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Thick deltaic sedimentation and detachment faulting delay the onset of continental rupture in the Northern Gulf of California: Analysis of seismic reflection profiles

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[1] The transition from distributed continental extension to the rupture of continental lithosphere is imaged in the northern Gulf of California across the obliquely conjugate Tiburón-Upper Delfin basin segment. Structural mapping on a 5–20 km grid of seismic reflection lines of Petroleos Mexicanos demonstrates that ~1000% extension is accommodated on a series of NNE striking listric-normal faults that merge at depth into a detachment fault. The detachment juxtaposes a late-Neogene marine sequence over thinned continental crust and contains an intrabasinal divide due to footwall uplift. Two northwest striking, dextral-oblique faults bound both ends of the detachment and shear the continental crust parallel to the tectonic transport. A regional unconformity in the upper 0.5 s (two-way travel time) and crest erosion of rollover anticlines above the detachment indicates inversion and footwall uplift during the lithospheric rupture in the Upper Delfin and Lower Delfin basins. The maximum length of new crust in both Delfin basins is less than 40 km based on the lack of an acoustic basement and the absence of a lower sedimentary sequence beneath a wedge-shaped upper sequence that reaches >5 km in thickness. A fundamental difference exists between the Tiburón-Delfin segment and the Guaymas segment to the south in terms of presence of low-angle normal faults and amount of new oceanic lithosphere, which we attribute to thermal insulation, diffuse upper-plate extension, and slip on low-angle normal faults engendered by a thick sedimentary lid.

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1. Introduction

[2] The partitioning of strain during oblique rifting and the effects of thick sedimentary deposits in the rheological behavior of the continental crust and upper mantle are important yet poorly understood parameters that control the dynamics of continental breakup and onset of seafloor spreading. Numerical models predict that thick sedimentary deposits reduce the density contrast between stretched lithosphere and adjacent continental margins, favoring localization of strain and rapid evolution from wide to narrow-rift mode [*Bialas and Buck*, 2009]. However, thick sedimentary deposits also act as a thermal insulator that inhibits dissipation of heat from the upwelling mantle by convective hydrothermal systems such as midocean ridges [*Davis et al.*, 1999; *Stein and Fisher*, 2003]. Thermal softening of the lower crust and lithospheric mantle by sedimentary insulation may also promote flow along ductile shear zones at shallower levels in the crust [*Kuznir and Park*, 1987; *McKenzie et al.*, 2000]. Thus, though thick sedimentation may promote focusing of extension within a rift basin, the sediment enhanced crustal thickness and resulting higher temperatures will dramatically weaken the lithosphere [*Lynch and Morgan*, 1987] and could prolong lithospheric stretching, especially if the flux of sediments is sufficient to maintain the thickness of the crust. Hence, it is not clear from existing models whether the addition of thick sediment to a rift system will enhance or inhibit localization of strain and progress to lithospheric rupture.

[3] In the northern Gulf of California and Salton Trough region, sediments delivered by the Colorado River exert a poorly understood influence on the rheological behavior of continental crust during oblique rifting. This region may illustrate the effects of a thick sedimentary section during the thinning and rupturing of the crust and lithospheric mantle because it records the transition from continental to oceanic rifting in two diachronous, subparallel rhombochasm basin systems located along the same transport parallel transect: (1) the active Delfin, Consag, Wagner, Cerro Prieto, and Salton basins in the west and (2) the inactive Tiburón-Tepoca-Altar basin system

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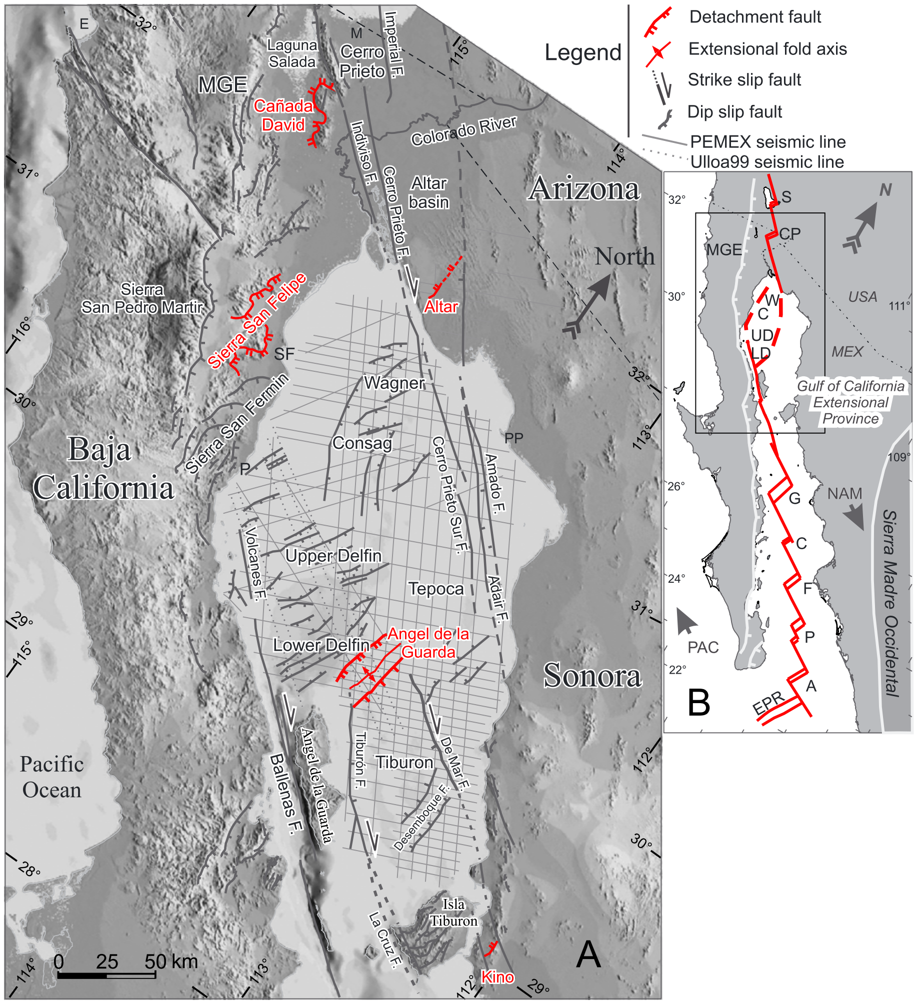

Figure 1. (a) Structure of the northern Gulf of California region based on interpretation of Petroleos Mexicanos (PEMEX) seismic reflection data. Faults in Baja California include the Cañada David detachment [*Axen and Fletcher*, 1998; *Fletcher and Spelz*, 2008], and the Sierra San Felipe Detachment [*Seiler et al*., 2010], and faults in the Sierra San Fermin [*Lewis and Stock*, 1998], central Puertecitos Volcanic Province [*Martín-Barajas et al*., 1995] and the southern Puertecitos Volcanic Province [*Oskin*, 2002]. Faults in Isla Tiburón are from *Oskin* [2002], and those in coastal Sonora are from *Gastil and Krummenacher* [1977] and *Bennett* [2012].SF San Felipe, P Puertecitos, SPMF San Pedro Mártir fault. Seismic lines are PEMEX data; dotted lines are high-resolution seismic lines of the Ulloa99-5 cruise [*Persaud et al*., 2003]. (b) Inset shows the regional morphotectonic features along the Gulf of California Extensional Province from the western edge of the Sierra Madre Occidental to the Main Gulf Escarpment (MGE) in Baja California. Red lines mark the main plate boundary transform faults and intervening proto-oceanic basins. Box is area of Figure 1a.

in the east [*Aragon-Arreola and Martín-Barajas*, 2007] (Figure 1). Both basin systems contain >6–7 km of sediments derived primarily from the Colorado River since latest Miocene time; [*Dorsey et al*., 2007; *González-Escobar et al*., 2009; *Helenes et al*., 2009; *Mar-Hernández et al*., 2011], but the two sets of basins have distinctly different histories of rifting and continental rupture.

[4] Analysis of a limited number of seismic reflection profiles from the active Delfin and Wagner basin system in the northern Gulf of California suggests that beneath the >6 km thick sedimentary fill, the continental lithosphere is ruptured in narrow axial troughs (Figure 1) [*Aragon-Arreola and Martín-Barajas*, 2007; *González-Escobar et al*., 2009; *Persaud et al*., 2003]. The active axial-rift zone is characterized by high heat flow, magmatic intrusions, and stratiform volcanic deposits within the late-Neogene sandstone-siltstone sequences [*Sánchez-Zamora et al*., 1991] [*Aragon-Arreola and Martín-Barajas*, 2007; *Persaud et al*., 2003]. Plio-Pleistocene synrift volcanic rocks are composed of intermediate to felsic magmas with high εNd values and variable $^{87}Sr/^{86}Sr$ ratios indicating a Pacific-type mantle source with <10% crustal contamination [*Martín-Barajas et al*., 2008a; *Schmitt et al*., 2013; *Schmitt and Vazquez*, 2006].

