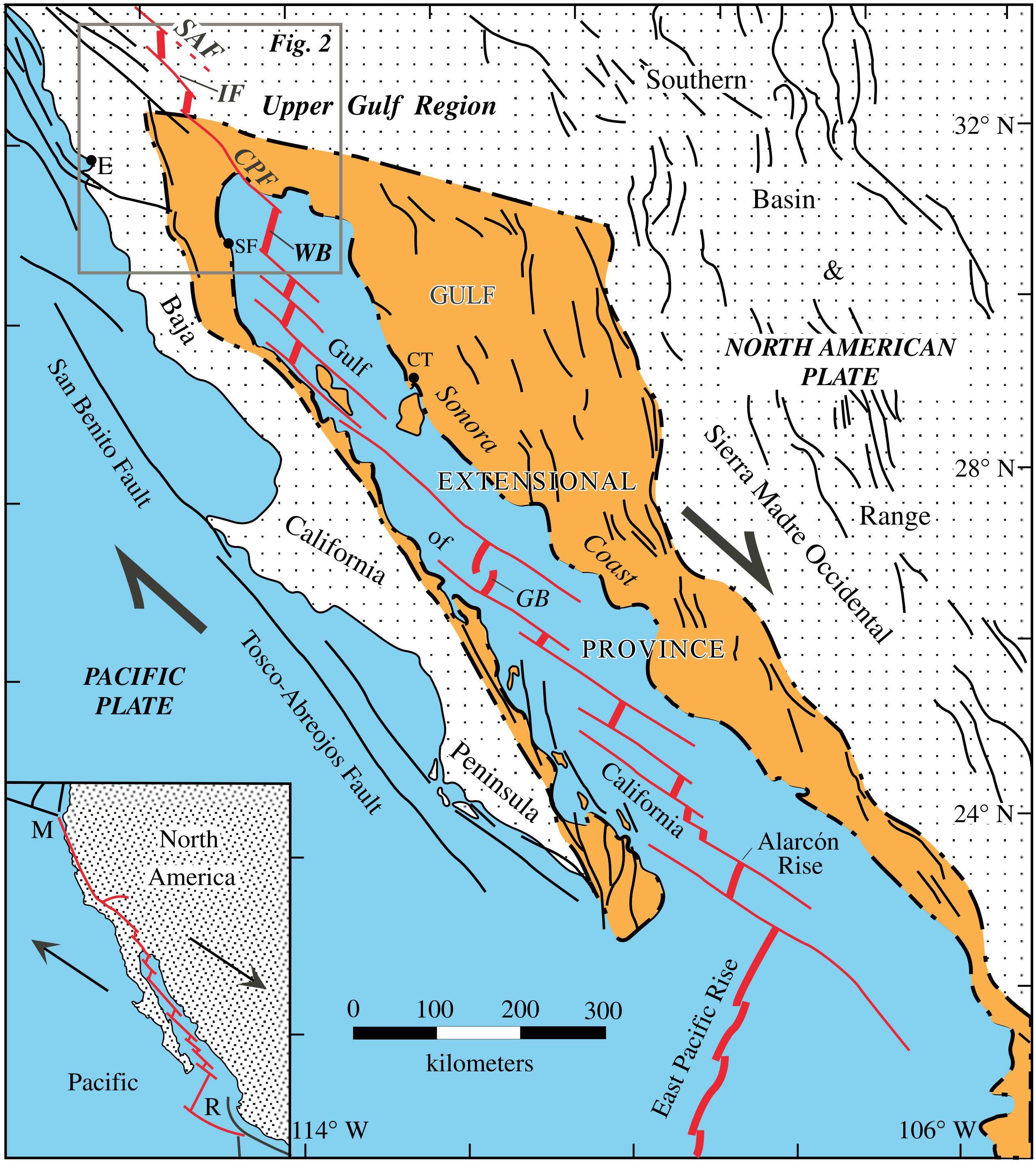

Figure 1. Tectonic and structural framework of the Gulf of California and surrounding regions in northwestern Mexico. The system of transform faults and spreading centers that constitute the main plate boundary between the Pacific and North American plates (the San Andreas-Gulf of California fault system) is depicted in red. The relative motion between the plates is indicated by two arrows. Abbreviations: SAF = San Andreas Fault; IF = Imperial Fault; CPF = Cerro Prieto Fault; WB = Wagner Basin; GB = Guaymas Basin; E = Ensenada; SF = San Felipe; CT = Cabo Tepoca. Inset: M = Mendocino Triple Junction; R = Rivera microplate.

basins are actually the trace of transform active faults (Figure 1).

Even though individual faults of the San Andreas-Gulf of California system cannot be delineated in the Upper Gulf, the alignment of epicenters is clear evidence of the existence of these faults (Figure 3). Geehan (1978) has suggested that the most prominent tidal current ridges in the Upper Gulf might be structurally controlled, since the epicenters of an earthquake swarm were located along this ridge. This seismic event was ascribed to shallow, normal faulting.

Some of the faults extend inland and connect the Wagner Basin with the active spreading center in the Mexicali-

Imperial Valley, such as the Cerro Prieto and the Brawley basins. Among the active faults recognized inland are the Imperial and the Cerro Prieto faults. The Imperial Fault first broke after the May 18, 1940, El Centro earthquake (M= 7.1), producing a ground rupture that extended for 40 miles into the Mexicali Valley and clear evidence of right lateral displacement (Kovach *et al.,* 1962).

The Cerro Prieto Fault extends from the Cerro Prieto geothermal field to the Gulf of California, connecting the Wagner and Cerro Prieto basins (Figure 2). The trace is clear from Mesa de Andrade and along the west coast of Sonora into the gulf tidal flats (Biehler, *et al.,* 1964) (Figure 2).

