Stratigraphy and structure of the Altar basin of NW Sonora: Implications for the history of the Colorado River delta and the Salton trough

Martín Pacheco[1], Arturo Martín-Barajas[1,*], Wilfred Elders[2], Juan Manuel Espinosa-Cardeña[1], Javier Helenes[1], and Alberto Segura[3]

[1] División de Ciencias de la Tierra, CICESE, Km 107 Carr. Tijuana-Ensenada, Ensenada, Baja California, Mexico.
[2] Department of Earth Sciences, University of California, Riverside, CA 92521, USA.
[3] Activo Regional de Exploración, Región Norte, PEMEX, Poza Rica, Veracruz, Mexico.
amartin@cicese.mx

ABSTRACT

The Altar basin in northwestern Sonora, Mexico, is a subsidiary basin forming a now inactive part of the Colorado River delta. Its sedimentary record illustrates how the delta prograded in the last 4–5 Ma over a late Miocene, structurally distinct, marine basin at the northern end of the Gulf of California. Our interpretation of outcrop data, and data from seven exploratory wells, six analog seismic lines of Petróleos Mexicanos (PEMEX), and magnetic and gravity surveys from various sources indicates the existence of three sedimentary sequences, A, B, and C, which can be correlated at regional scale and have a thickness >5 km at the basin depocenter. The lower sedimentary sequence A is a shale unit representing open marine conditions (outer neritic). It grades into a thick sequence of interstratified mudstone, siltstone, and sandstone (sequence B), which grades in turn into poorly consolidated sand (sequence C). Extensive outcrops of a sandy, cut and fill succession exposed along the coast of Sonora are consistent with sequences B and C being the sub-aqueous and the sub-aereal parts of the delta, respectively. A contact at the base of the sequence A, where pre-marine continental deposits are missing, and where the marine sequence overlies crystalline basement, is interpreted as tectonic transport along a top-to-the-northwest detachment fault. The Altar basin became inactive as result of the westward shift in the locus of tectonic activity from the Altar fault to the Cerro Prieto fault, coupled with realignments in the course of the Colorado River during Pleistocene time.

Key words: stratigraphy, rifting, Colorado River delta, Altar basin, Gulf of California.

RESUMEN

El Desierto de Altar en el noroeste de Sonora, contiene una cuenca subsidiaria ubicada en la parte inactiva del delta del Río Colorado. El registro sedimentario ilustra cómo el delta progradó sobre una cuenca marina estructuralmente independiente del Mioceno tardío, hacia la terminación norte del Golfo de California. La interpretación de datos de afloramientos, datos de siete pozos exploratorios y seis líneas sísmicas analógicas de Petróleos Mexicanos (PEMEX), además de datos magnéticos y gravimétricos compilados de diversas fuentes, indican la existencia de tres secuencias sedimentarias, A, B y C, con más de 5 km de espesor y con una distribución de escala regional. La secuencia inferior (secuencia A) es una unidad de lutita marina de ambiente nerítico externo. Esta unidad grada a una potente secuencia de lodolita, limolita y arenisca (secuencia B), la cual a su vez grada a una secuencia de arena poco consolidada (secuencia C). Las secuencias B y C se interpretan como parte del sistema submarino y subaéreo, respectivamente, que progradó hacia la cuenca marina. Afloramientos de una secuencia arenosa de corte y relleno, interpretada como depósitos fluviodeltaicos y expuesta a lo largo *de la costa de Sonora, son consistentes con una interpretación en donde la secuencia C forma parte de la planicie fluvial del Río Colorado. El contacto discordante de la base de la secuencia A sobre el basamento cristalino y la ausencia de depósitos premarinos se interpreta como el resultado del transporte tectónico a lo largo de una falla de despegue con transporte de la placa superior hacia el nor-noroeste. La subsidencia en la cuenca de Altar cesó debido al cambio en la localización de la actividad tectónica de la falla Altar a la falla Cerro Prieto, así como al cambio en el cauce del Río Colorado hacia el Valle de Mexicali durante el Pleistoceno.*

Palabras clave: estratigrafía, rifting, delta del Río Colorado, Cuenca de Altar, Golfo de California.

INTRODUCTION

The Colorado River delta largely fills the depression known as the Salton trough, comprising the Imperial Valley, in Southern California, and the Mexicali Valley, in northern Baja California (Figure 1). The trough is traversed by active faults associated with the southern San Andreas fault system and the Gulf of California extensional province, and so the Colorado delta is somewhat unique among the world's major deltas in being structurally confined and lying across a major plate boundary between the Pacific and North American plates (Figure 1) (Elders, *et al.*, 1972; Lonsdale, 1989). The delta also contains a record of the erosion of its source in the Grand Canyon and Colorado Plateau in Arizona (Winker and Kidwell, 1996, and references therein; Elders *et al.*, 2001; Hunt and Elders, 2001). However, to date, no synthesis of the geological structure and history of the whole delta had been possible because some areas are still poorly known. Therefore, we used data from onshore wells and seismic reflection profiles from PEMEX (national petroleum company of Mexico), and from magnetic and gravity surveys, to gain insight into the sedimentation and structure associated with this transform fault plate margin and its relationship to the geological history of the Grand Canyon and Colorado River (Elders *et al.*, 2003; Espinosa-Cardeña and Elders, 2003).

The Altar basin in northwestern Sonora shares a common history with other basins within the trough, and therefore exemplifies basin evolution in this tectonic environment. Each of these basins has experienced the effects of three main geological events: 1) an initial period of extension and subsidence; 2) an intermediate stage of marine sedimentation; and 3) a later stage of basin filling, largely dominated by the growth of the Colorado River delta, and to a lesser extent by alluvial deposits from the basin margin. Where age constraints for these three geologic events exist, the onset and end of this sequence differs from basin to basin, depending on its position relative to major depocenters and on the configuration of the delta complex. The construction of the Colorado River delta isolated the Altar basin and the northern gulf from basins located to the north and west within the Salton trough. Also, in the north-central part of the trough, the growth of the delta produced lacustrine environments that were periodically flooded by discharges of the Colorado River (Dibblee, 1984; Winker and Kidwell, 1996).

Besides sharing a complex structural control, the individual basins also share an early stage dominated by marine deposits, framed by basin-margin alluvial deposits, which predated rapid deltaic progradation into the marine basin. However, marine conditions may have persisted on both flanks of the delta because the rift margins continued to widen and subside. The Altar basin, east of the active modern delta (Figure 1), is a good example of an abandoned basin, whereas the Laguna Salada to the west is a good example of a still active basin (Dorsey and Martín-Barajas, 1999; Martín-Barajas *et al.*, 2001), although both are the result of changes in the locus of tectonic deformation. On the Sonoran side of the gulf, less is known about the timing of major subsidence and the stratigraphic record produced by the three major geological processes of transtensional tectonics, proto-gulf marine sedimentation and deltaic progradation.

The Altar basin covers an area between San Luis Río Colorado and Bahía Adair in northwestern Sonora (Figure 2). It is assumed that this area was once part of the delta complex, although the surface of the Altar basin is now above the level susceptible to flooding by the Colorado River and is an extensive eolian dune field. Until now, no stratigraphic data had been published to interpret the nature of the basin fill, inferred to be at ~5 km depth (Sumner, 1972).

Exploratory seismic reflection surveys and drilling for hydrocarbons and geothermal resources have produced a large amount of data, which for many years remained unpublished, apart from a few preliminary reports (PEMEX, 1985; Guzmán, 1981). In this paper, we integrate data from the Altar basin that include seven well logs and six analog seismic lines (Figure 2). Additionally, we use the gravity and magnetic anomalies to interpret the structure of the Altar basin. We also studied the sedimentology of outcrops along the western margin of the Altar basin (Figure 2) to gain insight of the sedimentary environments for the uppermost part of sequence. Then, we contrast our model of the structure and stratigraphy of Altar basin to other co-genetic basins located to the west and northwest in the Salton trough, and finally, we discuss the tectonic implications of

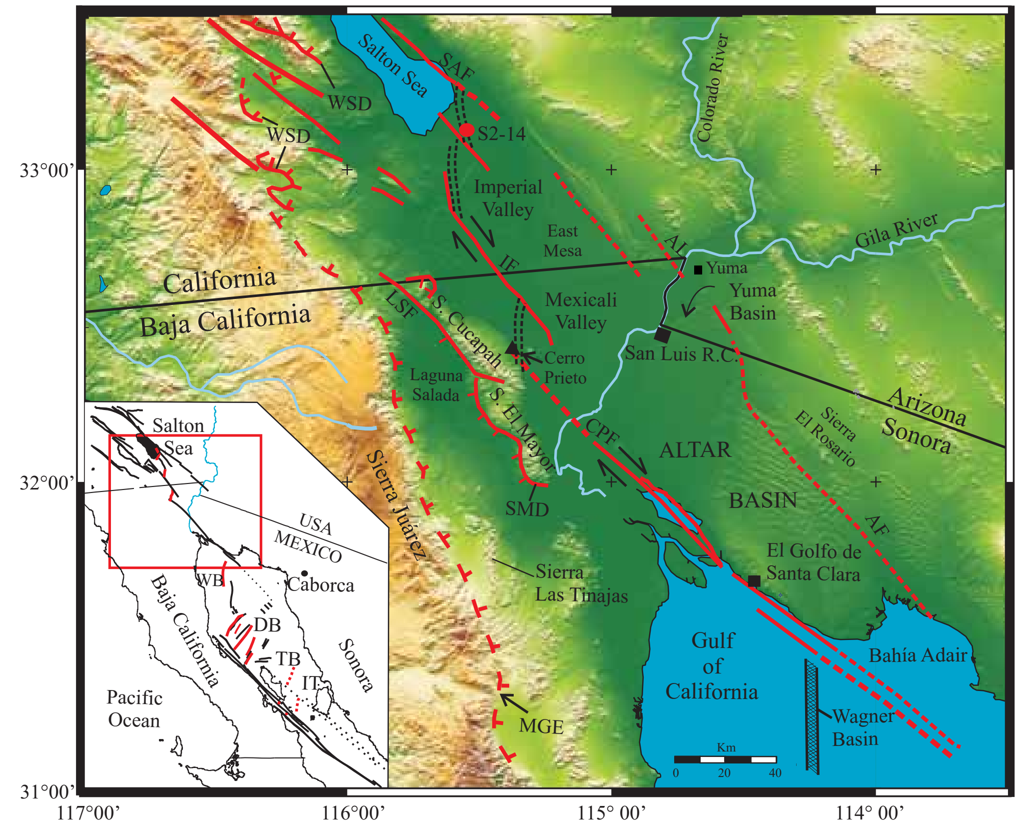

Figure 1. Digital elevation model (DEM) map, and main tectonic features in the northern Gulf of California and Salton trough regions. The figure shows the lower course of the Colorado River and delta, and the main physiographic and structural features. AF: Altar fault, AL: Algodones fault, CPF: Cerro Prieto fault, IF: Imperial fault, LSF: Laguna Salada fault, MGE: main Gulf escarpment, SAF: southern San Andreas fault, SMD: Sierra Mayor detachment, WSD: western Salton detachment, S2-14: well State 2-14. The inset map shows the main structural features in the northern Gulf of California, DB: Delfin basin, IT: Isla Tiburón; TB: upper Tiburón basin; WB: Wagner basin.

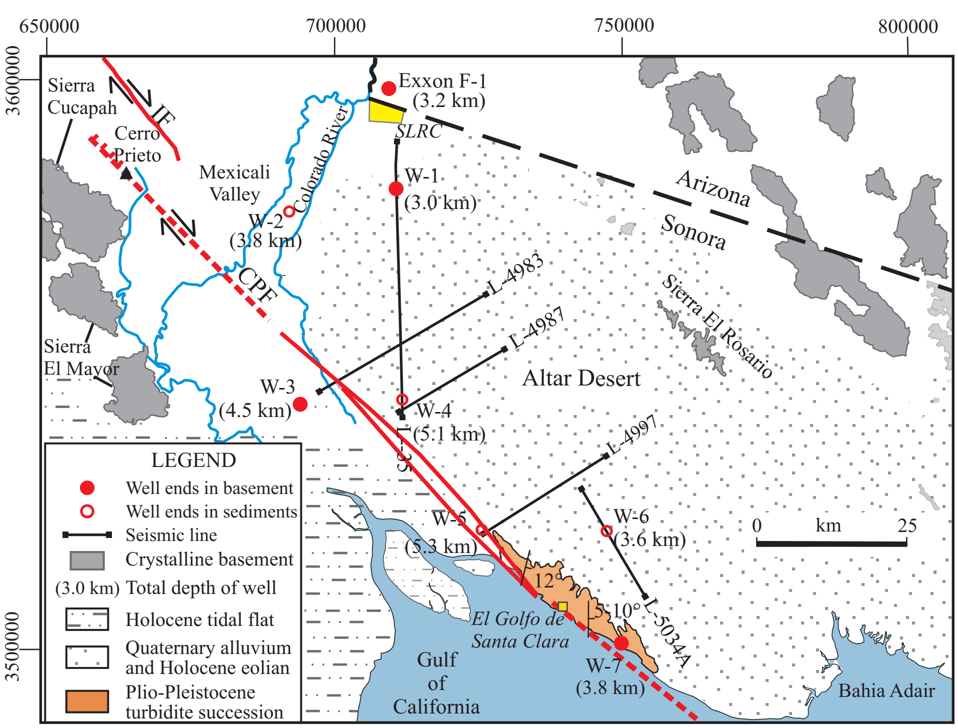

Figure 2. Simplified geologic map of northeastern Baja California and northwestern Sonora, and the modern delta of the Colorado River. Exploration wells and seismic reflection lines studied here are from PEMEX. Exxon F-1 is well Exxon-Federal #1 drilled in the Yuma basin (Eberly and Stanley, 1978). CPF: Cerro Prieto fault, IF: Imperial fault, SLRC: San Luis Río Colorado.

our results. We first present a summary of the tectonic and sedimentary background, which is necessary to understand the conceptual model proposed here.

TECTONIC AND SEDIMENTARY BACKGROUND

Onset of extension in the northern Gulf of California Extensional Province

Major pulses of Cenozoic extension in northern Sonora include development of detachment faults and metamorphic core complexes in late-Oligocene to middle-Miocene times (Nourse *et al.*, 1994). Continental basins in central Sonora are capped with middle-Miocene basaltic flows (McDowell *et al.*, 1997). No time constraint for the onset of extension has been reported for the area west of Caborca, nor in the Altar Desert (Figure 1). However, the northwest trending Basin and Range physiography (Figure 1) suggests that this area has undergone a large amount of extension similar to that documented in northern Sonora and southwestern Arizona.