[5] In contrast, the inactive Tiburón, Tepoca, and Altar basins lack evidence of syntectonic volcanic activity and are likely floored by stretched continental crust. Independent evidence for the presence of highly extended continental crust in the eastern basin system includes a seismic refraction profile along the

Tiburón basin with seismic velocities corresponding to lower continental crust density [*González-Fernández et al.*, 2005]. Stretched continental crust was also imaged over the rift margins and across the structural high between Tiburón and Delfin basins in seismic reflection profiles [*Aragon-Arreola and Martín-Barajas*, 2007; *González-Fernández et al.*, 2005]. Farther north, Mesozoic crystalline basement underlies >5 km thick Late Miocene to Plio-Pleistocene deltaic deposits in the Altar basin east of the Cerro Prieto transform fault [*González-Escobar et al.*, 2012; *Pacheco et al.*, 2006]. However, the extent of continental crust has not been mapped in detail in the deep basins, and thus the extent and width of new magmatically formed ocean crust are poorly defined in the northern Gulf of California.

[6] Sediment-starved rift basins of the southern Gulf of California contain well-exposed oceanic crust with Pacific mantle Sr-Nd isotopic signatures [*Castillo et al.*, 2002]. In the south, seafloor spreading started prior to 3.5 Ma ago [*DeMets*, 1995; *Lonsdale*, 1991] and has produced nearly 280 km of oceanic crust in the Guaymas basin and ~150 km in the Alarcon basin [*Lizarralde et al.*, 2007; *Sutherland et al.*, 2012]. Mapping the extent of continental crust in the northern rift basins is critical for understanding the possible effects of thick sedimentary deposits in controlling the mode of extension and onset of lithospheric rupture.

[7] In this paper, we use Petroleos Mexicanos (PEMEX) seismic data to map out the extent of new crust in deep basins of the northern Gulf of California that are filled with thick sediments of the Colorado River. We find that the width of new crust, which forms in the wake of continental rupture, is much smaller than the larger width of new oceanic crust seen in the Guaymas and Alarcon basins to the south. The general basin geometry and master faults in the northern Gulf of California are known from interpretation of portions of the PEMEX seismic data [*Aragon-Arreola and Martín-Barajas*, 2007; *González-Escobar et al.*, 2009; *Mar-Hernández*, 2009; *Pacheco et al.*, 2006]. Here we use 90% of the available seismic array to document the fault geometry and extent of thinned continental crust that floors a pair of major rift basins located along the same transport-parallel transect in the northern gulf: Tiburón and Delfin basins (Figure 1). Analysis and interpretation of these data provide new insights into: (1) rift segmentation as defined by major normal and strike-slip faults, (2) the lateral extent of thinned continental crust and new ocean crust in the Tiburón and Delfin basins, (3) structural patterns of strain partitioning in oblique rifts, and effects of sedimentation in active rift systems. We conclude that addition of thick sediment to basins in the northern Gulf acted to insulate the lithosphere and may have also sufficiently elevated pore fluid pressures to favor development of large offset, low-angle normal faults. We hypothesize that these thermal and mechanical conditions promoted regional lower crustal flow from underneath the rift margins towards the northern Gulf of California delaying complete rupture of continental lithosphere.

2. Geologic and Tectonic Setting

[8] The Gulf of California is located along the western portion of the southern Basin and Range Province [*Henry and Aranda-Gómez*, 1992] (Figure 1B). Large-magnitude E-W to NE-directed extension occurred in metamorphic core complexes and normal oblique faults in north-central Sonora during ~27 to 12 Ma [*Gans*, 1997; *Nourse et al.*, 1994; *Wong and Gans*, 2008]. This older extension likely represents the core-complex mode of continental extension, which is thought to be accompanied by lower crustal flow to compensate for large magnitude of upper crustal extension by detachment faulting [*Buck*, 1991]. This early phase of rifting widened the Sonoran margin and created the distinctive Basin and Range physiography west of the Sierra Madre Occidental (Figure 1a). In central Sonora, the extensional basins are filled with early Miocene continental deposits interbedded with basaltic lava and capped by 12.8–10.5 Ma rhyolite rocks [*González-León et al.*, 2010; *McDowell et al.*, 1997; *Vega-Granillo and Calmus*, 2004]. However, continued sedimentation and rotation of beds younger than 11.5 Ma indicate that extension in central and western Sonora continued in late Miocene time coeval with initial evolution of the Gulf of California [*McDowell et al.*, 1997].

[9] A significant but poorly constrained amount of extension has also occurred along the Sonora margin since late Miocene time [*Bennett et al.*, 2013; *Gastil and Krummenacher*, 1977; *Pacheco et al.*, 2006]. Mountain ranges north of Bahía Kino in coastal Sonora are oriented NW-SE, and mapped strike-slip faults in Sonora have this trend, but it is unclear if this rift-parallel orientation of mountain ranges is an inherited physiography of mid-Miocene extension, or alternatively, was entirely produced during the current stage of oblique rifting. Recent structural and geochronology studies in coastal Sonora indicate ~6 km of transtensional shear and up to 120% extension occurred, mostly between 7 and 5 Ma across a linked system of strike-slip faults, low-angle normal faults, and intervening block rotation [*Bennett et al.*, 2013; *Darin et al.*, 2010]. Additional dextral faulting is recognized in coastal Sonora from juxtaposition of terranes with differing volcanic cover, but the timing and amount of offset are incompletely constrained [*Oskin and Stock*, 2003a, 2003b; *Bennett et al.*, 2013]. Age constraints for the onset of extension in Isla Tiburón include a post-6.5 Ma synrift shallow marine sedimentary section that crops out in the southwestern side of the island [*Gastil et al.*, 1999; *Oskin and Stock*, 2003a, 2003b], as well as differential tilting between 12.6 Ma and 6.4 Ma tuffs along the western part of the island [*Oskin*, 2002]. However, the amount of oblique extension in coastal Sonora is still poorly known over the integrated history of rifting. Oskin and others [*Oskin et al.*, 2001] proposed that most of the ~260 ± 10 km of oblique rifting has occurred offshore since 6.5 Ma.

[10] Continental extension across the northern Gulf Extensional Province shifted west-northwest and likely started in Baja California sometime after 12 Ma [*Aragon-Arreola and Martín-Barajas*, 2007; *Axen et al.*, 2000; *Lee et al.*, 1996; *Stock and Hodges*, 1989]. Recent structural mapping and kinematic analysis in the Sierra San Felipe in northern Baja California indicate that transtensional deformation and exhumation of rifted continental blocks started between ~7 and 9 Ma [*Seiler et al.*, 2010]. The structural analysis by *Seiler et al.* [2010] demonstrates that Sierra San Felipe experienced oblique extension through a series of low-angle faults that were kinematically linked across discrete accommodation zones since 7–9 Ma. Detachment faults in the Sierra San Felipe region exist in the hanging wall of the San Pedro Mártir fault, which forms the Main Gulf Escarpment and listric breakaway fault of a detachment system that roots to the southeast and defines the northwestern limit of the Tiburón-Delfin transect presented in this study (Figure 1a).

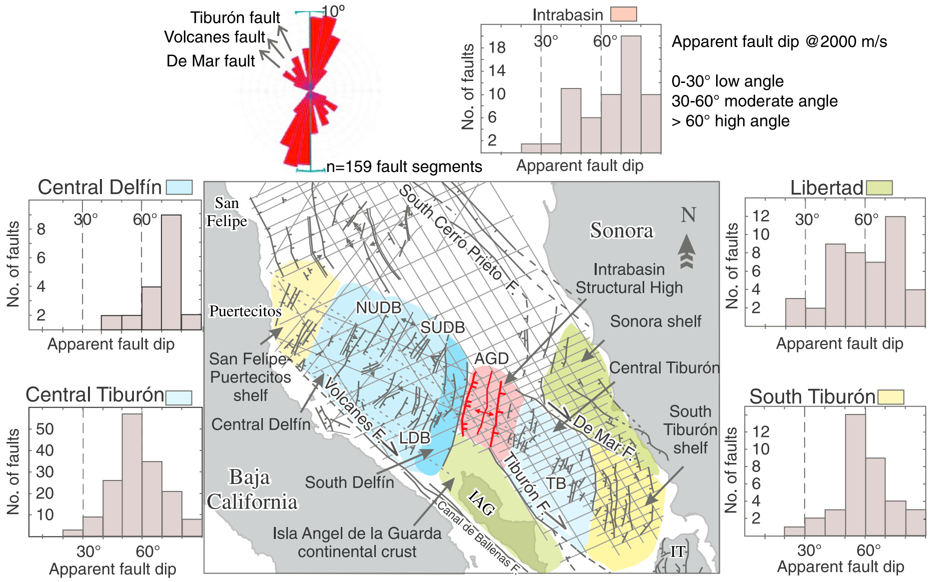

Figure 2. Simplified map of the Tiburón-Delfin rift basins segment showing structural domains described in text. Histograms with fault true dip for the five principal domains indicate mostly moderate to high-angle faults. Listric-normal faults have lower angles below 2 s of TWTT. Dominant fault trend is to the N-NE. Strike of Tiburón, DeMar, and Volcanes dextral-oblique faults is to the northwest.

[11] Interpretation of PEMEX seismic profiles indicates a major westward shift in the locus of extension: the same late Pliocene sedimentary sequence that is thin (<300 m) and postdates rifting in the Tiburón-Tepoca basins becomes dramatically thicker (>5 km) and accumulated during extension in the Upper Delfin basin [*Aragon-Arreola and Martín-Barajas*, 2007]. This stratigraphic pattern records a lateral shift in the locus of extension and opening of the lower Delfin basin that must coincide with activation of the Ballenas transform, which detached the crustal block of Isla Angel de la Guarda from Baja California [*Lonsdale*, 1989; *Stock*, 2000]. A heating event near the sheared continental crust at ~1.8 Ma was documented with apatite fission tracks and (U/Th)/He dating of two transects perpendicular to the Ballenas Transform fault [*Seiler et al.*, 2009]. These results strongly suggest that shearing along the Ballenas Transform fault started in latest Pliocene time and thus constrain the age of the shift in transtension to the west and northwest.