According to Ness and Lyle (1991), the Cerro Prieto Fault extends into the Gulf of California and bounds the east side of

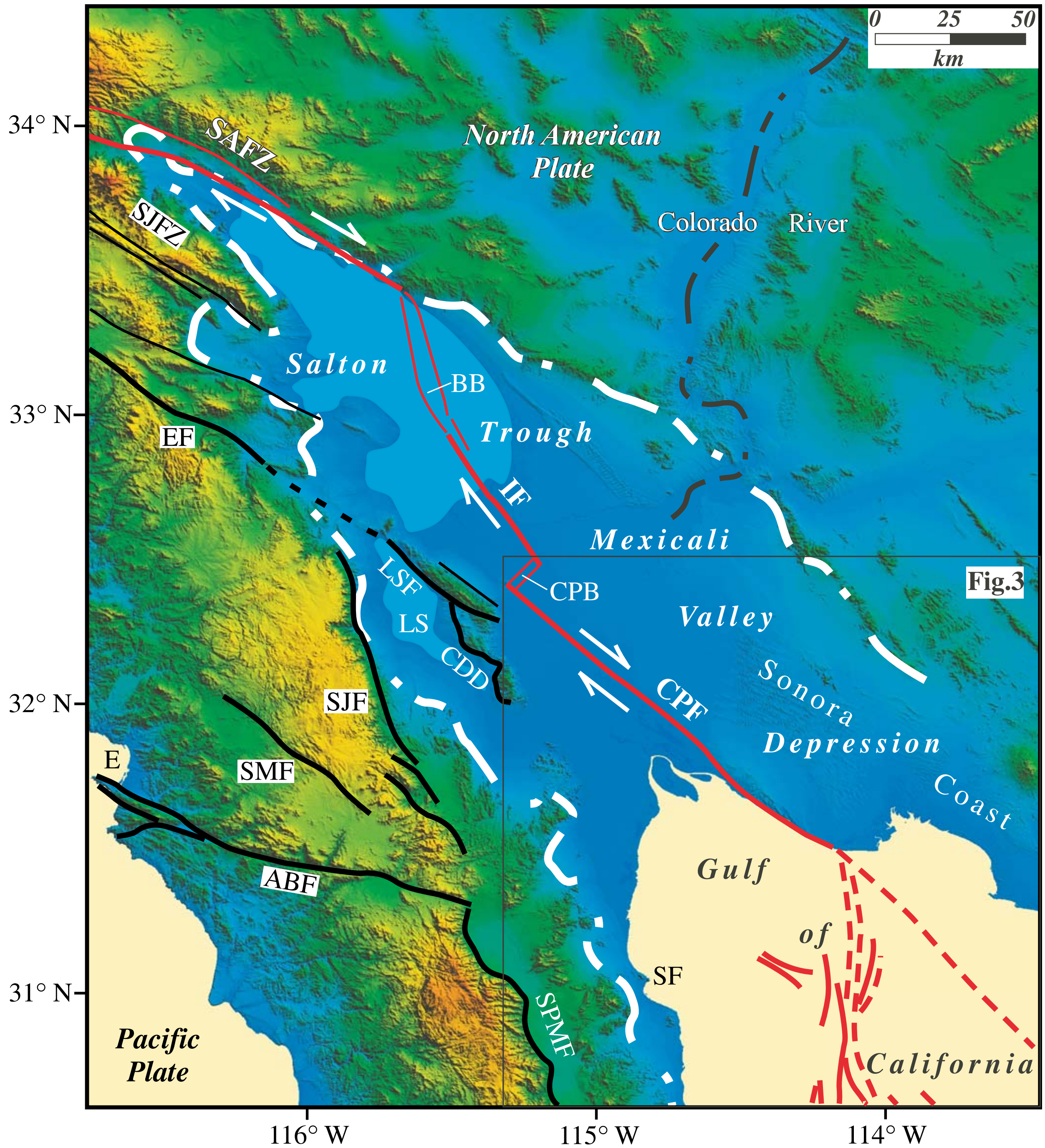

Figure 2. Tectonic map of northern Baja California and the Upper Gulf region in northwestern Mexico. The main plate boundary between the Pacific and North American plates is depicted as thick red lines. Abbreviations: SAFZ = San Andreas fault zone; IF = Imperial Fault; CPF = Cerro Prieto Fault. The basins or incipient spreading centers between these transform faults are: BB = Brawley Basin, and the CPB = Cerro Prieto Basin. The structural elements on the Pacific plate side are: SJFZ = San Jacinto fault zone; EF = Elseinor Fault; LSF = Laguna Salada Fault; CDD = Cañada David Detachment; SJF = Sierra Juárez Fault; SMF = San Miguel Fault; ABF = Agua Blanca Fault; SPMF = San Pedro Mártir Fault. Geographic locations are: E = Ensenada; SF = San Felipe. The Salton Trough-Mexicali Valley depression is depicted as a white discontinuous line. This region is the northward prolongation of the Gulf of California. The background image is a 3 arc sec color DEM.

the Wagner Basin and continues to Cabo Tepoca in Sonora. This basin is the northernmost spreading center in the Gulf of California. It is a closed basin oriented roughly northeast, representing a median depression at the ridge axis. Along the east and west sides, the basin is bound by transform faults roughly striking in a northwest direction, although the western fault is not as clear as the eastern one (González-Escobar, *et al*., 2009).

2. Data

The bathymetric surveys were made between 1994 and 1997 using an Ocean Data Equipment continuous depth recorder and GPS on board the *B/O Francisco de Ulloa* of Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California (CICESE). Shallower areas were surveyed with a Raytheon DE-719 portable fathometer. Sounding lines across the Upper Gulf were set perpendicular to the bottom relief features partially described in earlier studies. Depth readings were adjusted to depths relative to mean sea level by removing the tidal elevation using predictions at San Felipe, Puerto Peñasco and Santa Clara. Seismic data were obtained from the records of the Seismic Network of Northwestern Mexico (RESNOM) 1976-2000 (Figure 3), and from Thatcher and Brune (1971) (Figure 6). Current observations using lagrangian tracers, current meters and one acoustic current profiler provided basic tidal current statistics at opposite sides of the Upper Gulf. Current measurements are described further in Alvarez (2003), and Alvarez and Jones (2004), and the seismic reflection data is from Petróleos Mexicanos (PEMEX) as part of the San Felipe-Tiburón prospect (Pérez-Cruz, 1982; Aguilar-Campos, 2007).