In southwestern Arizona, a pulse of extension that has been named "late-Miocene block-faulting episode" (Eberly and Stanley, 1978), produced Basin and Range structures and thick continental and lacustrine deposits with local marine intervals in the Yuma basin (Figure 1) between ~13 and >10.5 Ma (Eberly and Stanley, 1978). This is consistent with the post-17 Ma age for widespread normal faulting in the Yuma area proposed by Spencer *et al.* (1995). The age of the Altar basin is not well constrained, but, owing to its proximity to the Yuma area, we consider a late- to middle-Miocene age as the most likely time for the onset of extension in the basin.

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 Sierra Juárez (Lee *et al.*, 1996; L. Forsythe, unpublished ages). In the southern end of Laguna Salada, trachyandesite lava flows from Sierra Las Tinajas were emplaced at ~10.5 Ma, and they overlie three continuous, welded to unwelded tuffs dated at ~12 Ma (Mendoza-Borunda *et al.*, 1998). These lava flows and tuffs are cut by a series of east- and west-dipping normal and oblique faults (Mendoza-Borunda *et al.*, 1995, 1998) and provide maximum age for the onset of extension along the Main Gulf Escarpment in Baja California. Additionally, exhumation ages of crystalline rocks on Sierra El Mayor at the western edge of the delta plain constrain the early uplift of this intra-rift crystalline block between approximately 15 and 10 Ma beneath a detachment fault (Axen *et al.*, 2000).

In the southwestern Salton trough, an early- to middle-Miocene period of continental sedimentation occurred during the emplacement of arc-related lava flows of the Alverson Volcanic unit (22–14 Ma) (Kerr, 1984). This early phase of weak extension preceded a late-Miocene phase of high-magnitude extension and rift-basin development along a top-to-the-east detachment fault system (Axen and Fletcher, 1998; Winker and Kidwell, 2002). This detachment system changes polarity to the south in the Laguna Salada basin (Axen, 1995), and both detachments were coeval with strike-slip faults of the San Andreas system (Axen *et al.*, 1999).

In summary, onset of extension in the area now occupied by the Altar basin may have occurred sometime after ~16 Ma, which is suggested by field data on both rifted margins of this basin. However, little evidence exists for the timing of strike-slip motion transference into the northernmost part of the gulf, and of full establishment of modern wrench tectonics along the Cerro Prieto fault zone (*c.f.*, Stock and Hodges, 1989). Low-angle normal faults and transtensional faults may have co-existed in the western Salton trough and the Laguna Salada basin (Axen and Fletcher, 1998; Axen *et al.*, 1999). The Altar basin thus lies between two detachment fault systems of distinctly different age: (1) the late-Miocene Salton trough (and Laguna Salada) detachment to the west, and (2) an older detachment system in central Sonora and southwestern Arizona (Eberly and Stanley, 1978; Nourse *et al.*, 1994; Spencer *et al.*, 1995).

The proto-Gulf of California

The concept of a proto-gulf was first used by Karig and Jenski (1972) to refer to the early period of extension in the Gulf of California, an analog to other "volcano-tectonic rift zones associated with an active trench-arc system". Subsequently, the term proto-gulf has been used indiscriminately as a synonym for the presence of early basins and marine incursion in the gulf area (Gastil *et al.*, 1975; Stock and Hodges, 1989), and to name the early period of orthogonal extension and basin development (Dokka and Merriam, 1982; Henry and Aranda-Gómez, 2000; Roldán-Quintana *et al.*, 2004). We use the term proto-gulf extension, as defined by Henry and Aranda-Gómez (2000), to name the extensional event that affected the entire Gulf Extensional Province (GEP) from ~12 to ~6 Ma. This event is the result of the partitioning of strain in strike-slip faults in the Pacific margins offshore Baja California and extensional faults within the GEP (*c.f.*, Stock and Hodges, 1989). The upper limit for the proto-gulf stage is placed at 7–6 Ma, when the plate boundary became localized in the gulf area and the modern transform fault system developed (Curray and Moore, 1984; Lonsdale, 1989; Oskin *et al.*, 2001).

A middle-Miocene age for the proto-gulf marine basins at Isla Tiburón was suggested by Gastil and Krumennacher (1977) and Gastil *et al.* (1999). However, Oskin and Stock (2003) determined a younger age for the marine section in Isla Tiburon (<6.2 Ma), and proposed that the marine incursion in the northern Gulf of California occurred after 7 Ma, when the boundary between the Pacific and North American plates moved fully into the gulf region. This is consistent with published ages of the oldest marine deposits cropping out in the northern Gulf of California and Salton trough areas as being younger than 7.4 Ma (Quin and Cronin, 1984; Dean, 1996; McDougall *et al.*, 1999; Martín-Barajas *et al.*, 2001). Nevertheless, the possibility of an older age for the first marine incursion cannot be completely ruled out. Paleontological evidence of reworked microfossils of middle-Miocene age identified in some localities with late-Miocene to Pliocene marine sequences, and discrepancies in chronological distribution of key microfossil species (J. Helenes, A.L Carreño, unpublished data; Lozano-Romen, 1975; Gastil *et al.*, 1999; Helenes and Carreño, 1999; Delgado-Argote *et al.*, 2000; Kris McDougall, personal communication) maintain the argument for a somewhat older marine incursion in the northern gulf region. Additionally, ongoing biostratigraphic studies of cutting samples from a PEMEX well in the upper Tiburón basin, indicate the presence of middle-Miocene marine microfossils at depth (Helenes *et al.*, 2005).

The delta of the Colorado River

Field studies in the western Salton trough and NE Baja California indicate that Pliocene-Pleistocene fluvio-deltaic deposits from the Colorado River prograded over late-Miocene to early-Pliocene marine deposits (Johnson *et al.*, 1983; Dibblee, 1984; Winker and Kidwell, 1986; Dorsey and Martín-Barajas, 1999; Martín-Barajas *et al.*, 2001). The change from marine to fluvio-deltaic environments was induced by the entry of the Colorado River into the northern gulf. The establishment of an integrated Colorado River occurred either by headward erosion (Lucchita *et al.*, 2001) or by lake overflow near Lake Mead (Spencer and Pearthree, 2001; Meek and Douglass, 2001); the course of the Colorado River below Grand Wash and the site of the Hoover Dam was established post 6 Ma and pre 4.8 to 4.3 Ma (Howard and Bohannon, 2001). This age interval marks the time when the upper Colorado River integrated its course to that of the lower Colorado, so drainage from the Rocky Mountains reached the Gulf of California and dramatically increased the sediment supply and the growth rate of the delta (Johnson *et al.*, 1983; Winker and Kidwell, 1986). However, the position and extent of the delta complex in early-Pliocene time is poorly constrained because of the complexities produced by the tectonic activity. Early Colorado River sediments recognized within the Wind Cave Member of the Latrania Formation, in the southwestern Salton trough, include a >200 m-thick submarine fan turbidite sequence dated at the transition between late Miocene and early Pliocene (Winker and Kidwell, 1996; Dorsey *et al.*, 2005). This age constraint in the Salton trough can be extrapolated to the Altar basin because its depocenter was closer to the Split Mountain area in early-Pliocene time. We can infer 175 to 200 km of tectonic restoration assuming that most of this displacement occurred by dextral shear between the Cerro Prieto fault and the Main Gulf Escarpment in southeastern California and Baja California (Winker and Kidwell, 1986, 1996) (Figure 1).

DATA SET AND METHODS

Gravity and magnetic data

We made a compilation of gravity and magnetic data covering the Mexicali valley, Mesa Sonora and southern Arizona to produce magnetic and gravity anomaly maps (Figures 3a and 3b, respectively). All gravity data were merged and reduced to Bouguer gravity anomalies using the 1971 international gravity formula (Morelli, 1976), a reduction density of 2.67 g/cm^3, and a datum plane at mean sea level. Terrain correction was available for most of data. The merged data were then gridded at an interval of 2.5 km and contoured to produce a Bouguer gravity anomaly map. Magnetic data over parts of northern Sonora and northern Baja California were obtained from a digital magnetic anomaly database of North America (USGS, 2002). This data base resulted from leveling and merging aeromagnetic surveys from the U.S. Geological Survey, and Consejo de Recursos Minerales (Finn *et al.*, 2001). The data are gridded to a spacing of 1 km and continued to an elevation of 3.5 km above the terrain.

Seismic profiles

PEMEX made six large-format, analog seismic profiles available to this study (Figure 2). These seismic profiles were originally processed in the early 1980's at the Instituto Mexicano del Petróleo. The seismic profiles are 48 fold and six seconds of register. The filters applied to the raw data affected the higher frequencies and render the upper 0.3 seconds (two-way travel time, TWTT) practically useless. Although these seismic lines are of medium quality, they show little coherent noise (multiples) so that the boundaries of the major sedimentary sequences could be traced and interpreted in this study.

Well data

Interpretation of digital and analog well logs from seven exploratory wells (Figure 2) allowed us to interpret the lithostratigraphy of the Altar basin from gamma ray (GR), self-potential (SP) and resistivity logs, and from the mud-log reports (Serra, 1984; PEMEX, unpublished well reports). The petrographic descriptions of several sediment cores helped calibrate the response of the well logs to the lithology.

For each PEMEX well, we computed a velocity profile from stacking velocities and used it to convert depth

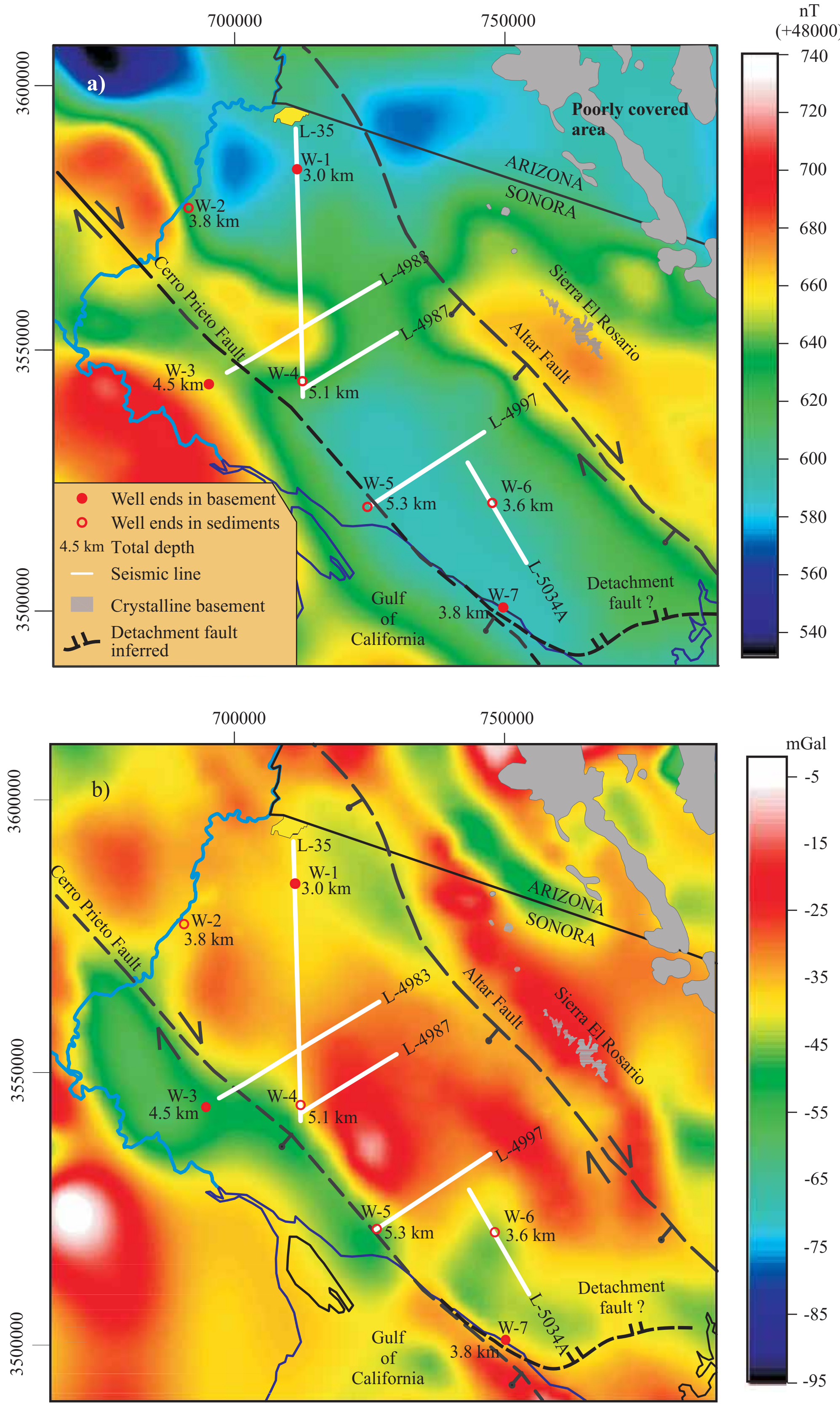

Figure 3. a) Magnetic anomaly map of the northern Gulf of California, northwestern Sonora, and southern Arizona. The Altar basin is clearly imaged by a broad magnetic low bounded to the east by a northwest trending magnetic gradient inferred to be produced by the Altar fault and the rise of crystalline basement. b) Bouger anomaly map showing northwest trending lineations in the Altar basin, which include a local gravity high north of well W-5. Note the elongated gravity low west of the Cerro Prieto fault.

to time in order to incorporate the well stratigraphy into the nearest seismic profiles. As the seismic digital data are not available to us, we used the method of Metcalf (1981) to estimate the interval velocity, the average velocity, and the cumulative depth to any given horizon as defined with pairs of TWTT and normal move-out velocity (NMO). The method uses the equations developed by Dix (1955) (see Appendix 1 for details).

Geologic mapping at El Golfo de Santa Clara

Extensive outcrops of the upper ~200 m of the sedimentary section where studied along the shore centered at El Golfo de Santa Clara (Figure 2). These outcrops provided useful stratigraphic and sedimentological information to interpret and constrain the depositional environments of the uppermost sequence along ~25 km of outcrop. Selected samples where also investigated for microfossil content.

RESULTS

Structure of the Altar basin

The Altar basin is bounded by two major oblique normal faults on its eastern and southwestern side. Both, the Altar and Cerro Prieto faults, are inferred to have significant dextral offset, but both drop the southwestern side down (Figures 3a, 3b). The southeastern edge of the Altar basin is a north dipping detachment fault that was active while most of the sedimentary sequence deposited (see below).