3. Seismic Data

[12] In this paper, we interpret two sets of seismic data to map the structure and seismic stratigraphy in the Tiburón and Delfin basins in the northern Gulf of California (Figure 2a). The PEMEX seismic data comprise a grid of seismic lines with a 5–15 km spacing that were collected during the early 1980s [*Pérez-Cruz*, 1982]. The data were recorded with 48 channels for 6 s (TWTT). Seismic processing took place in three main workflows. About 35% of the seismic data was processed using Seismic Unix free software [*Aragon-Arreola and Martín-Barajas*, 2007; *Aragón-Arreola*, 2006]. Additional reprocessing of the same seismic lines was completed at Centro Nacional de Procesado Sismólogico (PEMEX) using ProMax© (workflow 1). Subsequent processing of seismic lines in specific regions was completed during Master thesis projects at CICESE (workflow 2) using ProMax software [*Aguilar-Campos*, 2007; *Hernández-Pérez*, 2008; *Mar-Hernández*, 2009; *Soho*, 2012]. Seismic lines 5028, 5040, 5042, and 5044 were scanned and vectorized from film copies held at PEMEX archives. These seismic lines were originally processed at Instituto Mexicano del Petroleo during the exploration project in the early 1980s (workflow 3).

[13] For our structural mapping, we integrated the high-resolution, 48-channel seismic data (2 s of recording) from seismic lines of the Ulloa99-5 cruise [*Persaud et al.*, 2003]. The seismic lines were integrated and interpreted using the SeisWorks software of Landmark®. In this paper, we focus in the Tiburón and Upper Delfin basins, although our structural map includes a regional interpretation of offshore faults and acoustic basement using all seismic data of PEMEX and Ulloa99-5 in the northern Gulf of California (Figure 1a).

[14] The PEMEX seismic grid is oriented along azimuths of 330° and 060° in the northern Gulf of California, and thus the seismic array is ~20° clockwise oblique to the Pacific North America plate boundary tectonic transport direction of ~310° as defined by the Ballenas and Cerro Prieto Transform faults (Figure 1a). Seismic lines 5471 and 5451 of PEMEX and seismic lines ul25, ul27, and ul29 of Ulloa99-5 are oriented more favorably, 290° and 310° respectively, across the Delfin basins and provide key stratigraphic relationships for our study.

3.1. Criteria for Structural Correlation of Faults

[15] Correlation of major faults, fault patterns, and axes of extensional folds was completed in areas with a denser grid of PEMEX seismic lines (Figure 2). We used zig-zag panels with crossing seismic lines to determine the strike and dip of faults. Fault planes that converge in the lower part of the panels have apparent dips towards the interpreter. A correlated fault with diverging apparent dips in the panels indicates a true dip away from the interpreter. In general, a greater level of confidence was placed on faults correlated closer to the vertex of the panels and on major fault zones. The sense and amount

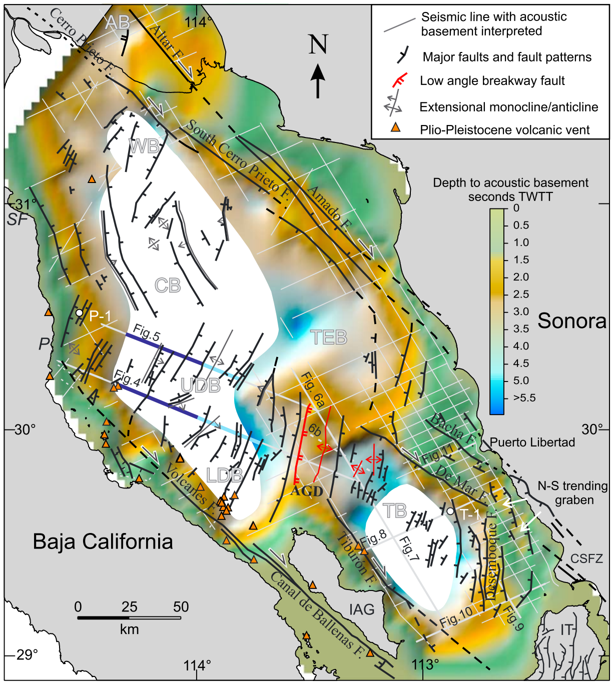

Figure 3. Depth to acoustic basement (seconds of two-way travel time), master faults, general fault patterns, and extensional fold axes define the main structure of the northern Gulf of California based on interpretation of seismic lines from PEMEX and Ulloa99-5 (dotted lines). The Tiburón basin is controlled by north-northeast striking normal faults that accommodate extension in a 40 to 60 km wide rift segment bounded by the De Mar and Tiburón dextral-oblique faults. The main breakaway fault of a top-to-southeast detachment (fault shown in red at 30°N, 113.5°W) is located northwest of the intrabasinal structural high dividing Tiburón and Delfin basins. Seismic sections across the Upper Delfin basin indicate the length of inferred (light blue) to unidentified (dark blue) continental basement as indicated in Figures 4 and 5. Note that numerous volcanic vents are located in the Lower Delfin basin and along the edge of the continental shelf of Baja California. IAG Isla Angel de la Guarda, IT Isla Tiburón, CSSZ coastal Sonora shear zone, AB Altar basin, WB Wagner basin, CB Consag basin, UDB Upper Delfin basin, LDB Lower Delfin basin, TEB Tepoca basin, TB Tiburón basin, AGD Angel de la Guarda Detachment. P-1 and T-1 are PEMEX wells.

of vertical displacement of distinctive seismic reflectors on crossing seismic lines were also important criteria for fault correlation.

3.2. Determination of Fault Orientation and Kinematics

[16] Apparent fault dips were measured at ~2 s of TWTT assuming a seismic velocity of 2 km/s. The true dip was calculated from either using the apparent dips of a fault correlated in profiles with different orientations or correcting the apparent dip of a fault in one profile for its independently determined strike. The apparent dip was projected to azimuth perpendicular to the fault trend interpreted across seismic lines. Therefore, the true dip reported in this study represents the inclination of the fault from the seafloor to a depth of ~2 km (Figure 2). However, most of the major normal faults bend listrically and have shallower dip angles below this depth. Strike-slip displacement in faults was inferred from flower structures, lateral discontinuity of distinctive reflectors across the fault, and/or structural inversions near the fault zone. The general criteria of [*Harding*, 1990] were applied in identification of strike-slip faulting in seismic lines.

4. Rift Basin Structure

[17] The Delfin-Tiburón segment of the rift can be divided into the Upper Delfin and Tiburón extensional basins, each with distinctive fault patterns, well-defined boundaries controlled by master faults, and presence of an acoustic basement (Figure 2). These basins contain stratigraphic relationships that clearly record the northwest migration of strain to its present position in the Upper Delfin basin. In the center of the rift segment, the basins are separated by the Intrabasin Structural High, a broad, basement-cored antiform, with evidence of listric-normal faults that project beneath the Tiburón basin. Below, we describe the overall structure of these basins, as well as the first order stratigraphic relationships between them, to constrain the maximum likely width of new crust in this segment of the rift. For the purposes of this study, new crust is defined as that which has formed in the gap of two separating plates following full rupture of continental lithosphere. Due to high sedimentation rates, the new crust in this transect does not appear as typical oceanic crust, but is instead a hybrid product of intense magmatic upwelling and sediment infilling similar to that documented in the Salton Trough [*Fuis et al*., 1984].

4.1. Upper Delfin Basin

[18] The Upper Delfin basin is bounded on its northwest margin by the San Felipe-Puertecitos shelf. The shelf is cut by a dense array of NNW striking, east dipping normal faults, and the dextral-normal Volcanes fault. Flower structures and lateral truncation of seismic reflectors suggest strike-slip shearing north and west of the northwest end of the Volcanes fault (Figure 3). Structural interpretation of PEMEX and Ulloa99-5 seismic lines show that this fault continues to the south, within the adjacent Lower Delfin basin, and is colinear with the Canal de Ballenas transform fault. The edge of continental crust is often clearly marked by a sharp drop of the acoustic basement produced by large offset on a series of normal faults (Figures 4 and 5). Elsewhere, volcanic intrusion and stratiform deposits along the Volcanes fault (Figure 3) produce shallower acoustic basement and noise shadows that mask the boundary of continental crust. Near the shelf edge offshore Puertecitos (Figure 3), well P-1 of PEMEX bottomed in Cretaceous granitic basement at 3000 m and cut a 150 m thick porphyritic andesite volcanic unit dated 8.0 ± 1.0 Ma (wr, K/Ar) (PEMEX, 1982, unpublished report). The Ulloa99-5 and PEMEX seismic lines also indicate that felsic intrusive and volcaniclastic deposits punctuate the late Miocene to Pleistocene siliciclastic sedimentary wedge on the continental shelf [*Helenes et al*., 2009; *Persaud et al*., 2003].