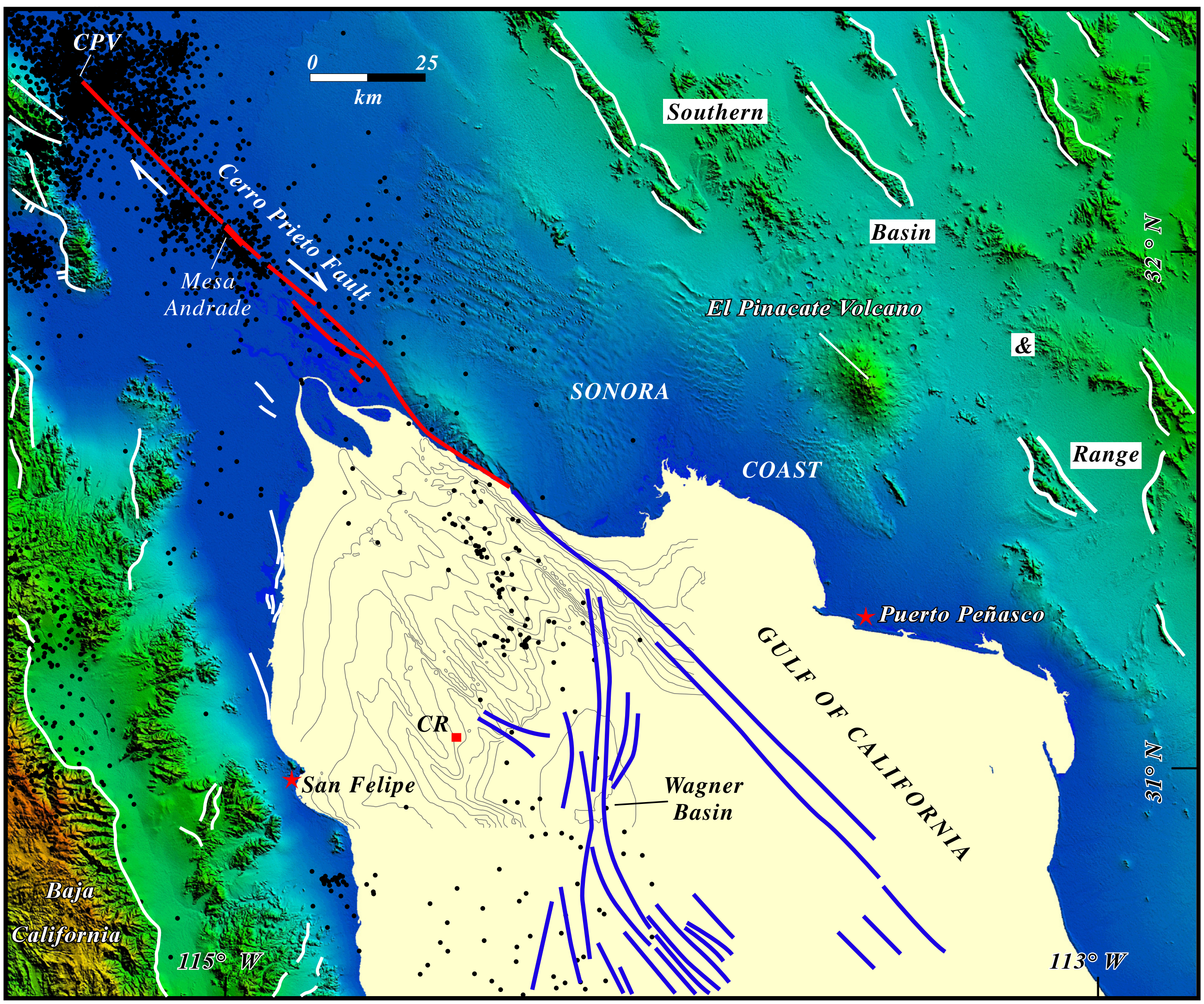

Figure 3. Seismicity, main tectonic elements and bathymetric data collected in this study for the Upper Gulf of California region in northwestern Mexico. The main boundary between the Pacific and North American plates is depicted as thick red (inland) and blue (offshore) lines. The offshore interpretation is from Fenby and Gastil (1991). The seismic data (black dots) sources are Thatcher and Brune (1971) and the Red Sismológica del Noroeste de México (RESNOM) operated by CICESE. The bathymetric lines appear as thin gray lines. Abbreviations: CPV = Cerro Prieto Volcano; CR = Consag Rock. The background image is a 3 arc sec color DEM.

3. Results

The bottom relief of the Upper Gulf is dominated by linear features nearly parallel to each other and oriented in northwest direction (Figure 4). Nine ridges and intervening troughs were identified between depths of 10 to 50 m running across the Upper Gulf's shallow shelf. Shallower depth contours reflect mostly the coastline morphology, while contours deeper than 50 m reveal the steeper slopes of the adjacent 200 m deep Wagner Basin. On the eastern side, five ridges of nearly symmetrical cross section have a wavelength 5-6 km and are bounded by two prominent narrower ridges (C and D in Figure 5). These two ridge-trough systems can be traced along 50 km to depths near 50 m at the edge of Wagner Basin. Their cross section is asymmetrical, with their southwestern flanks showing steeper slopes ~0.02 (1.1°). The northeastern flanks have slopes an order of magnitude smaller (~0.002). The deeper segments of both ridges bend slightly (10°–15°) towards the center of Wagner Basin.

Near surface currents attained 0.7– 0.9 m·s^{-1} in spring tides and reflect the dominant semidiurnal tidal forcing. The mean speed near the sea bed was 0.17 – 0.29 m·s^{-1}. The principal axes of the oscillatory currents were oriented within a narrow bearing range at the four sites (307°–327°), nearly parallel to the ridge and trough system, as shown in Table 1. The principal axes at four observation sites are shown superimposed on the bathymetric map in Figure 5.

Superposition of seismic activity epicenters on the recent bathymetry (Figure 6) show two parallel linear trends that coincide with the two prominent ridge-trough features of the sea bed. The remarkable match of epicenters near ridge C correspond to a seismic swarm recorded on March 20-28, 1969, and the location match with the trace of some of the faults identified in the reflection seismic lines (Figure 7; Aguilar-Campos, 2007; González-Escobar, *et al.,* in press). Most of the epicenters near ridge D were recorded from 1981 to 2002.