In our gravity and magnetic maps, the Altar basin is defined by a broad magnetic low, interrupted to the NW by a local magnetic high north of W-4, and bounded to the east by a positive magnetic lineation related to basement rocks merging into the NW-oriented range of Sierra El Rosario (Figure 3a). This range, composed of pre-Tertiary metamorphic and granitic basement rocks (Figure 2), clearly produces the magnetic and gravity highs that bound the basin to the east. On the basis of 2-D modeling of aeromagnetic data and localized gravity data, Sumner (1972) proposed a large NW-trending, west-dipping fault as the eastern structural boundary of the Altar basin, which we name here as the Altar fault. This structure is also inferred from the gravity and magnetic lineations that project from Bahia Adair toward the NW (Figures 3a, 3b), and by a subtle apparent dextral displacement of the magnetic and gravity highs. The northwest-trending magnetic and gravity gradients, and the horizontal displacement suggest continuation of the Altar fault to the northwest, where it is co-linear to the Algodones and San Andreas faults in the eastern edge of the Salton trough (Figure 1).

In the gravity and magnetic anomaly maps, the Cerro Prieto fault zone apparently bounds the northwest trending anomalies (Figures 3a, 3b). This fault zone crudely marks the western boundary of the magnetic low related to the Altar basin, but also bounds an elongated gravity low west of the fault trace (Figure 3b). To the south, a gravity high separates the southeastern end of the Altar basin from a gravity low in the northernmost gulf. Within the Altar basin, a gravity high with no associated magnetic anomaly is present to the north of well W-5. The NW-trending, high magnetic anomalies northwest of the Altar basin and southeast of the Nuevo León magnetic anomaly (Goldstein *et al.*, 1984) suggest the presence of basaltic intrusions along of the Cerro Prieto fault, although well W-3 cut Cretaceous granitic basement at 4.5 km depth in a zone with a gravity low.

An uplifted alluvial terrace up to 130 m high and the exposures of the ancient delta in ravines along the shore at El Golfo de Santa Clara indicate current tectonic uplift of the southwestern Altar basin along the trace of the Cerro Prieto fault zone (Ortlieb, 1991). This uplift is also consistent with subsidence produced by the Cerro Prieto fault in the basin southwest of the modern shoreline (Hurtado-Artunduaga, 2002; Sánchez-Guillén, 2004).

Stratigraphy of the Altar basin

Well logs in the Altar Desert and the eastern part of the Mexicali Valley indicate three main sedimentary sequences, which in some cases overlie crystalline basement (Figure 4). The scant paleontological data available from well samples of the older sequence help document the paleoenvironments and determine the age of deposition. However, age correlation between wells is not possible at this stage because age constraints are insufficient. Therefore we base our correlation on lithostratigraphic criteria, realizing that these facies could be laterally diachronous and may represent a more diverse and complex assemblage of sedimentary environments than the suggested here.

Basement rocks

Wells W-1, W-3, and W-7 bottomed in late-Cretaceous to early-Tertiary granitic rocks (Figure 4). The crystalline basement in well W-1 is a grey-greenish biotite granodiorite, with plagioclase, potassic feldspar and quartz. A K-Ar age in K-feldspar concentrate was reported as 63±5 Ma (PEMEX, 1985). The basement rock cut in well W-3 is a granodiorite, reported as having the same mineralogy as the basement in well W-1, but with less chloritized biotite; the K-Ar age reported for K-feldspar concentrates was 59±5 Ma. The crystalline basement in well W-7 consists of a biotite-muscovite-hornblende-garnet-bearing granitic rock, with quartz and K-feldspar; this rock has mildly granoblastic texture and is highly fractured, containing hematite as fracture fill, which could reflect deformation at and beneath the Altar detachment fault. The reported K-Ar ages in K-feldspar concentrates varies from 79±5 Ma to 61±5 Ma (PEMEX, 1985). Although these reported ages have large errors, we are confident that these three wells terminated in late-Cretaceous to

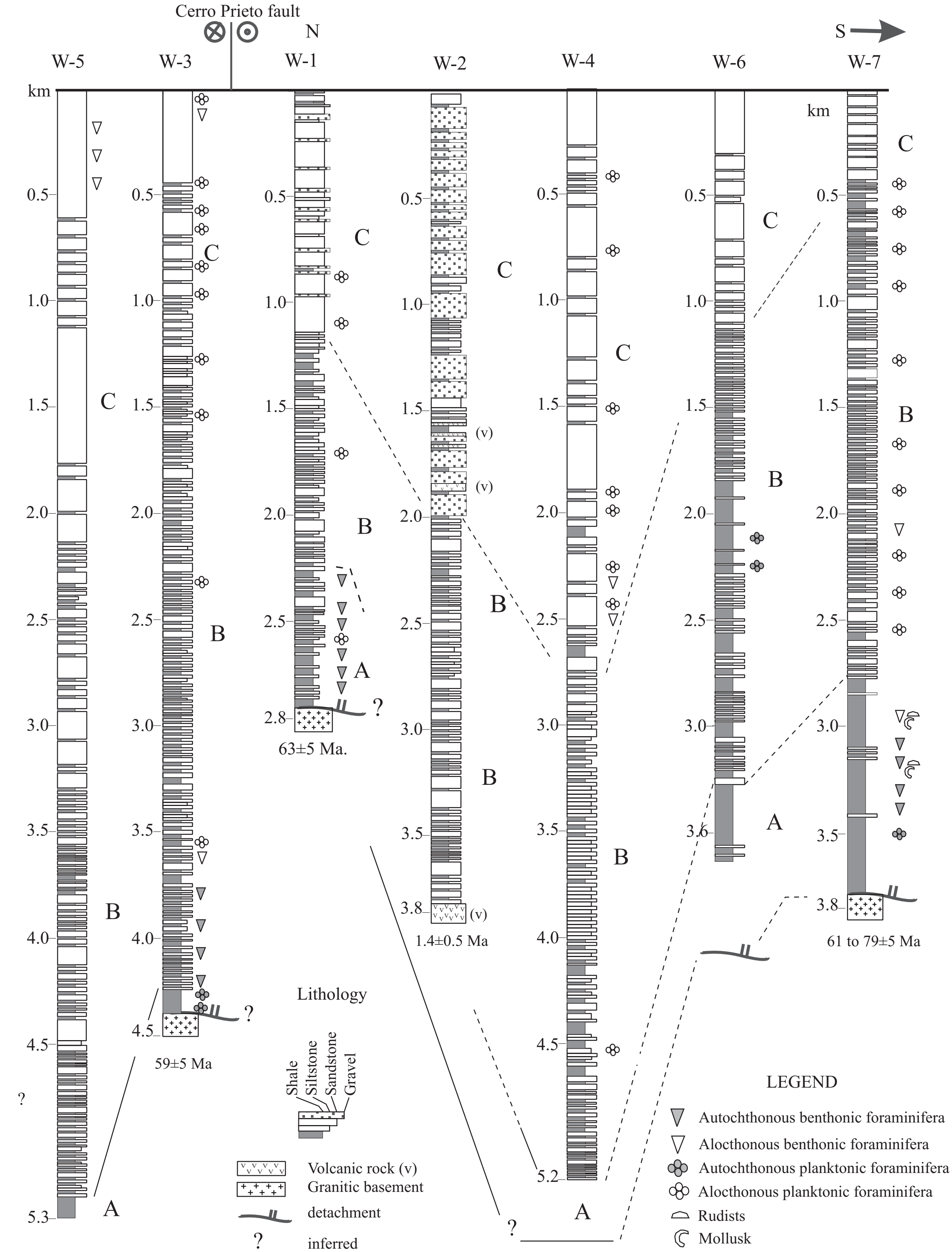

Figure 4. Stratigraphic logs interpreted from PEMEX well-log data. These wells comprise a basin fill sequence with the lower marine shale unit (sequence A) overlying Late-Cretaceous granitic basement. Sequence boundaries on each well are arbitrarily defined by an increase in the sand to mud ratio, and by microfossil assemblage between sequence A and sequence B. See figures 2 or 3 for location.

early-Tertiary granitic and metamorphic basement rocks and not in late-Cenozoic magmatic intrusions. However, well W-2 ends in a young volcanic intrusion, which classified as quartz-bearing andesite in the petrographic report by PEMEX. This rock was dated in 1.4±0.5 Ma by PEMEX (K-Ar in feldspar separates). The magnetic high west and southwest of well W-2 and the gravity high around it may reflect mafic magmatism in the area.

Sequence A. Marine shale

The lower stratigraphic sequence is a gray-black, well-indurated, mildly calcareous shale, with subordinate siltstone beds. This unit directly overlies granitic basement in three of the wells (Figure 4), and has a thickness of >1,000 m in well W-7, ~500 in well W-6, and ~500 m in well W-1 (Figure 4). The upper part of this mudstone sequence was also cut at depth in well W-5 (Figure 4).

The upper boundary of sequence A is transitional and is arbitrarily defined by an increase in silt and sand layers in the shale unit in each well. The shale lithofacies produce "cylinder-type" electrosequences, 5 to 30 m thick, separated by relatively thick (1–2 m) siltstone to sandstone beds as defined in the Spontaneous Potential (SP) logs (Figure 5a). The silt and sand layers within the shale unit produce "funnel-shaped" electrosequences (*e.g.* grain size increasing up-section), similar to the distinctive pattern of sequence B shown in the Gamma-ray (GR) and induction (IL) logs of Figure 5b.

Sequence B. Mudstone-sandstone sequence

The lower marine shale sequence progressively grades up-section into alternating mudstone-siltstone and sandstone beds. The regular increase in abundance of siltstone and sandstone beds marks the base of sequence B, a lithologically distinctive sequence with a thickness ranging from ~600 m in well W-6, to ~2,300 m in well W-3 and W-7 (see Figure 4).

Sequence B is composed of regularly inter-bedded, poorly cemented, fine-grained sandstone, siltstone and mudstone. Mudstone and siltstone beds are more abundant both towards the base and top of sequence B. The well logs show meter-scale, funnel-shaped and bell-shaped electrosequences, which specifically are abundant toward the upper part of sequence B. The funnel-shaped electrofacies represents upward-coarsening intervals, whereas the bell-shaped electrofacies represents upward-fining intervals (Figure 5b). However, this sequence also includes very thick sandstone intervals, up to 100 m thick (see well W-2), and mudstone intervals that can reach up to 400 m in thickness (see well W-6 in Figure 4).

Sandstone beds are composed of light grey to tan-colored, quartz-rich, poorly consolidated sands, whereas mudstone beds are composed of grey to black, indurated to poorly indurated, slightly calcareous mudstone.

Sequence C. Sandstone sequence

Moving up-section, the stratigraphy of the Altar basin is characterized by a substantial increase in the proportion of sand relative to mud and silt (Figure 4). Sand intervals are progressively thicker and include conglomerate deposits and subordinated mud-silt strata in wells located to the north. This coarse-grained, poorly-consolidated, sedimentary lithofacies is distinctive of sequence C, which varies in thickness from well to well, and reaches up to 2,970 m in well W-4, and 3,460 m in well W-5 (Figure 4). The smallest thickness is recorded in wells W-1 and W-6, located the

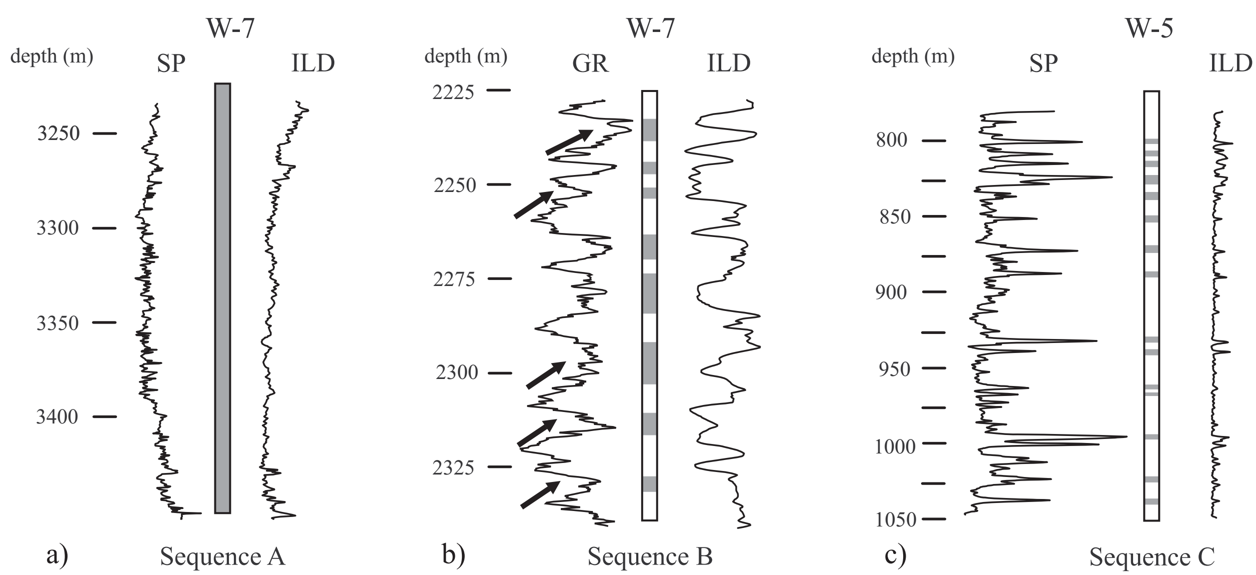

Figure 5. Example of well-log response to lithologic composition of sediments. a) shale interval of sequence A with cylinder-type electrofacies punctuated by silt-sand intervals; b) distinctive bell-shaped and funnel-shaped electrofacies in sequence B representing fining-up and coarsening-up parasequences, respectively. c). Cylinder-type electrofacies representing amalgamated sand and gravel deposits punctuated by fine-grained sediment intervals. GR: gamma-ray log, ILD: induction log; SP: spontaneous potential log.

farthest north and east from the Cerro Prieto fault zone, respectively (Figure 2).

Sand and gravel intervals show distinctive blocky-type electrofacies, with a saw-tooth shape, and low SP values in the well logs (Figure 5c). Individual sand and gravel intervals are 3 to 40 m thick and are separated by thin beds of muddy silt. Locally, fine-grained deposits are up to 2 m thick, and usually mark the boundary of a thick sand interval. Conglomerate deposits within sequence C are conspicuous in wells W-1 and W-2 (Figure 4). Well W-1 contains conglomerate beds alternating with sand deposits in the upper 1,000 m of the sequence. The conglomerate deposits are regularly interstratified, whereas in well W-2 the gravel facies dominates in the upper 1,900 m of the sequence.

Volcanic deposits are interstratified in gravel deposits between the 1,550–1,880 m depth interval in well W-2. This well is located ~45 km east of the Cerro Prieto volcano (Figure 2). The volcanic deposits are lithic tuffs, for which no age dating is so far available. This well also bottomed in andesite rocks dated at 1.5±0.5 Ma (K-Ar in plagioclase concentrate), but drill cuttings of sediments above this volcanic rock and well logs do not indicate any effects due to hydrothermal alteration, in spite of the proximity of this well to the Cerro Prieto geothermal field. No samples are available to define if this rock is an intrusive body.