[19] The central Upper Delfin basin lacks direct evidence of continental crust beneath the thick sedimentary sequence (Figures 4 and 5). The basin axis contains two overlapping northeast trending rifts and ridges with bathymetric expression; another, similar rift lies within the adjacent Lower Delfin basin (Figure 3). Extension is accommodated by a

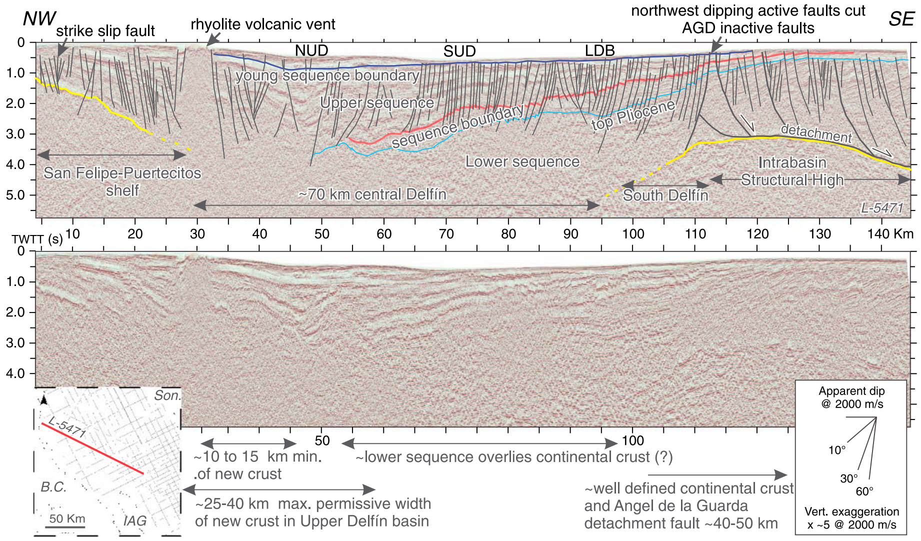

Figure 4. Seismic line 5471 across the structural high between the Upper Delfin basin and Tiburón basin. A series of southeast dipping listric-normal faults over the Intrabasin Structural High merge at depth into the basement high (yellow horizon). This surface is interpreted as a detachment (the Angel de la Guarda Detachment fault or AGD) that juxtaposes the sedimentary sequence and the continental crust. The seismic horizon in red indicates that the lower sequence was deposited in both basins, whereas the upper sequence is thin over the structural high and becomes progressively thicker towards the Upper Delfin basin. The light blue horizon is top Pliocene based on correlation of this seismic horizon in well T-1 of PEMEX [*Helenes et al*., 2009]. The Upper Delfin basin contains two active depocenters NUD-North Upper Delfin and SUD-South Upper Delfin. The LDB projects to the northeast and form a third active depocenter defined by narrow sag in this seismic section (also see figure S2).

fault array that strikes N20–30°E, with dips predominantly towards deeper parts of the basin (Figures 2 and 3). In the south subbasin (SUD), dip-slip faults are moderate to steeply northwest dipping, and strata cut by the faults are tilted to the southeast indicating that the faults may have formed at higher angles than their present dip (Figures 4 and 5). Surface bathymetric lows do not correspond to structural troughs in seismic sections (e.g., Figure 4), indicating movement of depocenters through time. The deepest trough in the north subbasin is filled with two sequences separated by a young regional unconformity (Figure 4). Above the unconformity strata dip to the southeast and fill the axial trough. The

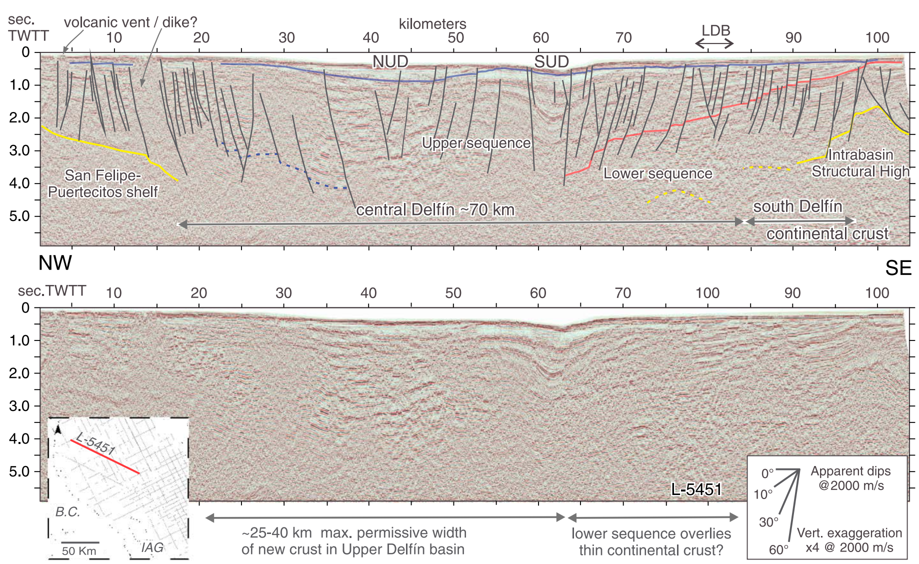

Figure 5. Seismic line 5451 across the Upper Delfin basin. The horizon in yellow is the acoustic basement interpreted as continental crust (inferred when dashed). The red horizon is a major sequence boundary that separates the lower and upper sequences. Note the thickening of the upper sequence towards the NUD. In this seismic section, the SUD has a deeper and narrower axial through as compared to the NUD. Note that expression of the active LDB diminishes in this seismic image.

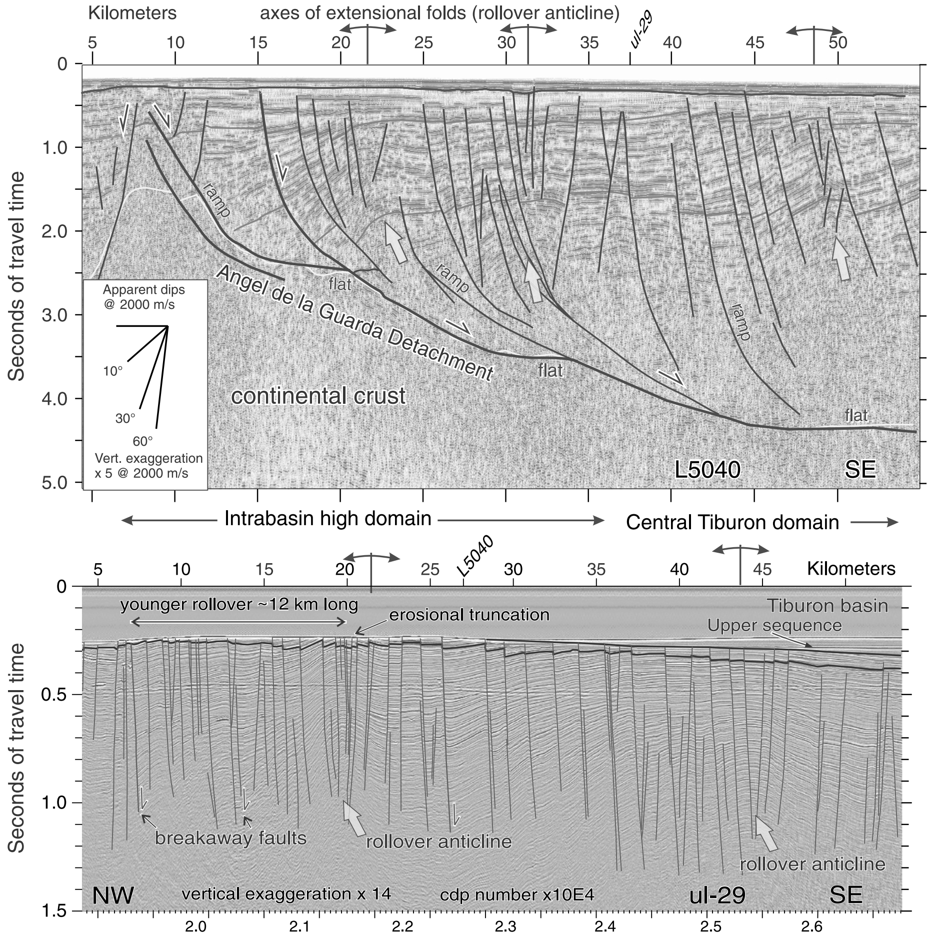

Figure 6. (a) Detail of seismic line 5040 across the intrabasin structural high (ISH). Southeast dipping listric-normal faults merge at depth into a detachment surface that juxtaposes the synrift sequence of Tiburón basin (lower sequence) over thinned continental crust. Two extensional folds and growth sequences form in successively younger strata toward the northwest and are related to different breakaway faults. Note that extensional folds develop over a ramp-flat surface limited by an older breakaway fault that cuts the acoustic basement. White arrows mark the axes of the rollover anticlines and the uppermost strata affected by extensional folding. (b) High-resolution image of line ul-29 with detail of two extensional folds over the Intrabasin Structural High beneath this image. Note that the crest of each anticline is cut by a dense, closely spaced array of normal faults with opposite heave from the axis of the anticline. The black seismic horizon marks an unconformity and a sequence boundary that separates the postrift and synrift sequences in Tiburón basin. Note erosion at the crest of the extensional fold near km 20. The two seismic lines are oriented NW-SE but intersect each other as indicated (see Figure 3).

bathymetric low in the southern subbasin is located at the toe of the uppermost young sequence, which thins to the southeast toward the Intrabasin Structural High.