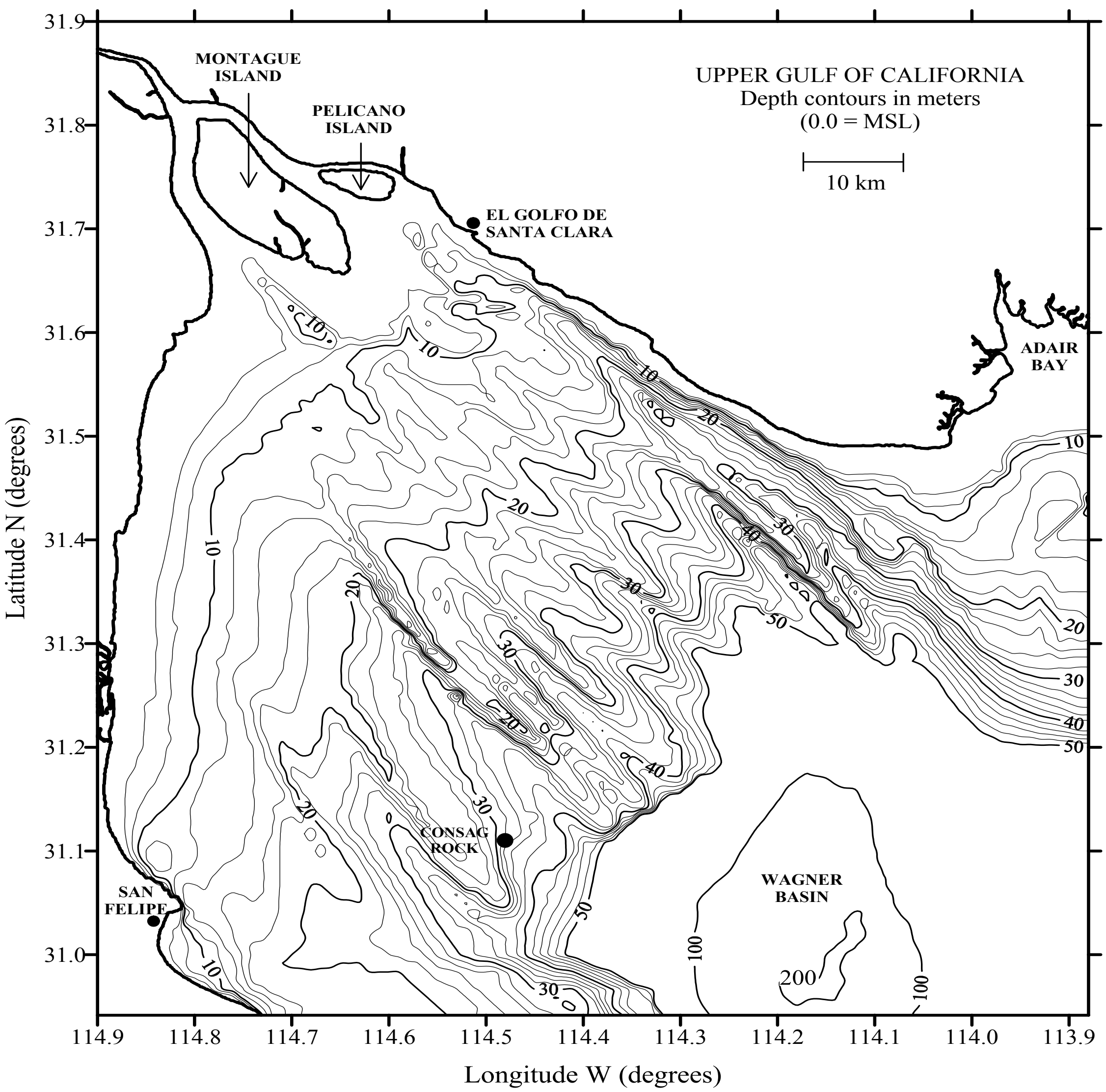

Figure 4. New bathymetry based on the 1994-98 surveys.