Biostratigraphy and age of sequences

To assign tentative ages to the sequences, we used the information on planktonic microfossils (Appendix, Table A) reported by PEMEX (1985), as well as preliminary results of our new studies in two wells. To help interpret depositional environments of the sequences, we used the benthonic assemblages (Appendix, Table B) also reported by PEMEX (1985).

Sequence A

This marine unit was deposited during latest-Miocene to early-Pliocene time in inner to middle neritic environments. The presence of benthonic and planktonic foraminifera, calcareous nannofossils, and dinoflagellates indicate open marine conditions. The dominant environments at the time of deposition for the mudstone intervals are inner to middle neritic, as indicated by the presence of the benthonic foraminifera *Elphidium*, *Cibicidoides*, *Florilus*, *Trochammina* and *Brizalina subaenariensis*. The presence of few planktonic taxa also supports this interpretation.

Shales from this sequence contain some reworked older taxa, together with microfossils indicative of a Miocene age. The following are the paleontological evidences found in the interval representing this sequence in some of the wells. Preliminary results from calcareous nannofossils and palynology (J. Helenes and A.L. Carreño, personal communication) in well W-1 indicate an undifferentiated Miocene age (25.2–5.2 Ma) for the interval from 1,975 to 2,895 m, corresponding to sequence A. Additionally, a probable age of latest Miocene to Pleistocene was assigned to sequence A in this well on the basis of the presence of the calcareous nannofossils *Calcidiscus macintyrei* (Miocene, NN4 to lower Pleistocene, base of NN19; 18–2 Ma), *Reticulofenestra pseudoumbilica* (Miocene NN7 to Pliocene NN15; 12–3.5 Ma), and *Sphenolitus neoabies* (latest Miocene, NN1 to Pliocene, base of NN16; 6–3 Ma) (Pemex, 1985). Although, Perch-Nielsen (1985, fig. 7) consider that the first appearance of *S. neoabies* could be as early as middle Miocene (NN7; 12 Ma).

An age assigned as Miocene to lower Pliocene at 3,295–3,300 m in well W-7 is based on *Globigerinoides obliquus*. In well W-2, a probable age assigned as Pliocene to Holocene at 4,255–4,265 m is based on *Sphaeroidinella* sp.? (Bolli and Saunders, 1985). However, this taxon could be caved or represent deposition in late-Miocene time, because *Sphaeroidinella* has been reported in upper Miocene strata (Srinivasan and Srivastava, 1974). Also, the identification of the taxon is uncertain, and it could represent a species of the closely related genus *Sphaeroidinellopsis*, in which case the age range could go from middle Miocene to Holocene.

Sequence B

This marine sequence contains reworked common Cretaceous to early-Tertiary taxa indicative of Colorado River influence. Unfortunately there are no clear paleontological evidences to assign a more detailed age to this sequence. The sandy and silty intervals of this unit contain benthonic foraminifera such as *Ammonia* and *Elphidium*, together with abundant ostracods and fragments of mollusks.

Sequence C

Microfossil determinations in fine-grained samples from sequence C in wells W-1, W-3 and W-7 exclusively indicate reworking of Cretaceous and Paleogene planktonic and benthonic foraminifera. Five mudstone samples collected in El Golfo de Santa Clara (facies lm) are barren of calcareous microfossils and palynomorphs. However, we tentatively assign an undifferentiated Pliocene-Pleistocene age to this sequence because the palynological content found in samples from this sequence is similar to that reported for the upper strata in an exploratory well drilled by CFE in the Laguna Salada (Martin-Barajas *et al.*, 2001). This similarity, and the age of the reworked fossils, suggest that sequence C was deposited in Pliocene-Pleistocene time, with a strong Colorado River input.

Correlation and distribution of sedimentary sequences

Interpretation of six analogue seismic lines (Figure 2) and correlation using lithostratigraphy from wells indicate that sequences A, B, and C have a regional distribution, and represent the basin fill during the progradation of a sub-aqueous and possibly a sub-aereal part of the Colorado River delta over the late-Neogene marine basin. The conversion of depth to time in the well logs (Metcalf, 1981) allowed us to trace the first order boundaries between the main sedimentary sequences, as interpreted from well logs, on the seismic lines. The major sequence boundaries interpreted from well logs in well W-1 can be traced in the long north-south trending seismic line L-35 (Figures 6 and 7). This ~50 km long seismic line runs from near the apex of the modern delta toward the south, very close to the Cerro Prieto fault zone. It shows the long, continuous reflectors that overlie a sequence of sigmoidal reflectors dipping and down-lapping to the south (Figure 7). In this seismic line, sequence boundary 1 (SB1) marks the contact between the marine mudstone (sequence A) and basement rocks. This boundary is defined by a nearly continuous, high-impedance reflector, which gently dips to the south (Figure 7). Below SB1, reflectors are rather discontinuous and chaotic, although some parallel reflectors, interpreted as coherent noise, are visible. Well control (W-1) indicates that basement rocks lie 2.8 km beneath the surface at the site, corresponding to ~2.1 second (TWTT) in the seismic line (Figure 6), and closely match the strong reflector of the acoustic basement. Along this line to the south, the acoustic basement loses resolution, but dip directions of the overlying seismic reflectors and sequence boundaries 2 and 3 (SB2 and SB3) suggest that the basement is progressively deeper to the south (Figure 7).

In our interpreted seismic lines, sequence A is characterized by short and wavy, high amplitude reflectors, which gently dip in opposite directions (Figures 6, 7). Apparent imbrication of reflectors and large mound forms are distinctive features of this marine shale sequence. In line 5034A, seismic reflectors of sequence A appear to thicken toward south and are cut by a north-dipping reflector interpreted as a detachment fault above crystalline basement (SB1) (Figure 8).

In line L-35 (Figures 6 and 7), sequence B shows distinctive parallel, low-amplitude, discontinuous reflectors. Farther to the south, sequence B is a pattern of long and better-defined seismic reflectors interrupted by zones of prograding, down-lapping reflectors. These overlie lens-shaped parasequences and clinoforms with sigmoidal patterns interpreted to be sequence A (Figures 6 and 7). In line 5034A (Figure 8), stratigraphic control provided by well W-6 indicates that SB2 is located slightly above (0.1 ms) a strong and continuous reflector, which we interpret as part of sequence A in this seismic line. Below SB2 in seismic line 5034A (Figure 8), we see the distinctive reflector pattern of sequence A and a large wedge-shaped sedimentary unit with reflectors having an apparent dip to the south-southeast. This interpretation of the stratigraphic relationship suggests that the lower part of sequences A and B have non-uniform thickness, with thicker shale deposits toward the southeast. In this seismic line, the unconformity between sequence A and basement rocks is clear, and the basement becomes shallower towards the southern end of the line; in well W-7, the basement was penetrated at ~3,700 m where it appears altered and highly fractured beneath the detachment fault. This structural relationship between sequence A and granitic acoustic basement is suspicious because we might expect that marine deposits should overlie pre-transgressive continental deposits, as is documented in some other coeval basins in the Salton trough (Kerr, 1984; Kerr and Kidwell,

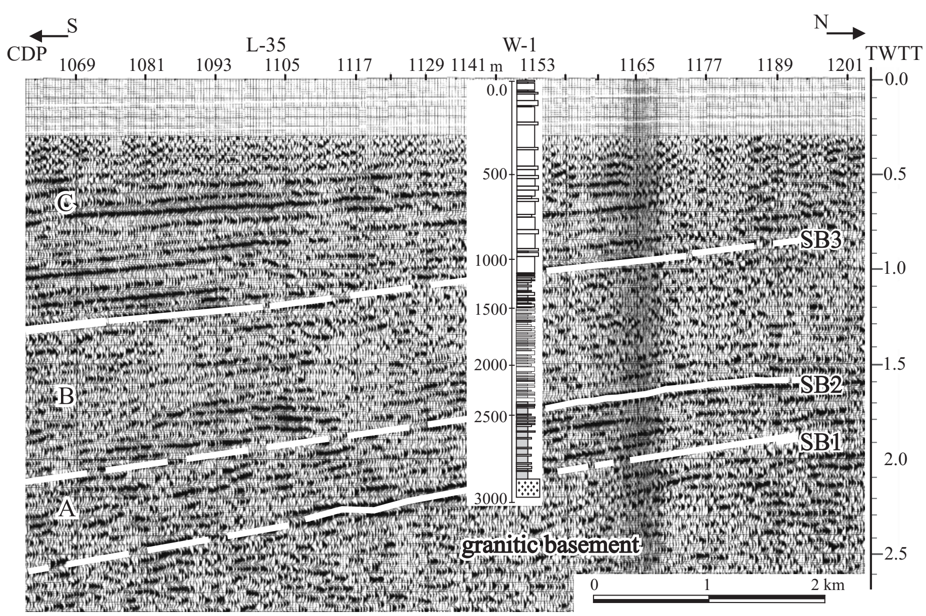

Figure 6. Northern end of seismic section L-35 and projection of well W-1 in the seismic line. Three seismic sequences match the lithostratigraphy based on well log data. Note that depths in wells have been adjusted to equivalent time (two-way travel time, TWTT) for correlation of seismic reflectors and lithology (see Appendix for details on conversion from time to depth). CDP: common depth point.

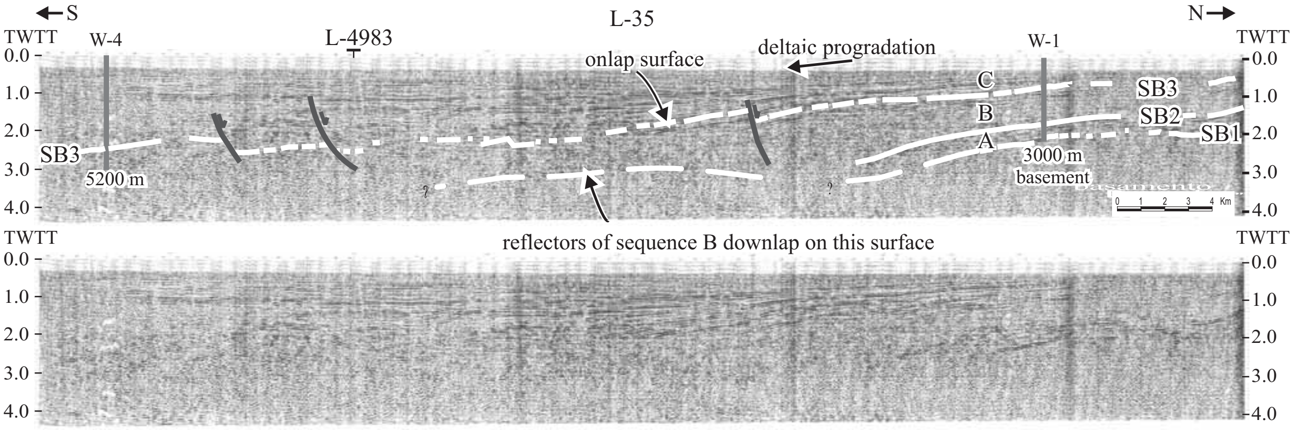

Figure 7. Seismic line L35 and interpretation based on seismic sequences and well logs. Sequence B is defined by sigmoidal clinoform interpreted as the southward progradation of the prodelta into the marine basin. Note that crystalline basement and sequence A deepens to the south. Lateral facies transition between sequences B and C is seen in the southward termination of this seismic line.

1991), and the Yuma basin (Eberly and Stanley, 1978).

The three seismic lines across part of the delta in a WSW-ENE direction provide a different perspective of sequences B and C. Line L-4987 can be tied to well W-4, but wells W-3 and W-5 are located across the trace of the Cerro Prieto fault at the end of seismic lines L-4983 and L-4997, respectively. This prevents matching these wells directly to the seismic reflectors on the seismic lines. However, two principal patterns of seismic reflectors can be depicted from these lines (Figure 9). The lower seismic pattern is composed of variable length, high impedance reflectors, with lateral downlap-onlap geometry, that produce paleohills and valleys (Figure 9). Well W-4 in the western end of line L-4987 suggests that this lower pattern may correspond to sequence B. Well W-4 is located two km north from this seismic line, and the lower boundary of the sandy facies of sequence C correlates with wavy reflectors at 2.6 seconds (TWTT). An alternative interpretation is that this irregular pattern is formed by pre-marine deposits and/or basement rocks.

Well W-5 is at or west the trace of the Cerro Prieto fault at the end of seismic line L-4997. This line presents a

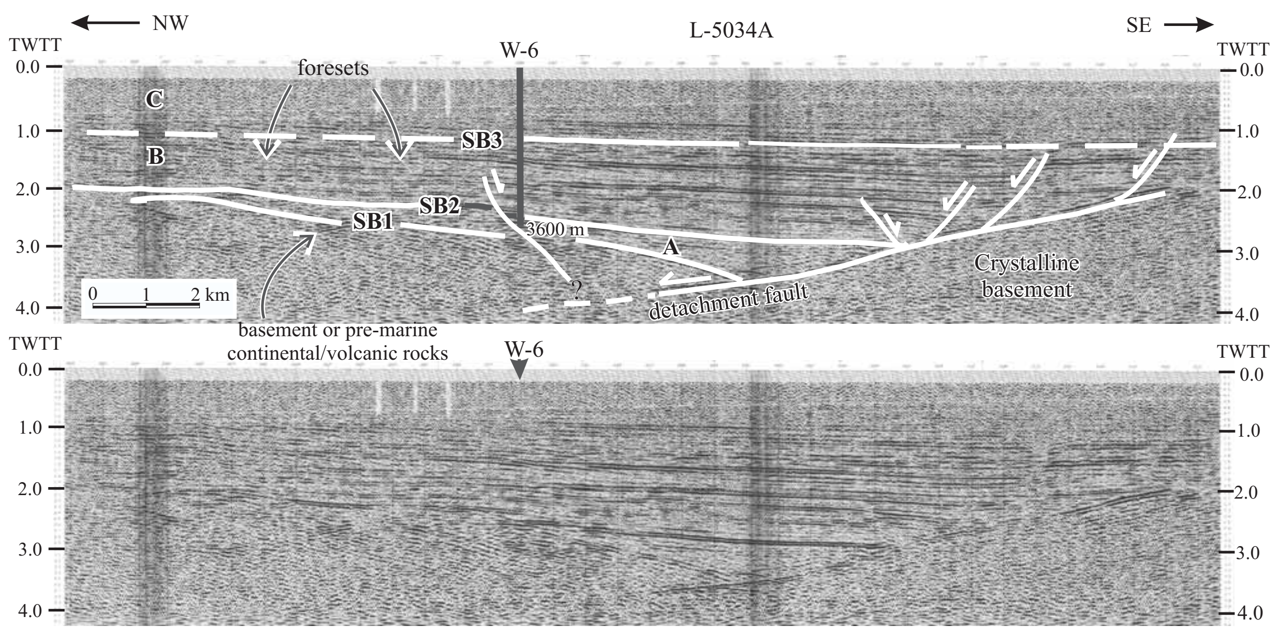

Figure 8. Seismic line L5034A and depth projection of well W-6. Seismic reflectors of sequence A appear to be in angular unconformity beneath SB2, and are cut by a strong acoustic reflector interpreted as a-top-to-the-northwest detachment fault. This detachment is SB1 and juxtaposes the sedimentary sequence and crystalline basement. Note that sequences B and C flatten upwards.