[20] The northeast trending axial trough within the Lower Delfin basin is deepest in the southwest, with steep fault-controlled scarps nearly 400 m high near its intersection with the Ballenas Transform fault [*Persaud et al*., 2003]. These faults and the axial trough project northeastward with smaller vertical offset and opposed throw in both flanks (Figure 3, e.g., between km 90 and 100 in Figures 4 and S2), forming a relatively narrow, ~8 km wide depocenter controlled by active faults that produce small bathymetric scarps. A significant difference in thickness of the upper synrift sequence up to 3.5 s thick in the Upper Delfin basin and <1.0 s thick in the Lower Delfin basin (e.g., near km 45 and 90, respectively, in Figure 5) indicates that more extension and subsidence have occurred in the Upper Delfin basin compared to the Lower Delfin basin, which had a later onset of extension. The diffuse eastern boundary of the Upper Delfin and Lower Delfin basins is probably controlled by a N-NW striking fault system parallel to South Cerro Prieto fault (Figure 3). Coverage of seismic lines in the area between the South Cerro Prieto fault and the eastern end of the Upper Delfin basin is insufficient to correlate individual faults.

[21] Continental basement is imaged along the southern margin of the Upper Delfin basin (Figure 3) and the northwest flank of the Intrabasin Structural High (Figures 3 and 4). Active northeast striking, northwest dipping normal faults in this area produce fault scarps and active subsidence to the northwest. The active faults cut older northeast striking, southeast dipping, mostly inactive faults found over the northwest flank of the Intrabasinal Structural High (near ~ km 110 in

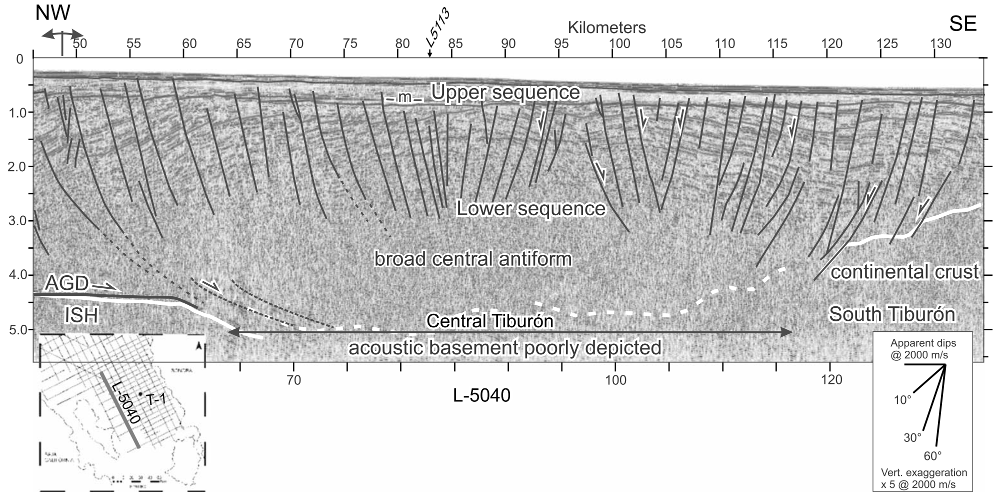

Figure 7. Seismic line 5040 across the Tiburón basin. To the left (NNW), the acoustic basement constitutes the footwall block of the Angel de la Guarda Detachment fault (AGD) that juxtaposes the late Neogene sedimentary deposits and continental basement. An acoustic basement becomes poorly defined towards the central Tiburón near 5.0 s. The central Tiburón contains a broad antiform with strata gently dipping towards both the NW and SE basin margins. NE striking dip-slip faults with opposed throw direction cut the strata. The acoustic basement is poorly defined between kilometers 65 to 120 in this profile.

Figures 4 and S2). These older faults tilt the strata to the northwest above the domed basement.

[22] The Upper Delfin basin contains two main stratigraphic sequences that provide key information about when Tiburón and Delfin basins became separated and oblique extension localized to the northwest. The lower sequence overlies acoustic basement of the Intrabasin Structural High (Figures 4 and 5) and thickens to the northwest into the Delfin basin where acoustic basement is not imaged. The sequence boundary deepens below resolution near ~3.5 s (at km 55, Figure 4). The upper sequence in the Upper Delfin basin becomes systematically thicker to the northwest, toward the continental shelf, where it is cut by a series of northeast striking normal faults at the shelf edge (Figure 4). Here the upper sequence reaches 4–5 km (3.5 s) thick, and the main depocenter is located at the intersection of the Volcanes fault zone and the northeast striking fault array that splays into the Upper Delfin basin (Figure 3). Over the Intrabasin Structural High, the upper sequence thins to the southeast where it becomes a thin veneer or is entirely absent (Figure 4). Therefore, we interpret the upper sequence to mark the onset of rapid subsidence in the Upper Delfin basin and the waning of subsidence in the Tiburón basin, where a regional unconformity marks the base of the upper sequence.

[23] Seismic lines 5471 and 5451 across Upper Delfin basin indicate the gap where no acoustic basement can be image is less than 70 km in both (Figures 4 and 5). Therefore, a 70 km long basement gap is the maximum possible width of new crust across the Upper Delfin basin. Furthermore, new crust is likely less than 40 km wide if the lower sedimentary sequence is inferred to everywhere overly continental basement, even where it lies deeper than can be directly imaged (Figures 4 and 5).

4.2. Intrabasin Structural High

[24] The Intrabasin Structural High separates the Upper Delfin basin from the Tiburón basin. This extensional domain contains three main structural elements: (1) A north-northeast trending intrarift basement high, (2) distributed north-northeast striking faults and extension-related folds, and (3) a northeast striking detachment fault with transport direction of the upper plate to the southeast. The intrabasin basement high is a broad antiform with axis oriented ~ N12°E. It is recognized over a distance of ~50 km, from the northern tip of Isla Angel de la Guarda towards the north-northeast (Figure 3). Over this structural high, the acoustic (continental) basement is warped into a broad dome-shaped antiform that rises up to 1.5 s at its crest (TWTT). It is 10–14 km wide at 3 s and expands to 28 km wide at 3.5 s (Figures 4 and 5). Along the west flank of the structural high, northwest-directed, northeast striking normal faults define the boundary between the tectonically active Upper Delfin basin and the inactive Tiburón basin.

[25] Correlation of faults and extensional folds axes over the Intrabasin Structural High defines three low-amplitude, gentle asymmetric anticlines 2 to 4.5 km wide (see Figures 3, and 6a and 6b). The axis of the largest anticline trends ~ N10°E and is located ~12 km southeast of the axial crest of the much broader basement high (see Figure 6a). Two shorter anticlines are located farther southeast of the larger anticline (Figure 6b), but all three anticline axes are oriented subparallel within a north-northeast trend. The three folds are asymmetric and resemble northwest dipping monoclines; their crests are cut by a pattern of closely spaced normal faults that strike on average N10°E and have opposite throw on both fold limbs (Figures 6a and 6b). Strata in the northwestern flank of the largest monocline clearly define a fan-shaped sequence and terminate downward along a large north-northeast striking listric-normal fault (Figure 6a). This fault is a southeast-directed detachment—the Isla Angel de la Guarda detachment (AGD)—that is one of the main faults controlling the Tiburón basin.

[26] Due to their distinctive monoclinal geometry and relationship to the AGD, we interpret these extensional folds to be rollover anticlines with fold axes oriented perpendicular

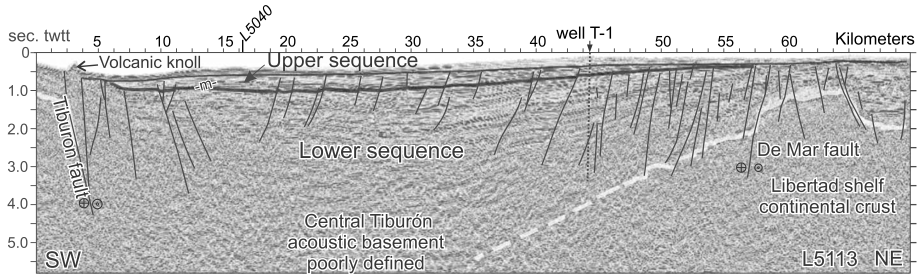

Figure 8. Seismic line 5113 across central Tiburón basin; the PEMEX well T-1 penetrated ~4.8 km of mid to late Miocene to Pleistocene marine deposits [*Helenes et al.*, 2009] without hitting basement, which deepens below resolution of the seismic image east of well T-1. Discontinuous deep reflectors probably indicate the base of the sedimentary sequence at nearly 5.5 s (> 7 km thick) towards the west. Two volcanic protrusions rise from seafloor on the Tiburón fault zone.

to the northwest tectonic transport. The fold axes are located 5 to 12 km away from northeast striking steep normal faults that root listrically into the AGD at depth (2.0–3.5 s of TWTT) (Figure 6a). The acoustic basement beneath the extensional fold is corrugated and contains discontinuous reflectors. The fold axes are clearly located over a flat acoustic reflector southeast of the fault ramp (see Figures 6a and S4). The flat segment is ~4–5 km long and bends antilistrically to deeper levels where it roots into a structurally lower detachment segment again apparently cut by an older listric breakaway fault with a hanging wall fault-bend fold (Figure 6a). Below 3.5 s, the basement is poorly defined, although a third extensional fold is detected at ~3.5 s (e.g., near km 50 in Figure 6a), suggesting that the pattern of listric fault splays and asymmetric hanging wall folds continues to depth toward the southeast. The fanning strata in the hanging wall of the listric-normal faults are each up to ~1.5 s thick, and the pattern of shallower (e.g., younger) fault-bend folds toward the northwest clearly indicates a progressive younging of activity in this direction, toward the axis of the Intrabasin Basement High.