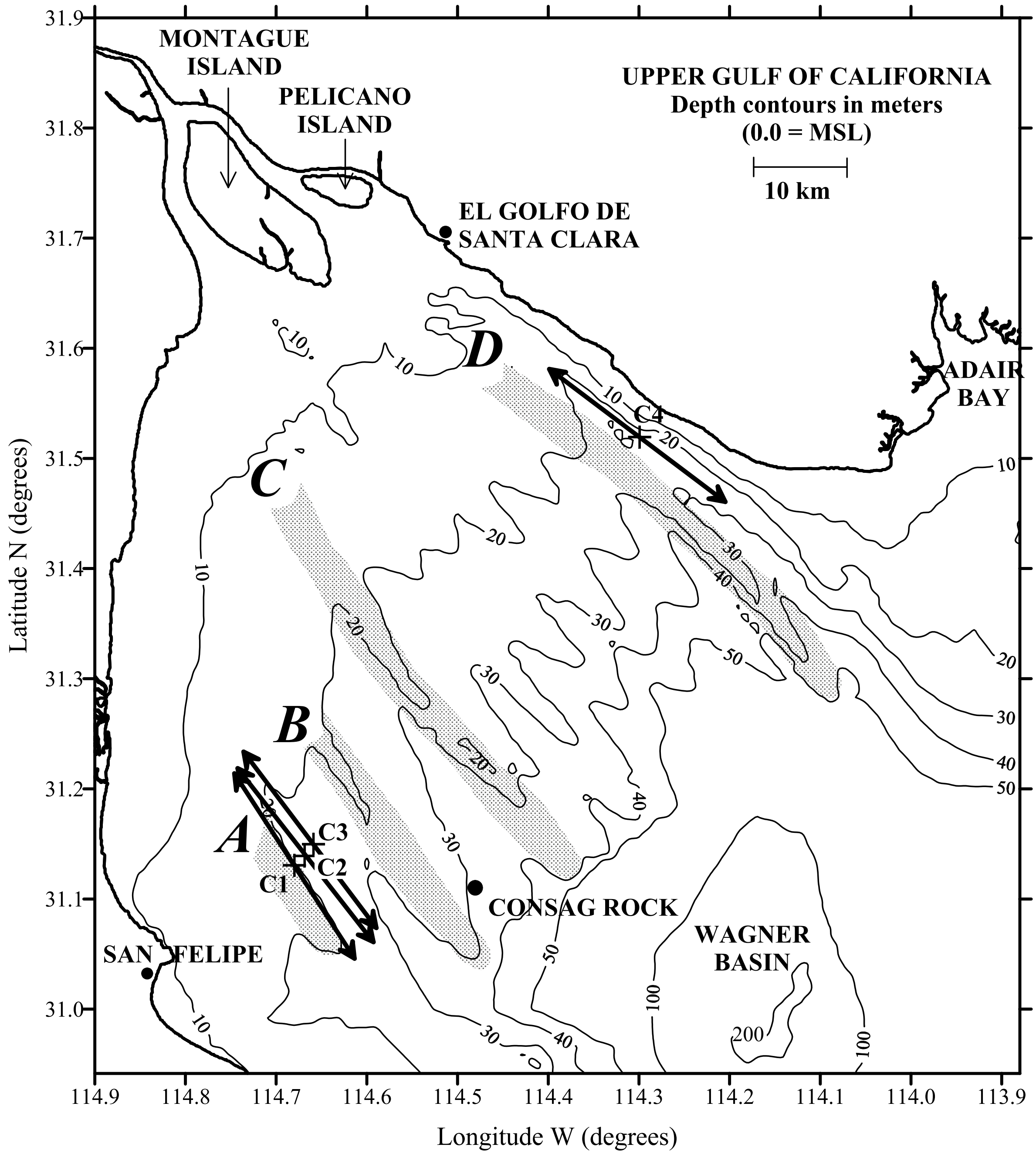

Figure 5. Bathymetric map showing four outstanding ridges (shaded) and the main axes of observed currents at four sites (arrows).

Table 1. Orientation of tidal ridges A, B, C, D and axes of tidal currents observed at sites C1, C2, C3, C4, shown in Figure 5. Currents at C1 and C2 were observed during one and four semidiurnal cycles, respectively. At sites C3 and C4 the observations were made during one fortnightly cycle.

Ridge axis (°) true	Observed currents at indicated sites				
	Site	Main axis (°) true	Mean speed and [std. dev.] (m s^{-1})	Observation level	Water depth (m)
A: 333	C1	327	0.29 [0.13]	1.2 m above bed	19
B: 329	C2	322	0.43 [0.20]	surface	18
C: 328	C3	323	0.17 [0.12]	1.2 m above bed	25
D: 310	C4	307	0.27 [0.17]	4.2 m above bed	30

4. Discussion

Large, linear offshore tidal ridges are typical of deltas debouching into narrow restricted depositional basins with low wave energy and high tidal range, such as the Upper Gulf of California (Coleman and Wright, 1975). With regard to sand distribution models, the Colorado River Delta corresponds to a delta with fingerlike protrusions of channel sands, and numerous linear offshore sand bodies that represent deposition by tidal action (Coleman and Wright, 1975). Tidal ridges in other seas are up to 50 km long, 6 km wide and 40 m high, with maximum flank slopes of 4° to 6°. The ridges are in general aligned oblique to the direction of peak tidal flow by a small angle, but reach as much as 20° (Stride, 1982). The ridges observed in the Upper Gulf are oriented 3°–7° clockwise from the principal tidal current axis.

It has been suggested that, in the northern hemisphere, tidal ridges maintain their shape if they are aligned counterclockwise by a small angle (8°–15°) relative to the major axis of the tidal current (Zimmerman, 1981). The theoretical study by Carbajal and Montaño (2001) on sandbank generation in the Colorado River Delta obtained a sandbank offset of 20° counterclockwise from the axis of the modeled tidal current. The reported sandbank orientation and spacing (wavelength ~4 km) in water depth of 10 m agreed well with those described by Thompson (1968). However, the new bathymetry shows that ridges in depths greater than ~15 m, on the western half of the Upper Gulf, are almost parallel or slightly clockwise from the main axis of the observed currents, as shown in Table 1. This difference suggests that the model proposed by Carbajal and Montaño (2001) does not apply to the whole region of ridge-trough topography but only to the shallow (<15m) northern end of the Upper Gulf, where the required bed load sand supply is available for active tidal ridge formation and maintenance. Furthermore, clockwise offset of ridges relative to the current axis observed in the Upper Gulf has also been reported in at least one major linear bank in the North Sea (Dyer and Huntley, 1999). For deeper waters of the Upper