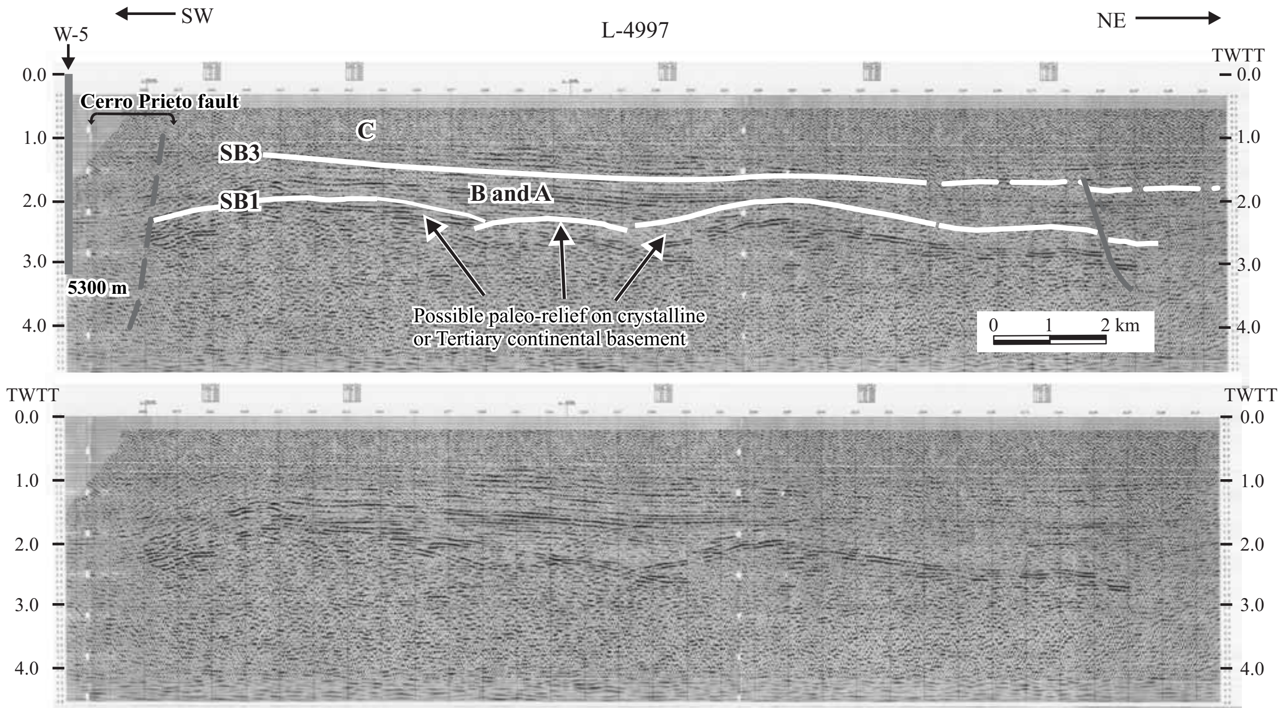

Figure 9. Seismic line L-4997 and depth projection of well W-5. This well is located across the Cerro Prieto fault in the southwestern part of the Altar basin. In this image, sequences B and A(?) overlie an irregular surface possibly developed on crystalline basement or Tertiary continental deposits.

distinctive lateral change in the pattern of reflectors across the fault zone (Figure 9): the long and parallel reflectors of sequence C change laterally into a zone of short, high impedance reflectors dipping to the SW (Figure 9). We interpret this change as the effect of the deformation close to the fault zone and the control that the Cerro Prieto fault exerted over sedimentation to the west.

Sequence C produces distinctive long and continuous, high impedance reflectors. Its base (SB3) in seismic line L-35 (Figures 6 and 7) marks the progradation of coarse-grained facies. Toward the southern end of seismic line L-35, the pattern of continuous reflectors changes to one of less continuous and/or poorly defined reflectors that are more characteristic of sequence B. Southward, the seismic line loses resolution and the seismic pattern of sequence C becomes chaotic and poorly defined, which is probably related to boundary conditions in the processing of seismic data (Figure 7). In the E-W trending seismic lines, SB3 is progressively deeper to the east (see Figure 9) and sequence C is apparently thicker in that direction. However, the seismic lines are not long enough to depict the eastern margin of the basin; besides, well W-6 contains a thinner sequence C compared to wells W-4 and W-5.

In summary, the stratigraphy of the Altar basin consists of three main sedimentary sequences (Table 1), which correspond to (1) a shale unit >600 m thick of late(?)-Miocene to early-Pliocene marine sedimentation (sequence A); (2) a 1,200–2,200 m-thick interval of interstratified sandstone, siltstone and mudstone, which represent sedimentation in presumed Pliocene time (sequence B); and (3) a predominantly sandstone unit up to 3,000 m thick, with subordinated conglomerate and mudstone, probably of Pliocene-Pleistocene age (sequence C).

Outcrops at El Golfo de Santa Clara

The upper 200 m of sequence C crop out along 25 km onshore at El Golfo de Santa Clara (Figure 2). The sequence gently dips 5–12° ENE, and is not affected significantly by faulting. The stratigraphic sequence consists of a series of cut and fill units each <1 m to 10 m thick composed of a distinctive facies pattern. The complete facies pattern includes a basal scour filled with lag conglomerate or breccia (up to 0.5 m thick), composed of >90% mudstone intraclasts up to 30 cm in diameter (Figure 10a). This rudite is matrix to clast supported, and grades upwards into lateral accretion bedsets of coarse sand. These two facies generally fill the scour and underlie a thick deposit (up to a few meters) of plannar beds and lamina of well-sorted, poorly consolidated, quartzose sand (Figures 10b, 10c). This sandy facies grades upwards into laminated to cross-bedded siltstone, and into a laminated mudstone facies (lm). The sand and silt rocks are the volumetrically dominant facies in these outcrops. The basal scour has a lateral extension of tens to hundreds of meters and the fine-grained facies, including the intraclast conglomerate, are more resistant to erosion and form laterally continuous beds, which likely produce the distinctive

Table 1. Age and sedimentary environments interpreted from microfossil assemblages, well log, and lithology for the three main stratigraphic sequences in the Altar basin. See Tables A and B in the appendix for microfossils description. Electrofacies after Serra (1984).

Sequence	Main microfosil content	Age	Dominant electrofacies	Sedimentary facies	Dominant sedimentary environment
C	Abundant reworked Cretaceous and Paleogene planktonic and benthonic foraminifera	Undetermined (Pliocene – Pleistocene?)	Cylinder shape (3 to 40 m thick)	Fluvial channel sand bars, levee splays, and over-bank deposits	Fluvial distributary channel and delta plain
B	Reworked Cretaceous and early Tertiary foraminifera. Common *in situ* Neogene benthonic foraminifera	Undetermined (Pliocene – Pleistocene?)	Funnel shape, bell shape and cylinder shape (5 to 10 m thick)	Low- to high-density turbidite deposits, intertidal channel sand bars, and mud flats	Delta front to prodelta
A	Neogene foraminifera, and calcareous nannofossils	Miocene	Cylinder shape (5 to 30 m thick)	Inner to middle neritic (0 to 100 m deep)	Prodelta to open marine

long and continuous reflectors of sequence C.

Soft-sediment deformation is conspicuous in the sand and silt facies. Large-scale flames and convolute lamination, as well as massive sand intervals, are distinctive features. The soft-sediment deformation is developed ubiquitously below channels and incised by the basal scour. Spatial relations suggest that soft-sediment deformation and incision may be genetically linked. Laminations of heavy minerals and clasts of silicified wood are very common. In contrast, marine calcareous shells are absent, and only small burrows occur in the silt and/or muddy facies.

Although the thickness of the sequence at El Golfo de Santa Clara is small compared with the sequence recorded in wells, these outcrops are important because they represent a pristine stratigraphic window into the upper part of sequence C, which is likely dominated by fluvial deposits. Well W-7 is located at the top of the outcrops near El Golfo de Santa Clara, and their upper 500 m are likely part of this sandy fluvial sequence.

DISCUSSION

Sequence correlation and stratigraphic evolution

We present a fence diagram showing the distribution of sequences A, B, and C correlated on the basis of their dominant lithology, characteristic electrosequences, biostratigraphic data, and distinctive seismic reflection patterns (Figure 11). In the following section, we interpret the implications of these stratigraphic sequences for the sedimentary evolution of the Altar basin.

Sequence A, and other proto-Gulf deposits in the northern Gulf of California

Correlation of the marine shale sequence A across the Altar basin is based on the presence of this unit in three wells that cut basement at depth (W-1, W-3 and W-7) (Figure 11). Additionally, this sequence was also cut in well W-6, and probably in the lower part of well W-5 (Figure 4). We interpret that sequence A is also present beneath sequence B in wells W-4 and W-5, as suggested by a shale interval in the lowermost 100 m in well W-5 (5,220–5,320 m) (Figure 4). The thickness of sequence A in wells that cut crystalline basement is ~600 m. This thickness is a minimum estimate for the total thickness of sequence A, because it clearly continues at depth in well W-6 as seen in its distinctive seismic pattern (Figure 8). These stratigraphic relationships strongly suggest that the marine sequence A has a widespread distribution in the Altar basin.

Correlation of the marine mudstones of sequence A toward the Yuma basin is possible because a similar unit was reported in the exploration well Exxon Federal No. 1 (Eberly and Stanley, 1978; Guzmán, 1981) (see location in Figure 11). In the Yuma basin, a marine upper-Miocene sequence (*c.f.*, Eberly and Stanley, 1978) is ~490 m thick and grades down section to a tuffaceous sandstone and coarse-grained conglomeratic sandstone. These, in turn, overlie a predominantly volcanic unit, dated at 16 Ma, and older continental clastics and volcanic intrusives. In the Altar basin, the middle- to early-Miocene volcanic and sedimentary section is missing in the three wells that penetrated in the crystalline basement. This indicates that more than 900 m of pre-marine volcanic and sedimentary rocks were preserved in the Yuma basin a few kilometers north of well W-1, but are absent in the Altar basin (Figure 2). This difference in the late-Cenozoic stratigraphy suggests that the Yuma basin and the Altar basin were separated basins prior to the first marine incursion in the northern gulf in late-Miocene time.

Our preliminary biostratigraphic dating favors a late-Miocene age for sequence A, which is consistent with a synchronous marine incursion in the northern gulf and Salton trough areas (McDougall *et al.*, 1999; Oskin and Stock, 2003). However, the presence of early- to middle-Miocene marine microfossils (Cotton and von der Haar, 1979, Helenes and Carreño, 1999; McDougall *et al.*, 1999; Helenes *et al.*, 2005) needs to be explained, and thus an even older age for proto-Gulf marine deposits cannot yet be ruled out.

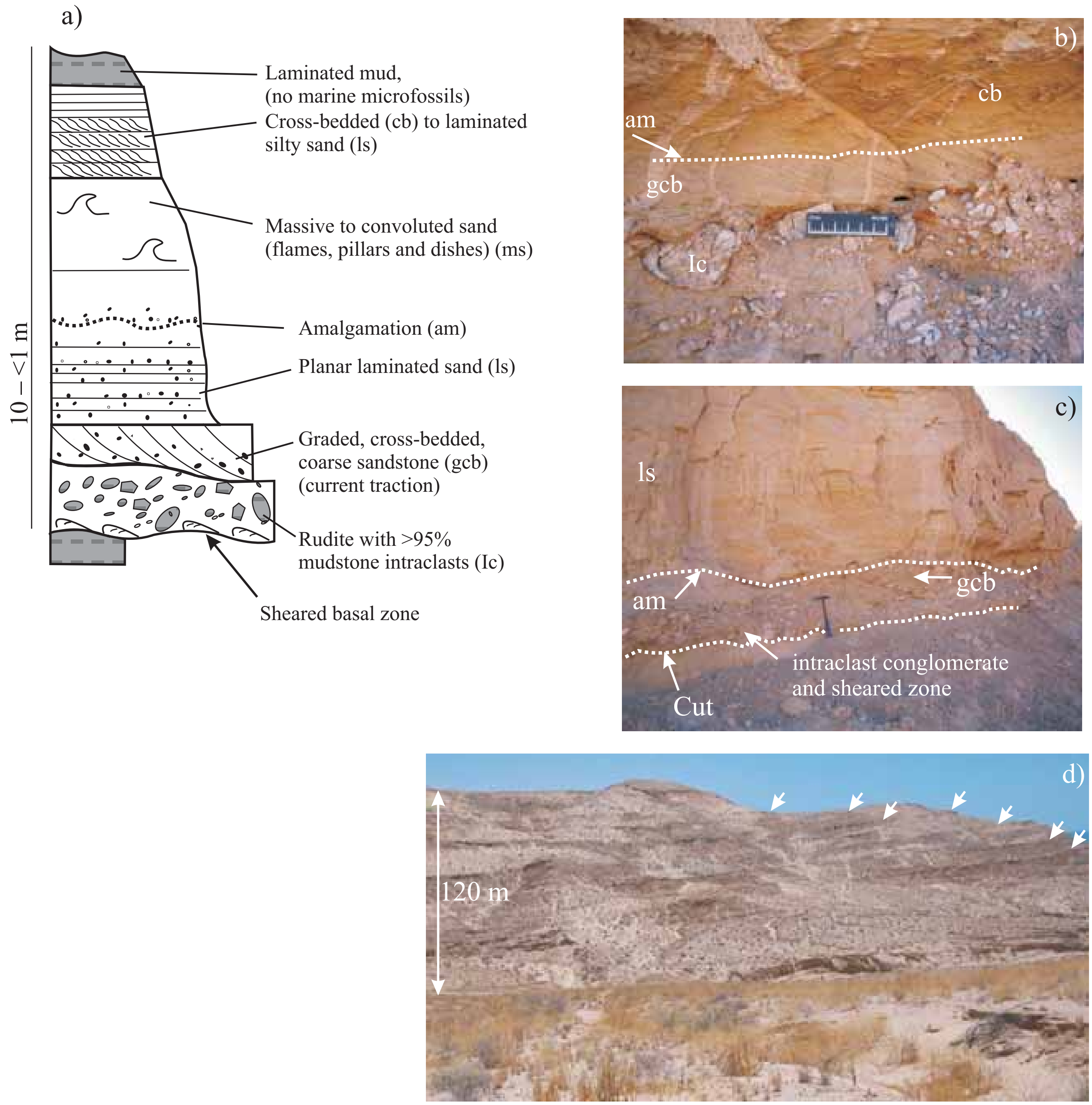

Figure 10. a) Composed fluvial-delta plain facies model for the stratigraphic section at El Golfo de Santa Clara. The entire stratigraphic section is composed of stacked fluvial deposits, interpreted as distributary channel and overbank facies in the delta plain. b) Detail view of the cut and fill sequence at El Golfo de Santa Clara. Note the basal scour filled with a matrix supported intraclast breccia overlain by cross-bedded foresets, and amalgamation of sand with planar stratification and climbing ripples. c) View of a depositional event with the basal lag and sheared zone underlying graded, cross-bedded sandstone (gcb) and a thick laminated sand deposit (ls). d) Panoramic view of the fluvial plain succession at El Golfo de Santa Clara. Arrows indicate the larger depositional events, although multiple cut and fill events are conspicuous within the stratigraphic sequence.