[27] A distinctive secondary fault pattern exists over the fold crest on the hanging wall of listric faults. The high-resolution seismic lines of Ulloa-99 show in great detail the upper (1.5 s) structure of the youngest and largest rollover anticline in the west (Figure 6b). A series of normal faults synthetic to the main fault ramp accommodates additional distributed extension on the more steeply dipping northwest limb of the monoclines. Past the crest axis to the southeast, the faults change throw direction mirroring and intersecting the synthetic faults at depth. These form a distinctive v-shape pattern over the crest of anticlines. Crest erosion of this fault-bend fold (Figure 6b) indicates that nearly 300 ms of sedimentary deposits has been removed over this anticline and a thin veneer of unconformable recent sediments overlies the fold crest and thickens to <0.2 s to the southeast. The unconformity suggests that fault-bend folds predate tectonic inversion and erosion of sediments at the crest.

[28] Timing of slip on the AGD correlates with the lower sequence that is tectonically juxtaposed (and thinned) over the Intrabasin Structural High that forms its footwall and correlates with the synrift sequence in the Tiburón basin [*Aragon-Arreola and Martín-Barajas*, 2007] (Figure 7). The AGD is well imaged below this section for ~40 km parallel to the inferred transport direction towards the southeast. The hanging wall of the detachment is cut by closely spaced, north striking, east dipping high-angle normal faults that merge at the detachment to the southeast (Figures 6a and 7).

4.3. Tiburón Basin

[29] The broad depocenter of the central Tiburón basin exhibits strata deeper than ~7 km (5.5 s). This domain is cut by a distinctive set of closely spaced, northeast striking normal faults (Figure 3). The dip direction changes near the axis of the basin and faults on either side dip inward toward the basin depocenter (Figure 7). Tilting associated with these northeast striking faults also produces two large-scale, very gentle low-amplitude antiforms. Overall, the sedimentary section dips gently away from the center of the Tiburón basin toward the northwest or southeast (Figures 7 and S4).

[30] Acoustic basement observed below the AGD within the Intrabasin Structural High is poorly resolved in the Tiburón basin due to the deterioration of resolution of seismic lines below 4.5 s TWTT; however, the basin contains more than 7 km of sedimentary fill that likely accumulated as the basin subsided above the AGD. This is consistent with the projection of PEMEX well T-1 in seismic line 5113 (Figure 8) that penetrated ~4.8 km of mid to late Miocene to Pleistocene marine deposits [*Helenes et al.*, 2009] without hitting basement. The east-west-oriented seismic lines indicate that the sedimentary section thickens towards the middle of the Tiburón basin rather than near the high-angle faults that delineate its lateral boundaries. Based upon the great thickness of gently deformed strata, and the lack of evidence for magmatic intrusions, we interpret that the continental basement beneath the Tiburón basin is intact and may correspond to the footwall of the AGD. However, the lack of a well-defined acoustic basement does permit that crustal rupture may have occurred here, with a maximum of ~60 km of new crust formed (Figures 7 and S4).

[31] The southern margin of the Tiburón basin comprises a continental shelf imaged in seismic lines north and northwest of Isla Tiburón (see Figures 9 and 10). Here the acoustic basement is well defined and extends relatively unfaulted northwestward for 25–30 km offshore Isla Tiburón to a maximum depth of 1.8 s below sea bottom (Figure 9). A basement drop to the west-northwest is controlled by two main faults named here West Desemboque and East Desemboque faults. These two faults mark an important structural basin boundary, forming a structural escarpment that drops the continental crust to below 4.0 s over a distance of ~10 km to the west-

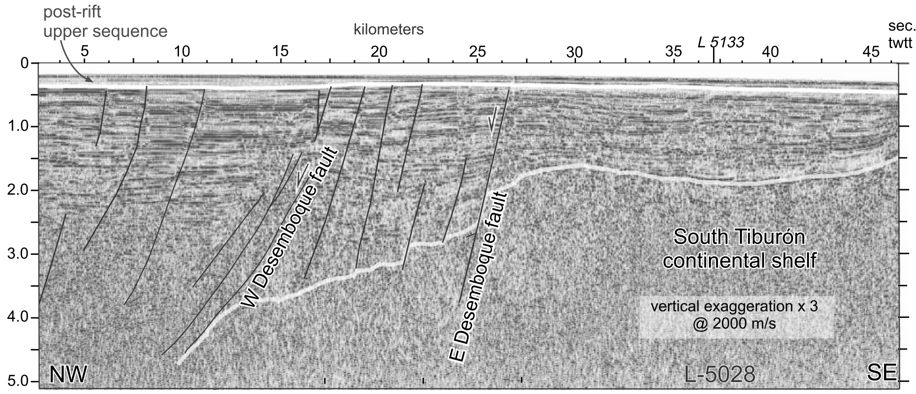

Figure 9. Seismic profile 5028 along the continental shelf in the south margin of the Tiburón basin. Here the continental crust extends ~25 km north into the basin. A fault zone between the East Desemboque and West Desemboque faults drops the basement through a series of northeast striking, northwest dipping normal faults. The upper horizon is the postrift sequence boundary that separates the lower and upper sedimentary sequences.

northwest. Multiple subparallel northeast striking, northwest dipping normal faults contribute to progressively deepen the acoustic basement (Figure 9). The West Desemboque and East Desemboque faults have their largest throw near the intersection with the De Mar dextral-oblique fault to the north and lose vertical displacement to the south-southwest. In this direction, the continental crust is cut instead by multiple north to northeast striking normal faults with smaller vertical throw towards the basin depocenter. The depth to acoustic basement imaged beneath the shelf reaches a maximum of 2.5 s ~10 km east of the Tiburón fault (Figure 10).

[32] The southernmost seismic line contains a prominent strike-slip fault zone that cuts crystalline basement and is interpreted to be part of the Tiburón fault system (see Figure 10). The overlying sedimentary sequence cut by the fault is ~2 km thick and clearly shows a well-defined unconformity near the top and a ~10 km-long lens-shaped sequence that laps down to the east and fills a channel near the trace of the fault. Several normal faults cut this unconformity but few faults cut the entire upper lens-shaped sequence. A conspicuous feature of the Tiburón fault in this area is a change in orientation from N35°W to N60°W (see Figures 3 and 10). We interpret that the southern projection of the principal fault zone shifts ~12 km to the east and indicates that either the Tiburón fault bends anticlockwise and/or the fault steps left. Alternatively, a separate fault may intersect and perhaps offset the Tiburón fault. The southernmost seismic line crossing the entire Tiburón basin also shows a prominent negative flower structure ~10 km east of the southward projection of the Tiburón fault (Figure 10). This fault zone is 3 km wide, and individual faults with small vertical throw merge at depth into a narrower fault zone that cuts the continental crust in the southern margin of the Tiburón basin (Figure 10).

[33] The Tiburon fault separates a block of continental crust that includes Isla Angel de la Guarda from the southwestern margin of Tiburon basin (Figure 3). Isla Angel de la Guarda is ~78 km long, 8–21 km wide, and predominantly composed of granitic basement covered with a nearly 1 km thick, middle Miocene volcanosedimentary arc sequence locally punctuated with synrift lava flows along the Ballenas Channel [*Delgado-Argote*, 2000; *Martín-Barajas et al.*, 2008a; *Martín-Barajas et al.*, 2008b]. The Neogene volcanosedimentary sequence overlies Cretaceous tonalite and prevolcanic arkosic sandstone in the northernmost and central parts of the island. This continental sliver detached from Baja California during the late Pliocene along the Canal de Ballenas transform fault. In seismic lines offshore, we interpret areas contiguous with Isla Angel de la Guarda as composed of similar upper crustal rocks. The abrupt structural boundary formed by the Tiburon fault loses expression towards the northwest, where its throw declines and the fault intersects many of the northeast trending faults and extensional folds of the Intrabasin Structural High. The northern third of the Tiburon fault also hosts two small volcanic edifices, which make up the only evidence of synrift volcanism within the Tiburón basin.

[34] The northeast margin of the Tiburón basin is formed by the continental shelf of Sonora. The principal structure is the De Mar fault, which strikes ~ N33°W along ~65 km

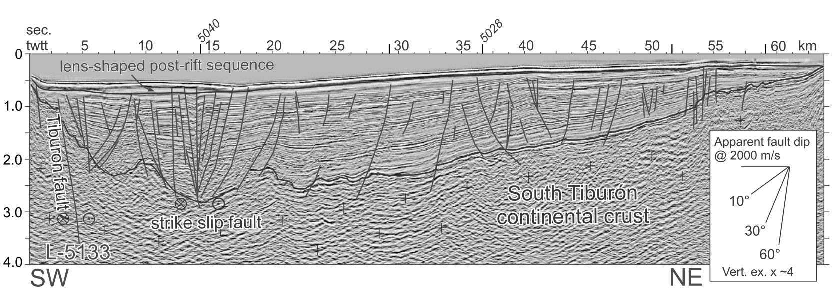

Figure 10. Seismic line 5133, across the south end of the Tiburón basin. This region contains a prominent strike-slip fault zone characterized by a broad negative flower structure east the trace of the Tiburón fault.