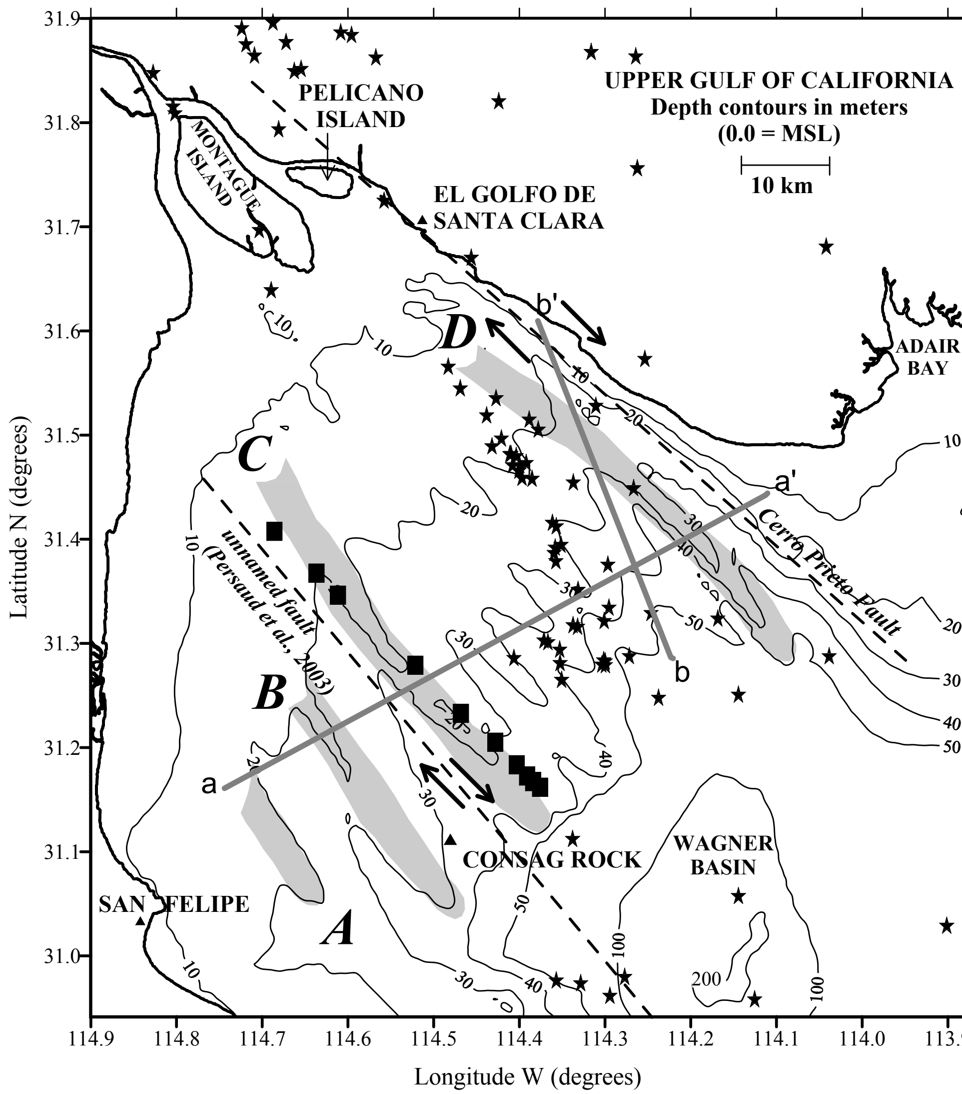

Figure 6. New bathymetry and seismicity recorded by RESNOM (stars) and by Thatcher and Brune (1971) (solid squares).

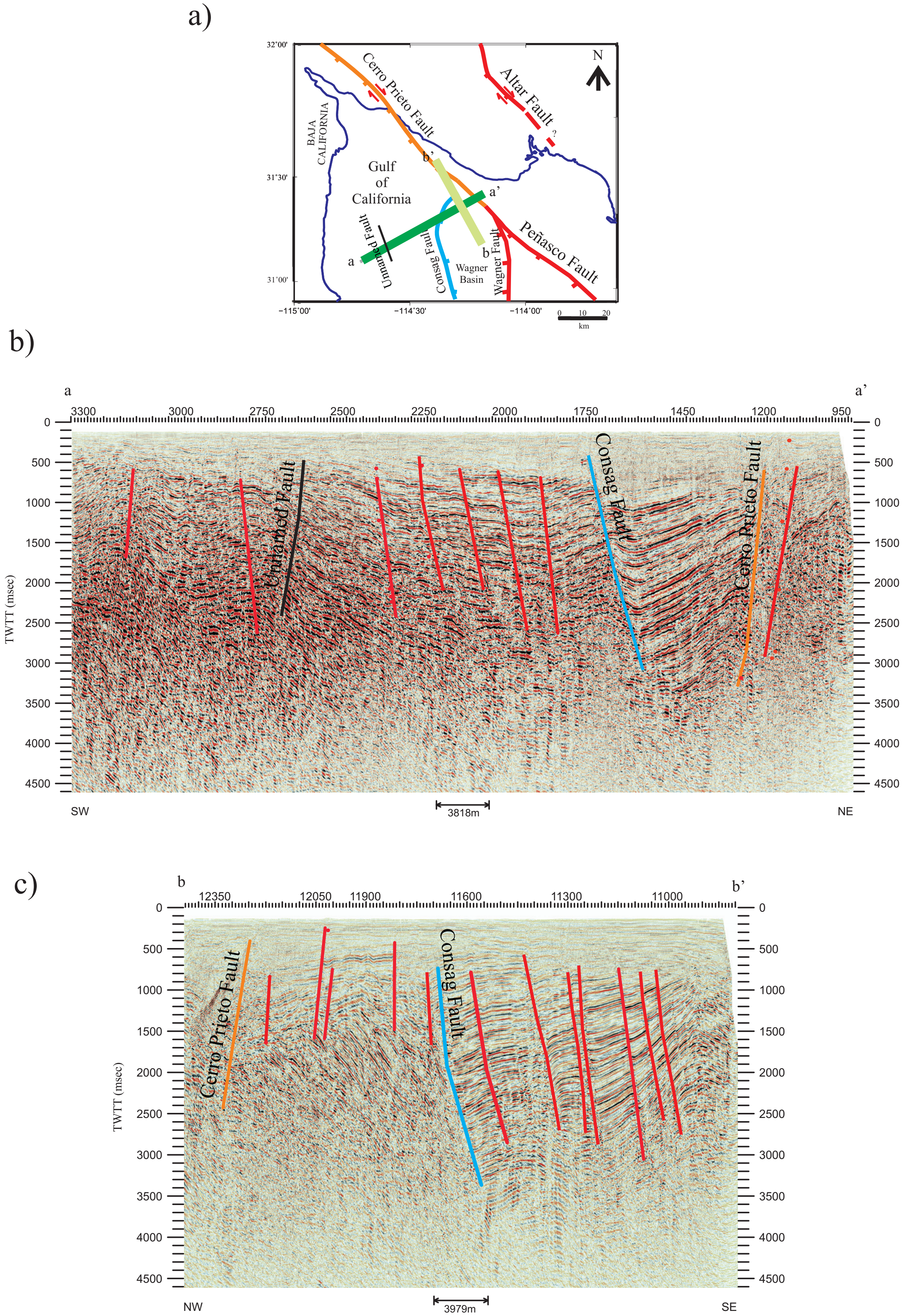

Figure 7. (a) Seismic reflection lines (a-a', b-b') in the Upper Gulf obtained by PEMEX; different colors indicate major geological faults in the region. (b) a-a' Cross-section transverse to Upper Gulf, showing the Cerro Prieto Fault (orange line), Consag Fault (blue line) and Unnamed Fault (Persaud et al., 2003). (c) b-b' cross-section longitudinal to the Upper Gulf, showing major faults. Red colored lines are faults that generally do not reach the surface.