Sequences B and C, and the growth of the delta

Both sequences B and C are intimately related to the construction of the Colorado River delta. The high-frequency alternation of mudstone, siltstone and sandstone in sequence B suggests cyclic processes in the sub-aqueous part of the delta apron. This indicates that sequence B and C represent the transition to a more proximal position within the delta system. Sequence C is dominated by sandy facies that we interpret as representing the progradation of the fluvial facies of the delta. The parallel and continuous pattern of reflectors, distinctive of sequence C, likely results from the stacking of deposits from successive flooding events. Based on the recognition of the cut and fill sequence at El Golfo de Santa Clara, we interpret the general blocky pattern of electrofacies in well log of W-7 to indicate amalgamated sandy deposits. This sandy facies includes reworked microfossils, abundant terrestrial fossil of Irvingtonian age (<2–1 Ma) (Shaw *et al.*, 2005), and a quartzose composition indicative of a Colorado River provenance. Sub-aereal deposits and evidence of exposure of the fluvial delta plain (*e.g.*, bioturbation, soil horizons), and lateral diversity of fluvial channel and overbank facies are seen along 25 km of exposure in the badlands of El Golfo de Santa Clara.

The transition from sub-aqueous to sub-aerial part of the delta complex cannot be defined yet because the seismic lines have poor resolution. Nevertheless, thickness variations of sequence C between wells suggest that coarse-grained facies are thicker in wells close to the path of the modern river, which indicate that conglomerates represent fluvial channel deposits. Wells W-4 and W-5, located in the western part of the basin, contain thicker sandy sequences (up to 3,000 m), whereas wells W-1, W-2 and W-3, located closer to the apex of the delta, contain thinner sandstone-conglomerate sequences (<1,000 m) and distinctive conglomeratic deposits indicating high-energy fluvial channel deposits. This thickness for the fluvial conglomeratic succession would require a unique set of circumstances to maintain the fluvial channels in position for the amount of time needed to preserve 1,000 m during subsidence.

Correlation of sequence B and C with other delta sequences in other basins in the Salton trough is difficult because the growth of the delta occurred in a relatively narrow, and tectonically active depression, which produced diverse sedimentary environments. For instance, a 3.2 km deep well in the Salton basin (State 2-14) reveals a stratigraphic record of predominantly lacustrine mudstone-siltstone deposits punctuated with basin margin alluvial deposits of latest-Pliocene and Quaternary age (Herzig and Elders, 1988). No evidence of marine sedimentation exists in this stratigraphic record, but it should be considered that the entire sequence cut in well State 2-14 is probably of Pleistocene age, as deduced from rapid sedimentation rates of 2.4 m/Ka (Herzig and Elders, 1988). Alternatively, it could have an upper Pliocene age if we accept lower sedimentation rates based on Holocene radiocarbon ages (van de Kamp, 1973). This probably implies that the lacustrine sequence penetrated by well in the modern Salton basin may be coeval with the upper part of sequence B, and the whole of sequence C in the Altar basin.

Outcrops of fluvial and other non-marine deltaic deposits in the southwestern Salton trough are 2–2.5 km thick (Johnson *et al.*, 1983). These deposits comprise the Palm Spring Group of Winker and Kidwell (1996), and build the bulk of the fluvial succession of the delta in Pliocene time. The fluvial succession in the southwestern Salton trough may correlate with our sequence B, although sedimentary facies differ. The Altar basin, and the whole region, were exposed to sea-level changes, and, for this reason, sequence B may include facies of marine and transitional environments.

In the Cerro Prieto geothermal field, the stratigraphic sequence indicates a complex sedimentary environment developed at the delta front (Lyons and van de Kamp, 1980). Near the eastern range front of Sierra Cucapah, a thick sandstone unit laterally passes eastward into an alternance of mudstone-siltstone-sandstone, which is lithologically similar to our sequence B. The thick sandstone unit is interpreted as deposited by tidal sand bars along a narrow seaway into the Salton basin (Lyons and van de Kamp, 1980). McDougal *et al.* (1999) document the presence of marine Miocene strata at Whitewater, at the northern end of the Salton trough. However, younger marine deposits are absent in the Salton basins and this precludes an extensive inflow of marine waters into the Salton Sea since mid-Pliocene time.

Tectonic implications and unresolved questions

The structure of the Altar basin appears to be controlled by northwest-trending faults as is indicated by the elongated gravity and magnetic anomalies (Figures 3a and 3b). To the east of the basin is the Altar fault proposed by Sumner (1972). Although this feature is not imaged in the seismic lines studied here, it remains a firm candidate to accommodate more than 5 km of subsidence recorded in well W-4 in the western part of the basin. The Altar fault is not seismically active today, and we interpret that its activity started in late-Miocene time because the marine shale sequence (sequence A), overlying the granitic basement, has that age and no older deposits are recorded within the basin. Seismic profiles from Bahía Adair and the northern gulf indicate a narrow zone of transform faulting that projects northwest into the Altar basin (Aragón-Arreola *et al.*, 2003). Additionally, gravity data across the southeastern termination of the Altar basin indicate a gravity low at the southeast projection of the Altar fault, which is interpreted as a depression in the basement (Kinsland and Lock, 2001). These authors also suggested that an ancestral Colorado River exited along this depression to enter the gulf at Bahía Adair. Although we cannot evaluate the amount of strike-slip offset of the Altar fault, this structure may have played a key role during the early definition of the modern transtensional regime. This fault may have been the southward extension of the San Andreas fault zone and the Algodones fault, and have been responsible of the NW elongation of the delta apron during Pliocene time.

The Cerro Prieto fault zone is a major fault active at the plate boundary today. This fault zone can be considered as forming the western structural boundary of the Altar basin. The proximity of the Cerro Prieto fault zone to the southwestern end of seismic lines L-4983 and L-4997 produces west-tilted reflectors and internally tilted blocks, as well as zones of chaotic reflectors (Figure 9).

Localization of subsidence toward the Cerro Prieto basin may have started in Pliocene-Pleistocene time, and

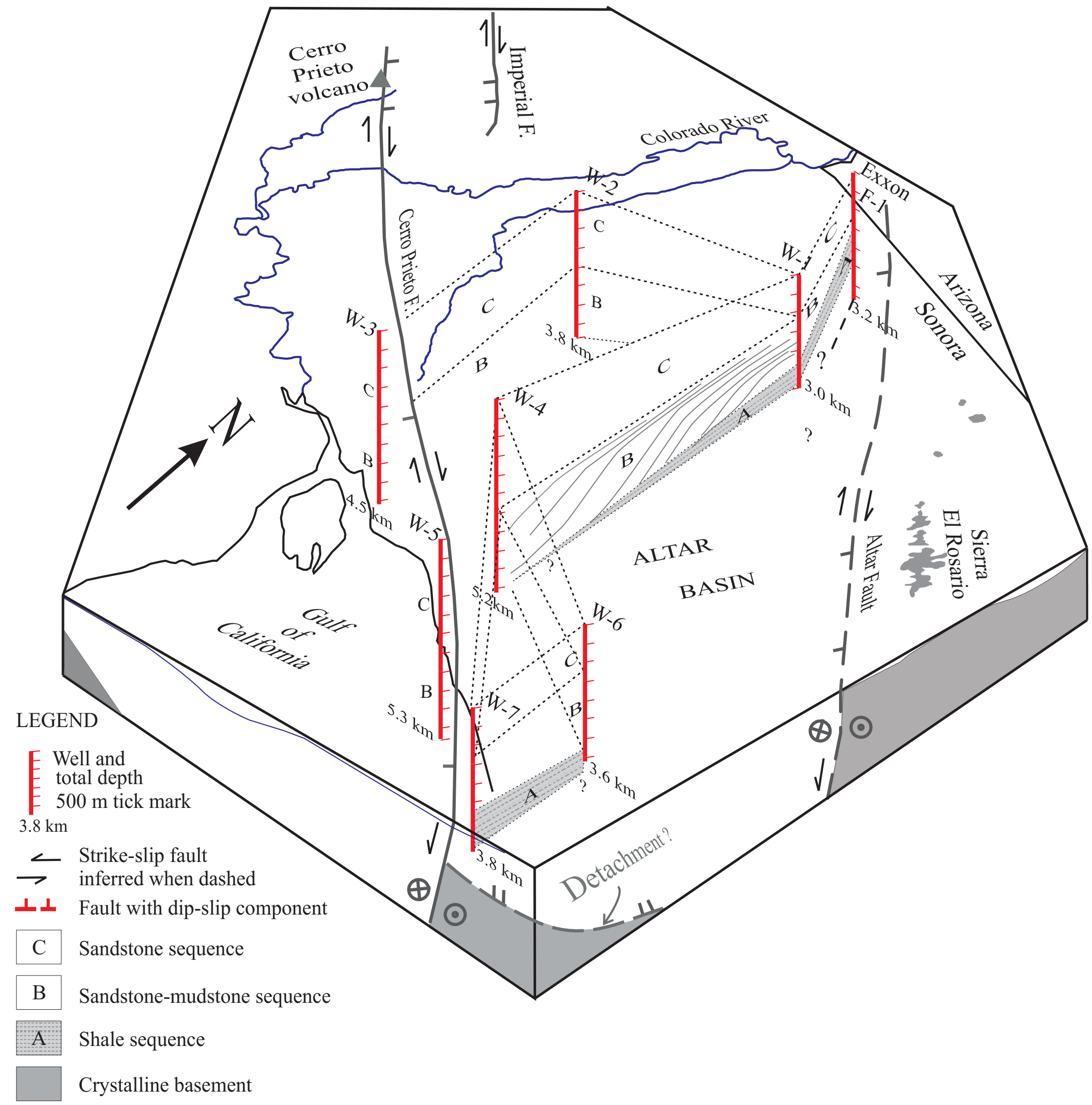

Figure 11. Fence diagram of the Altar basin and surrounding areas. Sequence correlation among wells is chiefly based on lithologic composition. Stratigraphic units in well Exxon F-1 are from Eberly and Stanley (1978). The eastern boundary of the Altar basin is the Altar fault, first proposed by Somner (1972). A dextral oblique movement on this fault is inferred from displacements in magnetic and gravity anomalies and because the San Andreas fault and the Algodones fault project to the southeast into the Altar fault. Correlation of sequences on wells 3 and 5 to other wells across the Cerro Prieto fault is not included in this interpretation.

so the Altar basin accumulated a large amount of subsidence before the main plate boundary shifted westwards into the Cerro Prieto fault. Along the southern half of the Cerro Prieto fault, near well W-7, the dip-slip component of the fault zone is to the west. We speculate that, at the time when the sediments of the Altar basin were deposited, the Cerro Prieto fault zone may have been a sub-parallel oblique (down to the east) fault, forming a narrow transtensional graben paired to the Altar fault to the east. This hypothetical fault was subsequently abandoned when the locus of subsidence was transferred northwest into the Cerro Prieto pull-apart basin. If this were the case, subsidence in the southern half of the Cerro Prieto fault zone would have changed its polarity, because this segment of the transform fault now accommodates subsidence toward the west in the northernmost Gulf of California. Thus, the Altar basin lies within the footwall block of the modern Cerro Prieto fault, and is being uplifted by recent activity (Ortlieb, 1991).

Our results are consistent with the view that the Altar basin started to subside in late-Miocene time when the transtensional tectonics of the modern plate boundary became localized in the Gulf of California (*c.f.*, Oskin *et al.*, 2001). However, the stratigraphic relationship between the mudstone unit and the crystalline basement in the Altar basin requires an alternative explanation other than a buttress unconformity. Early rift continental deposits reported in several localities in the western Salton trough and the Yuma basin (see Winker and Kidwell, 1996; and Axen and

Fletcher, 1998 for a review) are dismembered in the Altar basin by a detachment fault. The upper-Miocene to Pliocene marine sequence in the adjacent Yuma basin overlies more than 900 m of Oligocene to middle-Miocene continental and volcanic deposits that are absent to the south in most of the Altar basin (Figure 11). Although the abrupt depositional contact of marine shale over crystalline basement could be due to a rapid marine transgression, we favor the alternative explanation of a tectonic contact that juxtaposes the marine shale sequence and the granitic basement along a low-angle detachment fault. The wedge-shaped character of sequences A and B in seismic line L-5034A (Figure 8) is interpreted as growth-fault structures that affect most of the stratigraphic sequence. The detachment faulting that affected most of the stratigraphic section might have stopped at the end of deposition of sequence C, as indicated by the long reflectors downlapping the acoustic basement in line L-5034A (Figure 8).

Late-Miocene to Pliocene subsidence in several localities along the western margins of Salton trough in the Imperial Valley and northern Baja California was accommodated by eastwardly dipping, low-angle normal faults, partially concurrent with the onset of wrench tectonics (Siem and Gastil, 1994; Axen and Fletcher, 1998). Reconstruction of conjugate margins back to late-Miocene time indicates that the southwestern margin of the Salton trough formerly faced the present coast of the Altar Desert in Sonora (Winker and Kidwell, 1996). Top-to-the-west detachment faults in Laguna Salada probably rooted beneath the area occupied by the Altar basin before being displaced tectonically for 80–100 km along the Cerro Prieto fault. Where documented, these detachment faults were overprinted by high-angle normal and oblique faults, and later disrupted by the strike-slip faults that currently dissect the Salton trough and the Laguna Salada area (Winker and Kidwell, 1986, 1996; Siem and Gastil, 1994; Axen and Fletcher, 1998; Dorsey *et al.*, 2004).