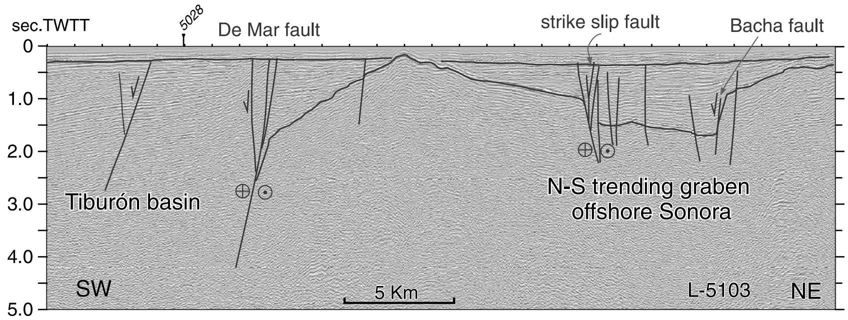

Figure 11. Seismic line 5103 across the Libertad domain showing a subparallel northwest trending graben in the continental shelf offshore Sonora. The Bacha and an unnamed strike slip fault are two N-NW striking oblique faults that control this graben. The strike-slip fault is defined by a negative flower structure typical of strike-slip faults. The Bacha fault controls a wedge-shaped sedimentary sequence above basement, indicating dip-slip westwards.

and ends near its intersection with the northeastward projection of the Angel de la Guarda detachment fault (Figure 3). The De Mar fault dips steeply to the west (>70° above 2 s) along its entire length, and, based on the lateral discontinuity of reflectors and a negative flower structure, this fault is interpreted to accommodate mainly dextral shear. This fault juxtaposes the thick sedimentary basin fill to the west, against crystalline basement to the east (Figure 11). The throw along the De Mar fault towards the central Tiburón basin is 1.3 s (~1.5 km) based on the vertical offset of the acoustic basement across the fault zone in the northern third of its length. The fault zone also includes two parallel faults located west of De Mar fault; the largest is located 3.3 km west and forms a negative flower structure that also suggests dextral strike slip (Figure 11).

[35] Northeast of the De Mar fault, the shallow continental crust underlies ~40 km wide shelf offshore Sonora west of Puerto Libertad (Figure 3). The acoustic basement in the footwall block of the De Mar fault rises up to ~500 ms (~1 s average) below the seafloor. Towards the northwest, the De Mar fault separates the Tiburón basin from the Tepoca basin, which constitutes a separate distinct rift segment along the eastern margin of the northern Gulf of California [*Aragón-Arreola and Martín-Barajas*, 2007].

[36] The continental shelf northeast of the De Mar fault contains two northwest trending grabens that are subparallel to the coastal ranges in Sonora (Figures 8 and 11). The largest graben is >50 km long and ~8 km wide, and the acoustic basement deepens to ~ 1 km (1.5 s) between the Bacha fault and an unnamed fault to the west. Lateral discontinuity of reflectors and a positive flower structure across these two faults strongly indicate that they also accommodate significant dextral slip (Figure 11). The acoustic basement in the Sonora shelf progressively deepens north into the Tepoca basin trough, which is cut by a series of northeast striking, west dipping normal faults that mimic the structure of the continental shelf offshore of Isla Tiburón.

5. Discussion

[37] The Tiburón and Delfin basins are located along a transport-parallel transect that records the history of opening of and lithospheric rupture in the northern Gulf of California. In this study, we have imaged and mapped the important faults that control subsidence of these major rift basins and have identified two major temporally discrete synrift sedimentary sequences. The earlier sequence was associated with detachment faulting beneath the Tiburón basin and exhumation of the intrabasin structural high. A similar history of detachment faulting probably also occurred within the Upper Delfin basin, as evidenced by thickening of early-formed strata towards the basin axis. Crustal rupture within the Upper Delfin and Lower Delfin basins is associated with increased magmatism, and focussing of extension and subsidence, forming a structural sag centered on the Upper Delfin basin axis. Here we summarize the evidence for this two-stage history of opening of the Tiburón-Upper Delfin transect and consider the implications of this history for the role of rapid sedimentation in the localization of rifting and lithospheric rupture.

5.1. Early Phase of Distributed Rifting and Deposition of Lower Rift Sequence

[38] The earliest record of rifting and crustal thinning observed in PEMEX seismic profiles is the deposition of the lower sedimentary sequence, which reaches more than 4 km in thickness in the Upper Delfin basin and likely >6 km in Tiburón basin. The lower sequence becomes much thinner (~1.5–2 km) but is deposited continuously across the Intrabasin Structural High that separates the two basins. Although faulting was broadly distributed across a progressively widening zone in the northern Gulf of California during the early phase of rifting, PEMEX seismic profiles demonstrate that basin-bounding normal faults evolved into two major detachment fault systems with dominantly ESE-directed tectonic transport. One is the Angel de la Guarda detachment, which exhumes the basement of the Intrabasin Structural High in its footwall, and the second is probably the listric San Pedro Mártir fault that forms the rift boundary in northeast Baja California, along with the related Sierra San Felipe and Sierra San Fermín detachment faults within its hanging wall [*Lewis and Stock*, 1998; *Seiler et al*., 2010] (Figures 12 and 13).

[39] The Tiburón basin is one of the largest rift basins in the northern Gulf of California at ~140 km length in the transport-parallel dimension. The PEMEX seismic data show that the northern part of Tiburón basin is floored by the Angel de la Guarda detachment (AGD), which can be traced for 40 to 50 km across the grid of seismic profiles (Figure 7). The dense

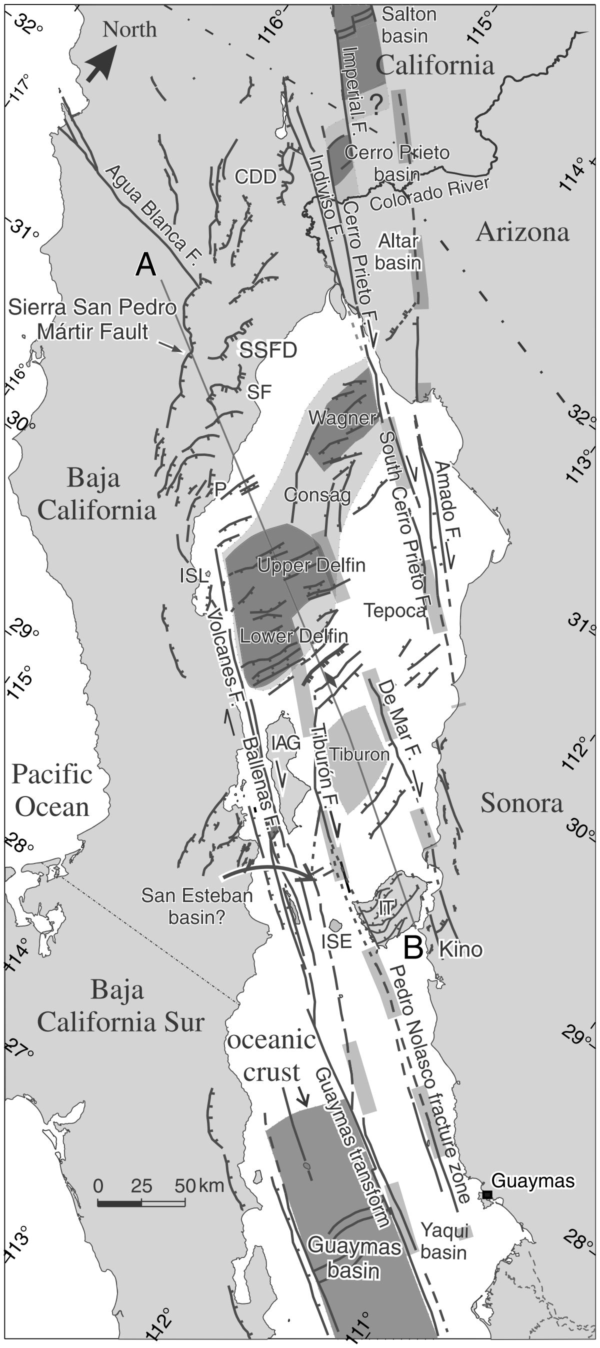

Figure 12. Summary tectonic map of the northern Gulf of California showing rift segmentation and extent of continental crust. Continental crust is not observed but inferred to exist in regions colored light grey. New crust formed by magmatic and sedimentary infilling following continental lithospheric rupture interpreted to exist in regions colored dark grey. Only the axial trough in Wagner basin is inferred to have new crust across the Tepoca-Wagner rift segment. In the Cerro Prieto and Salton Sea pull-a-part basins, the length of new crust is yet poorly defined, although preliminary results of the Salton Seismic Imaging Project indicate very shallow mantle velocities along the axis of the Salton Sea [*Han et al*., 2012]. To the south, the Guaymas rift segment has accumulated 240 to 280 km of new oceanic crust [cf. *Lizarralde et al*., 2007].

array of northeast striking normal faults is observed to sole listrically into the detachment. Although the acoustic basement is poorly depicted in the central Tiburón basin, we interpret that continental crust occupies the lower plate the AGD flooring the basin. This conclusion is based on three main observations: (1) the absence of intrusive igneous rocks and volcanism in the Tiburon basin, (2) the uniform thickness of the lower sedimentary sequence, and (3) the lack of significant, focused postdetachment deformation in the Tiburón basin. Our interpretation is consistent with results of González-Fernández and others [2005], and their 2D velocity-density model across Tiburon and Upper Delfin basin indicates a thicker lithosphere under the Tiburón basin, and an abrupt increase in seismic velocity from the lower crust to the mantle. In contrast, a low-density (partially molten?) upper mantle beneath Upper Delfin basins characterizes the velocity-density profile of *González-Fernández et al*. [2005]. Also, their seismic reflection profile shows layered seismic facies distinctive of mylonite fabrics in the lower crust beneath the Tiburón basin.