Gulf (20–30 m), Carbajal and Montaño (2001) obtained an increased ridge offset of 30°–35°, counterclockwise from tidal currents at 0.5 m·s^{-1}, which prevail at these depths. This discrepancy indicates that the observed prominent ridges having crests at depths near 25 m do not represent active tidal sandbanks as do those described by Carbajal and Montaño (2001) in shallower water. Further evidence of the relict character of the ridges is the sand fraction present in samples of surface sediments: Thompson (1968) reports 44-74% sand in samples from ridge flanks. According with Van Andel (1964), sediments from water depths of 27-40 m near the edge of Wagner Basin contain 70-89% sand (Figure 8). Equilibrium between present conditions and sediment texture would require bottom current velocities of 0.3-0.4 m·s^{-1} for the transport of sediments with particle size 2.25Φ to depths of 135 m. This velocities appear impossible in a wide basin with short fetch, such as in the northern Gulf of California. Other features located off the western shore, such as sub-tidal terraces located 12-15 m underwater and erosive notches at similar depths, have been interpreted as surface developed at lower sea level. This level corresponds to a temporary still stand before the Wisconsinian sea level rise ~8000 years B. P. (Thompson, 1968).

Based on the textural distribution of sediments, sea bed morphology and hydrodynamic conditions, the classification by Stride (1982) for the sand banks in north European seas was applied to the tidal ridges of the Upper Gulf. As shown in Figure 9, it is proposed that a single ridge may show segments pertaining to different classes:

(1) Active ridges which are dynamically maintained by the present tidal current regime, restricted to the shallow north part of the Upper Gulf where depths are less than ~15 m, currents are fast, and bed load sands are abundant. Here, a vertically averaged hydrodynamic numerical model yielded current amplitudes exceeding 0.5 m·s^{-1} due to the M2 tide (the largest semidiurnal harmonic constituent), and current

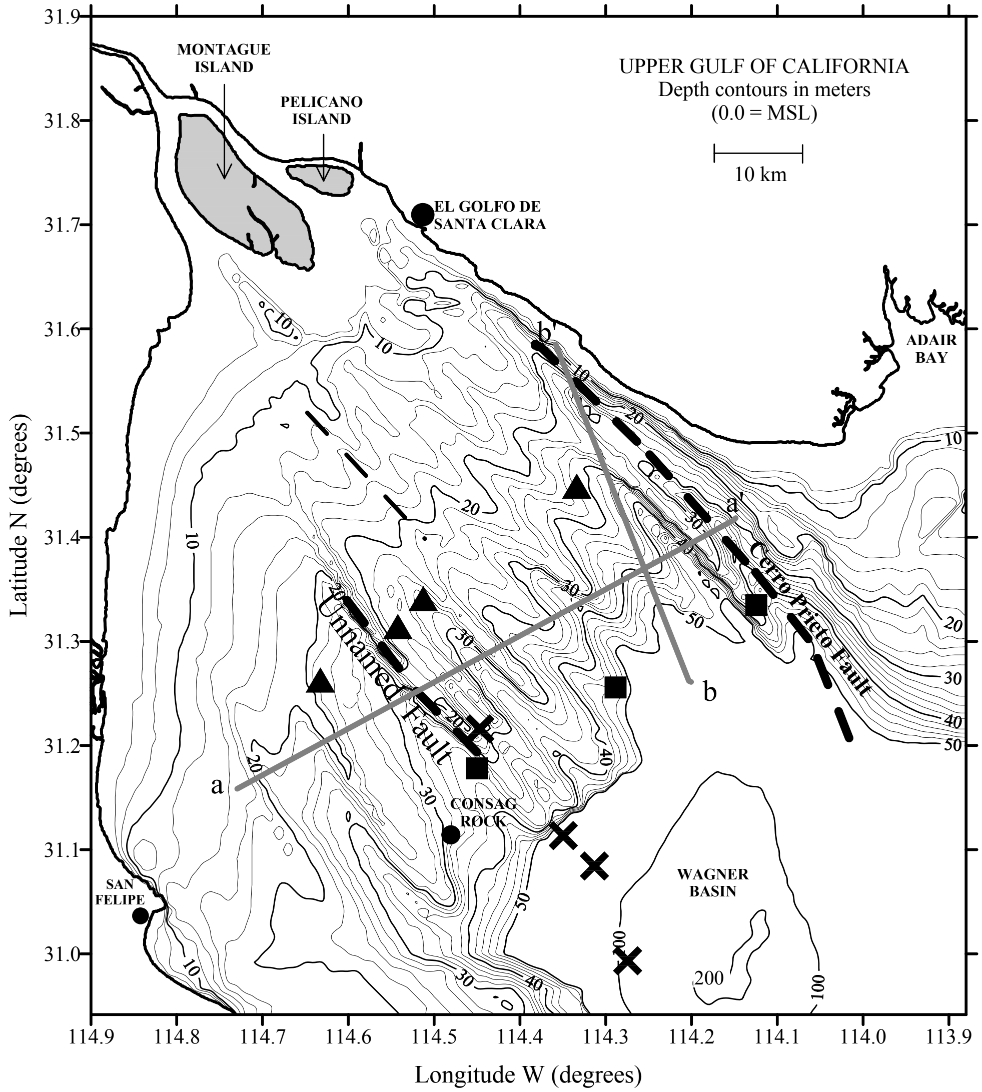

Figure 8. Sites in which sandy bed sediments have been reported: ■ van Andel (1964), ▲ Thompson (1968), × W. Daessle (pers. comm.). a-a', b-b' are seismic reflection lines (from PEMEX). The three dashed lines represent seismic active faults (Cerro Prieto and unnamed faults).