Independent constraints for the timing of transtensional strain onset in the Gulf of California indicate ~260 kilometers of oblique extension across conjugate rifted margins sometime after 6.3 Ma (Oskin *et al.*, 2001). Recent work based on the interpretation of extensive seismic reflection lines indicates that deformation in the gulf area followed a process of westward shifting of strain localization that has produced abandoned transtensional basins along the eastern margin of the Gulf (Aragón-Arreola *et al.*, 2003). The abandonment of the Altar basin may have resulted from this process of relocation of deformation into the Cerro Prieto fault and related basins.

CONCLUSIONS

Integration of geophysical data, exploration well data and outcrop mapping in the Altar basin at the northern end of the Gulf of California indicates that this structurally distinct basin contains three major sedimentary sequences, which can be traced across the Altar basin and record the growth of the sub-aqueous part of the delta as it prograded into the marine gulf since late Miocene – early Pliocene. The lower sequence (sequence A) records a late-Miocene to early-Pliocene marine incursion in the northern gulf. A minimum thickness of 600 m of marine shale (sequence A) in the Altar basin indicates that open marine conditions existed prior to the arrival of detritus carried by the Colorado River into northwestern Sonora. This is consistent with a regional marine transgression in the northern gulf (see review by Oskin and Stock, 2003) concurrent with localization of transtensional deformation in the gulf area at about 6.2 Ma (Oskin *et al.*, 2001).

Our data do not permit dating the first arrival of Colorado River sediments to the Altar basin. However, we consider that the Colorado River reached this area at approximately the same time as in the southwestern Salton trough, that is, between 5.3 and 4.2 Ma (Winker and Kidwell, 1996). Most probably, both areas were still adjacent in Pliocene time, and thus the age range for the arrival of the Colorado River into the SW Salton trough is likely the age of the base of sequence B in the Altar basin.

We interpret sequence B as the result of sediment accumulation at the toe of the prodelta fed by turbidite events. Sea-level changes may produce variations to shallower sedimentary environments, like delta front and tidal flats settings. High-frequency interstratification of sandstone, siltstone and mudstone, with bell-shaped electrosequences, which contain shallow water microfossils and mollusc shell fragments, are consistent with this interpretation. The cut and fill pattern for the uppermost part of sequence C cropping out at El Golfo de Santa Clara, and the evidence for sub-aereal deposits, support the interpretation of a fluvial plain facies.

The unconformity between the base of sequence A and the crystalline basement, recorded in three wells and in the seismic lines, indicates tectonic erosion along low-angle detachment faults. This interpretation is appealing because similar relationships are found in the Laguna Salada area (Isaac, 1987, Siem and Gastil, 1994; Dorsey and Martin Barajas, 1999). Although not imaged in our seismic data, the Altar fault likely controlled subsidence in this basin and may have also accommodated part of the strike-slip component in the early phase of transtensional deformation related to the oblique rifting process. The Altar fault and the detachment fault may have been linked to the transtensional domain of the southernmost San Andreas fault in late Miocene to Pliocene.

Our long-term aim is to make a comprehensive three-dimensional model of the evolution of the different sedimentary environments of the Colorado River delta, in order to understand how, and when, the delta formed and was deformed. The delta is a repository of information on its responses to tectonism, long-term climate changes, sea-level changes, and transient events such as catastrophic flooding.

The geological history of this region is the inescapable backdrop of the economic and environmental issues along the international border that arbitrarily divides the delta of the one of the world's major rivers between two nations.

ACKNOWLEDGEMENTS

This work was partially funded by UC-MEXUS project CN-02-49. We thank Adán Oviedo and Mario Limón from PEMEX for kindly providing well data and copies of analog seismic lines, and for permission to publish these results. The use of Geographix for interpretation and analysis of well logs data was possible under Landmark University Grant 2002-COM-015129 to CICESE. Thanks to D. Meloche and R. Dorsey for valuable discussions. Stimulating thoughtful reviews by S. Janecke and C. González-León greatly improved this manuscript.

REFERENCES

Aragón-Arreola, M., Martín-Barajas, A., Stock, M.J., 2003, Tectonic implications of abandoned and active basin architecture in the northern Gulf of California rift (abstract), *in* Geological Society of America, Cordilleran Section, 99th annual meeting, Puerto Vallarta, Mexico: Geological Society of America, Abstracts with Programs, 35(4), p. 21.

Axen, G., 1995, Extensional segmentation of the Main Gulf Escarpment, Mexico and the United States: Geology, 23(6), 515-518.

Axen, G.J., Fletcher, J.M., 1998, Late Miocene-Pleistocene extensional faulting northern Gulf of California, Mexico and Salton Trough, California: International Geology Review, 40, 217-244.

Axen, G.J., Fletcher, M.J., Cowgill, E., Murphy, M., Kapp, P., MacMillan, I., Ramos-Velazquez, E., Aranda-Gómez, G., 1999, Range-front fault scarps of the Sierra Mayor, Baja California; Formed above an active low-angle normal fault?: Geology 27(3), 247-250.

Axen, G.J., Grove, M., Stockli, D., Lovera, O.M., Rothstein, D.A., Fletcher, J.M., Farley, K., Abbott, P.L., 2000, Thermal evolution of Monte Blanco dome; Low-angle normal faulting during the Gulf of California rifting and late Eocene denudation of the eastern Peninsular Ranges: Tectonics, 19(2), 197-212.

United States Geological Survey (USGS), 2002, Digital data grids for the magnetic anomaly map of North America (en línea): Denver, Colorado, United States Geological Survey, Open-File Report 02-414, <http://pubs.usgs.gov/of/2002/ofr-02-414>.

Bolli, H.M., Saunders, J.B., 1985, Oligocene to Holocene low latitude planktic foraminifera, *in* Bolli, H.M., Saunders, J.B., Perch-Nielsen, K. (eds.), Plankton Stratigraphy: Cambridge, MA., Cambridge University Press, 155-262.

Cotton, M.L., von der Haar, S., 1979, Microfossils from Cerro Prieto Geothermal wells, Baja California, Mexico, *in* Third Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico, Proceedings/Acta: Berkeley, CA., Coordinadora Ejecutiva de Cerro Prieto, Comisión Federal de Electricidad, Lawrence Berkeley Laboratory-Earth Science Division, University of California, 162-172.

Curray, J.R., Moore, D.G., 1984, Geologic history of the mouth of the Gulf of California, *in* Crouch, J.K., Bachmna, S.B. (eds.), Tectonics and Sedimentation along the California Margin: Los Angeles, CA, Society of Economic Palentologists and Mineralogists, Pacific Section, 38, 17-36.

Dean, M.A., 1996, Neogene Fish Creek Gypsum, and associated stratigraphy and paleontology, southwestern Salton Trough, California, *in* Abbot, P., Seymour, D. C. (eds.), Sturzstroms and Detachment Faults, Anza-Borrego Desert Park, California: Santa Ana, CA, South Coast Geological Society, 123-148.

Delgado-Argote, L.A., López-Martínez, M., Perrilliat, M.C., 2000, Geologic reconnaissance and age of volcanism and associated fauna from sediments of Bahia de Los Angeles Basin, central Gulf of California, *in* Stock, J., Aguirre, G., Delgado, H. (eds.), Cenozoic Tectonics and Volcanism of Mexico: Boulder, CO, Geological Societty of America, Special Paper, 334, 111-121.

Dibblee, T.W., 1984, Stratigraphy and tectonics of the San Felipe Hills, Borrego Badlands, Superstition Hills, and Vacinity, *in* Rigsby, A.C. (ed.), The Imperial Basin; Tectonics, Sedimentation, and Thermal Aspects: Los Angeles, CA, Society of Economic Paleontologists and Mineralogists, Pacific Section, 40, 45-70.

Dix, C.H., 1955, Seismic velocities from surface measurements: Geophysics, 20, 68-86.

Dokka, R.K., Merriam, R.H., 1982, Late Cenozoic extension of northeastern Baja California, Mexico: Geological Society of America Bulletin, 93, 371-378.

Dorsey, R., Martín-Barajas, A., 1999, Sedimentation and deformation in a Pliocene-Pleistocene transtensional supradetachment basin, Laguna Salada, north-west Mexico: Basin Research, 11, 205-221.

Dorsey, R.J., Janecke, S.U., Kirby, S.M., Axen, G.J., Steely, A.N., 2004, Pliocene lacustrine trangression in the western Salton trough, southern California; Implications for regional tectonics and evolution of the Colorado River delta (abstract), *in* Geological Society of America Annual Meeting, Denver CO: Geological Society of America, Abstracts with programs, 36(5), 317-318.

Dorsey, R., Fluette, A., McDougall, K., Housen, B., Janecke, S.U., 2005, Terminal Miocene arrival of Colorado river sand in the Salton Trough, southern California; Implications for initiation of the Lower Colorado river drainage (abstract), *in* Geological Society of America Annual Meeting, Salt Lake City: Geological Society of America, Abstracts with programs, 37(7), p. 109.

Eberly, L. D., Stanley T. B., 1978, Cenozoic stratigraphy and geologic history of southwestern Arizona: Geological Society of America Bulletin, 89, 921-940.

Elders, W.A., Rex, R.W. Meidav, T., Robinson, P.T., Biehler, S., 1972, Crustal spreading in southern California: Science, 178, 15-24.

Elders, W.A., Espinosa-Cardeña, J. M., Martín-Barajas, A., Hunt, A.G., 2001, Synthesis of geological and geophysical data on the Delta of the Colorado River, with relevance to the evolution of the Grand Canyon, Arizona, USA (abstract), *in* American Geophysical Union Fall Meeting, San Francisco: Eos, Supplement, 82(47), abstract H52B-0411.

Elders, W.A., Martín-Barajas, A., Pacheco, M., 2003, Evolution of sedimentary environments on the Delta of the Colorado River (abstract), *in* Geological Society of America, Cordilleran Section, 99th annual meeting, Puerto Vallarta, Mexico: Geological Society of America, Abstracts with Programs, 35(4), p. 27.

Espinosa-Cardeña, J.M, Elders, W.A., 2003, Tectonic implications of gravity anomalies in the northern Gulf of California and Salton Trough rift systems *in* Geological Society of America, Cordilleran Section, 99th annual meeting, Puerto Vallarta, Mexico: Geological Society of America, Abstracts with Programs, 35(4), p. 26.

Finn, A.C., Pilkinton, M., Cuevas, A., Urrutia, J., 2001, New digital database helps to map North America: EOS, 82 (30), 1.

Gastil, R.G., Krummenacher, D., 1977, Reconnaissance geology of coastal Sonora between Puerto Lobos and Bahia Kino: Geological Society of America Bulletin, 88, 189-198.

Gastil, R.G., Philipps, R.P., Allison, E.C., 1975, Reconnaissance Geology of the State of Baja California: Boulder, CO, Geological Society of America, Memoir, 140, 170 p.

Gastil, R.G., Neuhaus, J., Cassidy, M., Smith, J.T., Ingle, J.C., Krummenacher, D., 1999, Geology and paleontology of southwestern Isla Tiburón, Sonora, Mexico: Revista Mexicana de Ciencias Geológicas 16(1), 1-34.

Goldstein, N.E., Wilt, M.J., Corrigan, D.J., 1984, Analysis of the Nuevo León magnetic anomaly and its possible relation to the Cerro

Prieto magmatic-hydrothermal system: Geothermics, 13, 3-11.

Guzmán, A.E., 1981, Posibilidades petroleras en el Desierto de Altar: Petróleo Internacional, 94-100.

Haq, B.U., Hardenbol, J., Vail, P.R., 1988, Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change, *in* Wilgus, C.K., Hastings, B.S., Posamentier, H.W., van Wagoner, J., Ross, C.A., Kendall, C.G.St.C. (eds.), Sea-level Changes; an Integrated Approach: Tulsa, Oklahoma, Society for Sedimentary Geology (SEPM), Special Publication, 42, 71-108.

Helenes, J., Carreño, A.L., 1999, Neogene sedimentary evolution of Baja California in relation to regional tectonics: South American Journal of Earth Sciences, 12, 589-605.

Helenes, J., Carreño, A.L., Esparza, M.A., Carrillo, R.M., 2005, Neogene paleontology in the Gulf of California and the geologic evolution of Baja California, *in* VII Reunión Internacional sobre Geología de la Peninsula de Baja California, Memorias: Ensenada, Mexico, Sociedad Geológica Peninsular, 2-3.

Henry, C.D., Aranda-Gómez, J., 2000, Plate interactions control Middle-Late Miocene, proto-Gulf and Basin and Range Extension in the southern Basin and Range: Tectonophysics 318, 1-26.

Herzig, T.C., Elders, W.A., 1988, Nature and significance of igneous rocks cored in the State 2-14 research borehole; Salton Sea Scientific Drilling Project: Journal of Geophysical Research, 93, 13069-13080.

Howard, K.A., Bohannon, R.G., 2001, Lower Colorado River: upper Cenozoic deposits, incision, and evolution, *in* Young, R.A., Spamer, E. (eds.), Colorado River; Origin and Evolution: Grand Canyon, AZ., Grand Canyon Association, Monograph, 12, 101-106.

Hunt, A.G., Elders, W.A., 2001, Climate change and the evolution of Grand Canyon and the Colorado River Delta, *in* Young, R.A., Spamer, E., (eds.), Colorado River; Origin and Evolution: Grand Canyon, AZ., Grand Canyon Association, Monograph, 12, 185-190.

Hurtado-Artunduaga, A.D., 2002, Modelo estructural de la cuenca de Wagner en el Golfo de California basado en sísmica de reflexión multicanal: México, D.F., Universidad Nacional Autónoma de México, Instituto de Geofísica, Master thesis, 109 p.

Isaac, S., 1987, Geology and structure of the Yuha Desert between Ocotillo, California, U.S.A., and Laguna Salada, Baja California, Mexico: San Diego, CA., San Diego State University, Master Thesis, 165 p.

Johnson, N.M., Officer, C.B., Opdyke, N.D., Woodard, G.D., Zeitler, P.K., Lindsay, E.H., 1983, Rates of late Cenozoic tectonism in the Vallecito-Fish Creek basin, western Imperial Valley, California: Geology, 11, 664-667.

Karig, D.E., Jensky, W., 1972, The proto-Gulf of California: Earth and Planetary Science Letters 17, 169-174.

Kerr, D.R., 1984, Early Neogene continental sedimentation in the Vallecitos and Fish Creek Mountains, western Salton Trough, California: Sedimentary Geology, 38, 217-246.

Kerr, D., Kidwell, S., 1991, Late Cenozoic sedimentation and tectonics, western Salton Trough, California, *in* Walawender, M.J., Hanan, B.B. (eds.), Geological Excursions in Southern California and Mexico, Guidebook, 1991 Annual Meeting, Geological Society of America: San Diego, CA, Department of Geological Sciences, San Diego State University Press, 397-416.