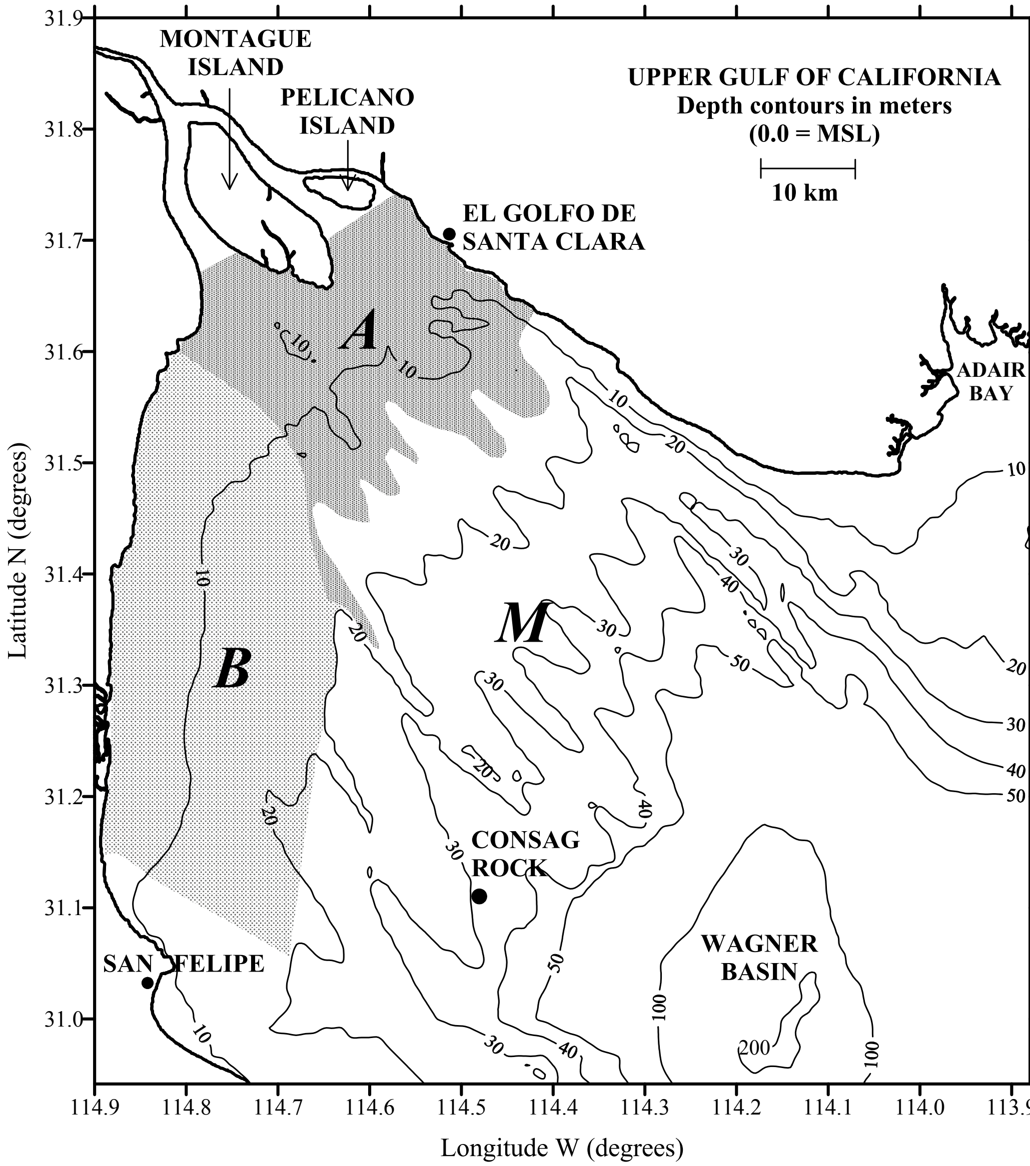

Figure 9. Proposed classification of tidal ridge segments: (A) active, (M) moribund, (B) buried.

direction similar to that observed at sites C1–C4.

(2) Moribund ridges, represented by the deeper segments with crests at depths down to ~40 m, where the M_2 tidal currents are at present less than 0.5 m·s^{-1}.

(3) Burial stage ridges, a condition that follows after the moribund stage, such as ridges on the western side of the Upper Gulf, off Baja California, where they have been partially covered by silt and clay deposits. All the ridges are thought to have developed as continuous structures resulting from marine transgression that left behind older segments of the tidal sand ridges. The reported high sand content in samples from deeper sections of the ridges provide evidence of the relict bed load sand deposits formed during lower sea level stages.

According to Huthnance (1973) the sand bank orientation that eventually predominates may be susceptible to external influences such as the trend of the coastline. It has been shown that differential erosion of the sea bed reflects the strikes of the fault lines over wide areas (Belderson *et al.*, 1982). The linear trends of microseismic epicenters near the two prominent ridges shown in Figure 6 support this idea. Interaction with tides is thought to involve erosion linked to active fault lines along which preferential sediment erosion occurred. This process is more efficient because tidal currents are almost parallel to the trend of the ridge-trough system. The proposed role of tidal currents preserves the old erosive features such as the steeper walls of the troughs next to the two largest ridges.

4.1. Active faults, bathymetry and seismicity

Recognizing active faults within the Upper Gulf of California is complicated. Through the combination of high resolution bathymetry, seismic reflection, and with the known seismicity in the area it is possible to delineate the trace of active faults. Based upon the high resolution bathymetry (Figure 4), seismicity records from Thatcher and Brune (1971) and RESNOM (Figure 3) and a PEMEX seismic reflection section (Figure 7) it is also possible to trace some of the active faults that bound the Wagner Basin, as well as those formed by the extensional regime within the basin and described by Persaud *et al.* (2003).

The location of two major tidal ridges within the Upper Gulf may be influenced by tectonic activity. The superposition of bathymetry, earthquake epicenters and faults delineated from seismic reflection profiles suggest that the two more prominent ridge-trough systems (C, D in Figure 6, 8) represent a surface signature of active geologic structures and reflect the geometry of the basement within the Wagner Basin. The notion that bottom relief is a surface manifestation of the tectonic activity is supported by the new data set presented here. It stands as further indirect evidence pending subsurface mapping of the Upper Gulf seafloor, a survey that should be encouraged.

5. Conclusions

Recent bathymetric data show a system of nearly parallel ridges and troughs that dominate the sea bed relief of the Upper Gulf of California, some of which can be traced for up to 50 km. Morphologic, sedimentary and hydrodynamic evidence indicate that ridges off Baja California are in a burial phase, while those at the north end, in water depths less than ~15 m, are still active ridges under the present tidal currents and bed load transport regime. Deeper portions of the ridges are thought to be in moribund stage, remaining as relict features formed during lower sea level stages. While the tidal origin of the ridges is clear, the location of two outstanding ridge-trough systems revealed a combined hydrodynamic, sedimentary and tectonic origin based on superposition of bottom relief, microseism epicenters and delineation of faults from seismic reflection profiles.

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