Kinsland, L.G., Lock, E.B., 2001, Proposed Lower Colorado River courses prior to 4.3 Ma, Sonora, Mexico, *in* Young, R.A., Spamer, E. (eds.), Colorado River; Origin and Evolution: Grand Canyon, AZ., Grand Canyon Association, Monograph, 12, 107-108.

Lee, J., Miller, M. M., Crippen, R., Hacker, B., Ledesma-Vazquez, J., 1996, Middle Miocene extension in the Gulf Extensional Province, Baja California; Evidence from the southern Sierra Juarez: Geological Society of America Bulletin 108(5), 505-525.

Lonsdale, P., 1989, Geology and tectonic history of the Gulf of California, *in* Winterer, D., Hussong, M., Decker, R.W. (eds.), The Eastern Pacific and Hawaii: Boulder, CO, Geological Society of America, The Geology of North America, N, 499-521.

Lozano-Romen, F., 1975, Evaluacion petrolífera de la península de Baja California, México: Boletín de la Asociacion Mexicana de Geólogos Petroleros, 27, 104-129.

Lucchita, Y., Curtis, G., Davies, M., Davis, S., Hanks, T., Finkel, R., Turrin, B., 2001. Rates of down cutting of the Colorado River in the Grand Canyon region, *in* Young, R.A, Spamer, E. (eds.), Colorado River; Origin and Evolution: Grand Canyon, AZ., Grand Canyon Association, Monograph, 12, 155-158.

Lyons, D.J., van de Kamp, P. C., 1980, Subsurface geological and geophysical study of the Cerro Prieto geothermal field, Baja California, México: Berkeley, CA., Lawrence Berkeley Laboratory, report LBL-10540, 95 p.

Martín-Barajas, A., Vázquez-Hernández, S., Carreño, A.L., Helenes, J., Suárez-Vidal, F., Álvarez-Rosales, J., 2001, Late Neogene stratigraphy and tectonic control on facies evolution in the Laguna Salada Basin, northern Baja California, Mexico: Sedimentary Geology, 144, 5-35.

McDowell, F.W., Roldán-Quintana, J., Amaya-Martínez, R., 1997, The interrelationship of sedimentary and volcanic deposits associated with tertiary extension in Sonora, Mexico: Geological Society of America Bulletin, 109(10), 1349-1360.

McDougall, K.A., Poore, R.Z., Matti, J.C., 1999, Age and paleo-environments of the Imperial Formation near San Gorgonio Pass, Southern California: Journal of Foraminiferal Research, 29, 4-25.

Mendoza-Borunda, R., Axen, J.G., Frías-Camacho, V., 1995, Fallamiento normal en la parte sur de la zona de falla de Sierra Juárez, en la vecindad del escarpe principal del Golfo; evidencia de cambios en la dirección de extensión en esa latitud (abstract), *in* Unión Geofisica Mexicana, Reunión Anual, Libro de Resúmenes: Geos 15(2), 69.

Mendoza-Borunda, R., Axen, G.J., Sandeman, H., Ortega-Rivera, A., Grover, T.M., 1998, Stratigraphy and geochronology of the Tertiary volcanic and sedimentary rock in the southern Sierra Juarez and northern Sierra Las Tinajas area, in northeastern Baja California, Mexico, *in* Unión Geofisica Mexicana, Reunión Anual, Libro de Resúmenes: Geos, 18(4), 292-293.

Metcalf, R.C., 1981, VINT, VAVG and Z computed from any number of two way time-VNMO pairs, *in* Ballantyne, E.J., Campbell, D.L., Mentemeier, S.H., Wiggins, R. (eds.), Manual of Geophysical Hand-calculator Programs: Tulsa, Society of Exploration Geophysicists, TI, 65-74

Meek, J., Douglass, J., 2001. Lake overflow; an alternative hypothesis for Grand Canyon incision and development of the Colorado River, *in* Young, R.A., Spamer, E. (eds.), Colorado River; Origin and Evolution: Grand Canyon, AZ., Grand Canyon Association, Monograph, 12, 199-206

Morelli, C., 1976, Modern standards for gravity surveys: Geophysics, 41(5), p. 1051.

Nourse, A.J., Anderson, H.T., Silver, T.L., 1994, Tertiary metamorphic core complexes in Sonora, northwestern Mexico: Tectonics 13(5), 1161-1182.

Ortlieb, L., 1991, Quaternary vertical mouvements along the coast of Baja California and Sonora, *in* Dauphin, J.P., Simoneit, B.R.T., (eds.), The Gulf and Peninsular Province of the Californias: American Association of Petroleum Geologists, Memoir, 47, 447-480.

Oskin, M., Stock, J., 2003, Marine incursions synchronous with plate boundary localization in the Gulf of California: Geology, 31, 23-26.

Oskin, M., Stock, M.J., Martín-Barajas, A., 2001, Rapid locatization of Pacific-North America plate motion in the Gulf of California. Geology 29(5), 459-463.

Petróleos Mexicanos (PEMEX), 1985, Proyecto de inversion San Felipe, estudio de evaluación de cuencas, prospecto San Felipe: México, Petróleos Mexicanos, Informe RNCH-008, 57 p.

Perch-Nielsen, K., 1985, Cenozoic calcareous nannofossils, *in* Bolli, H.M., Saunders, J.B., Perch-Nielsen, K. (eds.), Plankton Stratigraphy: Cambridge University Press, Cambridge Earth Sciences Series, 427-554.

Quin, A.H., Cronin, M.T., 1984, Micropaleontologyand depositional environments of the Imperial and Palm Spring Formations, Imperial Valley, California, *in* Rigsby, A.C. (ed.), The Imperial Basin; Tectonics, Sedimentation, and Thermal Aspects: Los Angeles, CA, Society of Economic Paleontologists and Mineralogists, Pacific Section, 40, 71-85.

Roldán-Quintana, J., Mora-Klepeis, G., Calmus, T., Valencia-Moreno, M., Lozano-Santacruz, R., 2004, El graben de Empalme, Sonora, México; magmatismo y tectónica extensional asociados a la ruptura inicial del Golfo de California: Revista Mexicana de Ciencias Geológicas, 21(3), 320-334.

Sánchez-Guillén, L, 2004, Estructura de la cuenca de Wagner y la Falla Cerro Prieto en el Golfo de California mediante el análisis de datos sísmicos de reflexión multicanal: México, D.F., Universidad Nacional Autónoma de México, Facultad de Ingeniería, Tesis de Licenciatura, 55 pp.

Serra, O., 1984, Fundamentals of well log interpretation, v. 1, The acquisition of logging data: Amsterdam, Elsevier, Developments in Petroleum Science, 15 p.

Shaw, C.S., Croxen, F.W., Sussman, D.R., 2005, Early Pleistocene Irvingtonian/Vertebrate Fauna of El Golfo, Sonora, Mexico, *in* Society of Vertebrate Paleontology, 65th Annual Meeting, Field Guide, Mesa, Arizona: Society of Vertebrate Paleontology p. 1-33.

Siem, M.E., Gastil, G.R., 1994, Mid-tertiary to Holocene extension associated with the development of the Sierra El Mayor metamorphic core complex, northeastern Baja California, Mexico, *in* McGill, S.F., Ross, T.M. (eds.), Geological Investigations of an Active margin, Geological Society of America, Cordilleran Section, Guidebook: San Bernardino, California, San Bernardino County Museum Association, 107-119.

Spencer, J., Pearthree, P., 2001, Headward erosion versus closed-basin spillover as alternative causes of Neogene capture of the ancestral Colorado River by the Gulf of California, *in* Young, R.A, Spamer, E. (eds.), Colorado River; Origin and Evolution: Grand Canyon, AZ., Grand Canyon Association, Monograph, 12, 215-222.

Spencer, J.E., Richard, S.M., Reynolds, S.J., Miller, R.J., Shafiqullah, M., Gilbert, W.G., Grubensky, M.J., 1995, Spatial and temporal relationships between mid-Tertiary magmatism and extension in southwestern Arizona: Journal of Geophysical Research, 100(B7), 10321-10351.

Srinivasan, M.S., Srivastava, S.S., 1974, *Sphaeroidinella dehiscens* datum and Miocene-Pliocene boundary: American Association of Petroleoum Geologists, Bulletin, 58, 304-311.

Stock, J.M., Hodges, K.V., 1989, Pre-Pliocene extension around the Gulf of California and the transfer of Baja California to the Pacific plate: Tectonics 8(1), 99-115.

Sumner, J.R., 1972, Tectonic significance of gravity and aeromagnetic investigations at the head of the Gulf of California: Geological Society of America Bulletin, 83, 3103-3120.

van de Kamp, P.C., 1973, Holocene continental sedimentation in the Salton Basin, California; a reconnaissance: Geological Society of America Bulletin, 84, 827-848.

Winker, C.D., Kidwell, S.M., 1986, Paleocurrent evidence for lateral displacement of the Pliocene Colorado River Delta by the San Andreas fault system, southeastern California: Geology, 14, 788-791.

Winker, C.D., Kidwell, S.M., 1996, Stratigraphy of a marine rift basin; Neogene of the western Salton Trough, California, *in* Abbott, P., Cooper, J.D. (eds.), Field Conference Guidebook and Volume, American Association of Petroleum Geologists, Annual Convention, San Diego, CA: Bakersfield, CA, American Association of Petroleum Geologists, Pacific Section, and Society for Sedimentary Geology (SEPM), 80, 236-295.

Winker, C.D., Kidwell, S.M., 2002, Stratigraphic evidence for ages of different extensional styles in the Salton Trough, southern California (abstract), *in* Geological Society of America, Annual Meeting, Denver: Boulder, CO, Geological Society of America, Abstracts with Programs, 34(6), 83-84.

Manuscript received: July 13, 2005
Corrected manuscript received: November 17, 2005
Manuscript accepted: December 13, 2005

APPENDIX

In order to elaborate the curves of double time versus depth, a program in Matlab language based on the algorithm of Metcalf (1981) was implemented. This program calculates the interval velocity, average velocity and the depth to seismic reflectors defined by pairs of two-way travel times and normal move out velocities. The two-way travel times and the normal move out velocities are taken directly from the analyses of velocities near the well. The algorithm of conversion of double times to depth is based on the equations of Dix (1955) which are expressed as follow:

$$\mathrm{VINT}_{(\mathrm{N\ a\ N-1})} = \left(\frac{(\mathrm{VNMO}_{\mathrm{N}}^{2} * 2\,\mathrm{T}_{\mathrm{N}}) - (\mathrm{VNMO}_{\mathrm{N-1}}^{2} * 2\,\mathrm{T}_{\mathrm{N-1}})}{2(\mathrm{T}_{\mathrm{N}} - \mathrm{T}_{\mathrm{N-1}})} \right)^{1/2} \quad (1)$$

$$\mathrm{Z}_{\mathrm{N}} = \left[\mathrm{VINT}_{(\mathrm{N\ a\ N-1})} * (\mathrm{T}_{\mathrm{N}} - \mathrm{T}_{\mathrm{N-1}}) \right] + \mathrm{Z}_{\mathrm{N-1}} \quad (2)$$

$$\mathrm{VAVG}_{\mathrm{N}} = \frac{\mathrm{Z}_{\mathrm{N}}}{\mathrm{T}_{\mathrm{N}}} \quad (3)$$

Where:
VNMO = Normal Move Out Velocity (m/s)
VINT = Interval Velocity (m/s)
VAVG = Average Velocity (m/s)
N = Horizon of interest
N-1 = Horizon immediately previous to the one of interest
Z = Depth to the given horizon (m)
T = Time of one way to the given horizon (s)

Note: VRMS≈VNMO*cos θ, where θ it is the acute angle of the dipping reflector and the horizontal. We assume that the reflectors are sub-horizontals, thus cosθ≈1, and therefore VNMO≈VRMS.

Table A. Planktonic taxa reported by PEMEX in wells W-1, W-3 and W-7 (PEMEX, 1985). F: foraminifera; N: nannofossil taxa.

Unit	Taxa	Age (Haq *et al.*, 1988)	
		Range	**Ma**
B	(F) *"Globorotalia"* sp.	Undetermined	Undetermined
B	(F) *Morozovella "Globorotalia" seudobulloides*	Lower Paleocene (P1 – P3)	66.5 – 59
B	(F) *Globanomalina chapmani ("Globorotalia elongata")*	Upper Paleocene (P3 – P5)	59 – 54
B	(F) *Heterohelix* sp.	Upper Cretaceous	84 – 66.5
B	(F) *Chiloguembelina* sp.	Middle – upper Eocene (P11 – P17)	46 – 36
A	(F) *Globigerinoides trilobus altiaperurus*	Lower Miocene (N5 – N6)	23 – 19
A	(F) *Globigerinoides obliquus*	Lower Mio – lower Pliocene (N8 - N19)	17 – 4
A	(F) *Globigerina* sp.	Tertiary	66.5 – 1.85
A	(F) *Orbulina* sp.?	Middle Miocene – Holocene (N8 – N23)	16.2 – 0
A	(F) *Sphaeroidinella* sp.?	Pliocene-Holocene (N18 – N23)	5.2 – 0
A	(N) *Calcidiscus macintyrei*	Miocene – lower Pleistocene (NN4 – base NN-19)	18 – 2.0
A	(N) *Sphenolitus neoabies*	Middle? Miocene to Pliocene (NN1 – base NN16)	6 – 3
A	(N) *Reticulofenestra pseudoumbilica*	Miocene to Pliocene (NN7 – NN15)	12 – 3.5

Table B. Benthonic taxa reported by PEMEX in wells W-1, W-3 and W-7 (PEMEX, 1985) and interpretation of bathymetric range.

Unit	Taxa	Paleobathymetric range	Depth (m)
B	*Ammonia* sp.	Transitional to inner neritic	0 – 20
B	*Ammonia beccarii*	Transitional to inner neritic	0 – 20
B	*Quinqueloculina* sp.	Transitional to inner neritic	0 – 20
B	*Textulariella* sp.	Transitional to inner neritic	0 – 20
B	*Protobotellina* sp.	Transitional to inner neritic	0 – 20
A	*Elphidium* sp.	Inner neritic	0 – 20
A	*Elphidium gunteri*	Inner neritic	0 – 20
A	*Elphidium* cf. *incertum*	Inner neritic	0 – 20
A	*Cibicidoides pseudoungeriana*	Inner neritic	0 – 20
A	*Valvulineria* sp.	Inner neritic	0 – 20
A	*Florilus scaphus*	Inner neritic	0 – 20
A	*Nonionella* sp.	Inner neritic	0 – 20
A	*Pseudonodosaria* sp.	Inner neritic	0 – 20
A	*Brizalina subaeraniensis*	Outer neritic	100 – 200