[40] The latest activity of the AGD is documented here by the existence of three discrete rollover anticlines expressed in successively younger strata toward the northwest (Figures 6a and 6b). These extensional folds are controlled by the ramp-flat geometry of listric-normal faults that constitute major strands of the detachment system. Thus, the younging of the rollover anticlines records northwestward migration of the northwestern margin of the Tiburón basin toward the intrabasin high.

[41] On the SE margin of the Tiburón basin, continental basement and strata of the lower sequence are cut by a series of WNW dipping normal faults that are antithetic to the ESE-directed AGD. Individual faults generally have small offset (<200 m), and none were observed to be associated with extensional folds that would indicate the presence of a different master fault on this margin of the basin. Therefore, we interpret the Tiburón basin to be a half graben controlled by the east-southeast-directed AGD, which contains the antithetic fault array of the southeast margin in its hanging wall and roots to the southeast beneath Isla Tiburón.

[42] Farther northwest in the Upper Delfin basin, structural controls on the lower sequence are not as clearly defined because key relationships are deeply buried beneath the younger stratigraphic sequences. Nonetheless, the Upper Delfin basin is located close to the Sierra San Felipe detachment system (Figure 12), which was active during the earliest phase of rifting starting at ~9–7 Ma along the Baja California margin [*Seiler et al*., 2010]. This system roots to the southeast, beneath the San Felipe-Puertecitos shelf and adjacent Upper Delfin basin, in a manner similar to how the Angel de la Guarda detachment roots beneath the Tiburón basin (Figure 13). The Upper Delfin basin is presently 110 km long in a transport-parallel dimension, which is intermediate in size between the Tiburón basin and supradetachment basins within Baja California rifted margin. Therefore, we suggest that the position of the Upper Delfin basin between two well-documented ESE-directed detachments, as well as the systematic decrease in hanging wall basin width from southeast (Tiburón and Upper Delfin basins offshore) to northwest (Sierra San Felipe and Valle Chico basin onshore) indicates that the entire Tiburon and Upper Delfin segment was controlled by an ESE-directed detachment fault system during

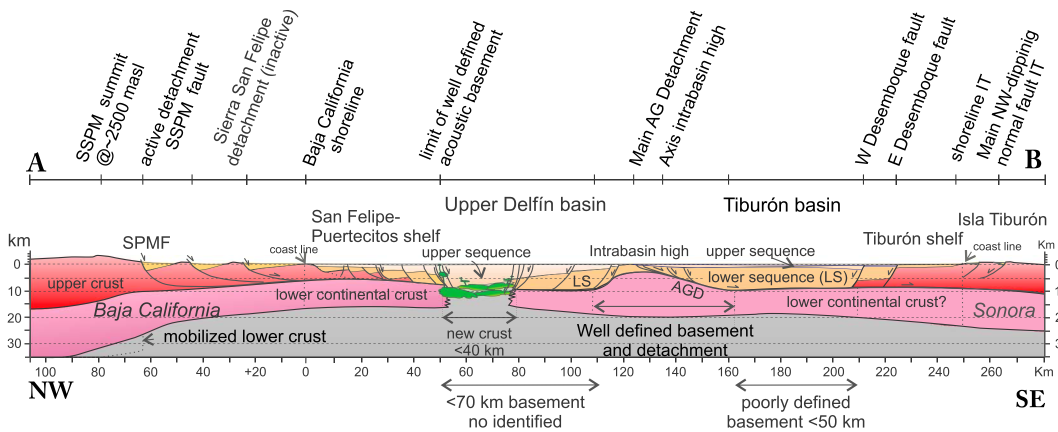

Figure 13. Crustal profile across Delfin-Tiburón basins used for calculations of the width of continental crust *versus* new crust along this rift segment (no vertical exaggeration). Our estimates (see Figure S1) indicate that continental crust floors a minimum of 65% of the ~250 km distance separating Baja California from the shoreline of Isla Tiburón. This requires lower crustal flow into the rift zone that delayed the onset of continental rupture in the Upper Delfin basin. The amount of lower crust added to this profile is significantly higher if the central Tiburón and the south Delfin basins are floored with lower continental crust. Thickness of the continental crust offshore is based on the seismic refraction profile of *González-Fernández et al*. [2005]. Crustal thickness onshore Baja California is from *Lewis et al*. [2001] and *Persaud et al*. [2007].

the early phase of rifting and deposition of the lower rift sequence. The consistent sense of tectonic transport and rotation of hanging wall strata strongly indicate that all of these basin-controlling faults merge at depth to form detachment faults that decouple the upper and lower crusts (Figure 13).

[43] During the first phase of rifting, faults along the lateral margins of the Tiburón basin linked with those of the Angel de la Guarda detachment system to accommodate the full three-dimensional strain of transtensional plate-margin shearing. The southwest margin is defined by the Tiburón fault, which has an arcuate trace and curves toward the northwesternmost breakaway fault of the AGD (see Figure 3). The De Mar fault defines the NE basin margin and has a more linear northwest trending trace. Both lateral-margin fault systems have segments that form flower structures and juxtapose stratigraphic sequences that cannot be correlated; thus, they likely accommodate large amounts of strike-slip displacement, presumably with a dextral sense. Nonetheless both faults largely dip inward toward the basin and record >2 km of dip-slip throw, and thus they clearly have oblique dextral-normal kinematics.

[44] In contrast to the Tiburón basin, discrete faults bounding the lateral margins of the lower stratigraphic sequence in the Upper Delfin basin were not identified in the PEMEX seismic lines. These structures may be obscured by younger strata, which are much thicker in the Upper Delfin basin, or they simply may not exist and instead the lateral boundary may be a more diffuse zone of penetrative deformation and vertical-axis rotation. Both types of lateral boundaries inferred from the compilation of seismic data have also been observed in on-shore structural analyses. The Laguna Salada fault is an excellent example of a discrete lateral ramp with oblique-slip kinematics that transfers extensional shearing on the Cañada David detachment, which controls the subsidence of the Laguna Salada basin [*Axen and Fletcher*, 1998]. In contrast, detachment segments in the Sierra San Felipe terminate gradually along northward-decreasing gradients in the amount of finite slip [*Seiler et al*., 2010; *Seiler et al*., 2011]. Therefore, we do not rule out the possibility that the northeast lateral margin of the Upper Delfin basin is defined by distributed faulting and block rotation in a broad accommodation zone.

5.2. Late-Phase Lithospheric Rupture and Deposition of Upper Rift Sequence

[45] Deposition of the upper synrift sedimentary sequence records a major reorganization of the transtensional fault network that accompanied lithospheric rupture along this transect in latest Pliocene time. The upper sequence is best developed in the Upper Delfin basin where it reaches >4 km in thickness and is penetratively faulted. The thickness of this upper sedimentary package decreases markedly toward the southeast against the Intrabasin Structural High and is uniformly thin (tens to a few hundreds of meters in thickness) in the Tiburón basin, where it postdates most of the faulting. The strongly reduced thickness of strata, diminished intensity of faulting, and the erosion of extensional fault-bend folds over the Intrabasin Structural High together clearly record the cessation of detachment faulting along the AGD beneath the Tiburón basin. Farther to the northwest along this transect, detachment faulting, which was broadly coeval with the lower synrift sequence during late Miocene to Pliocene time in the San Felipe region, was also observed to have ceased [*Seiler et al*., 2010]. Though the San Pedro Mártir fault and other rift-margin normal faults in northeast Baja California and Isla Tiburón remain active into the Quaternary at low rates, we interpret that the upper synrift sequence defines the widespread abandonment of early-phase detachment faults in the Sierra San Felipe and strong localization of plate-margin shearing into the Delfin basins.

[46] Voluminous synrift magmatism is unique to the upper sedimentary sequence in both Delfin basins and is not observed in the Tiburón basin or elsewhere along this rift segment. The largest volcanic edifices are generally located near

the axial trough of the Lower Delfin basin or adjacent to the Volcanes fault and the northwest margin of the Upper Delfin basin (Figure 3). The volcanic record in the northern Gulf of California and Salton Trough indicates that only evolved, less dense magma is injected in the thick sedimentary sequence. Andesite to rhyolite magma sampled in submarine and subaerial volcanic centers is derived from the differentiation of basaltic MORB-type parent magmas that are inferred to pond at depth in active rift basins [*Martín-Barajas et al*., 2008a; *Schmitt et al*., 2013; *Schmitt and Vazquez*, 2006]. We propose that new crust in the Upper and Lower Delfin basins is composed of basaltic and differentiated igneous rocks that intrude and metamorphose Late Miocene to Pliocene sedimentary rocks. This new hybrid crust should have an integrated lower density and attenuated magnetic responses compared to that of typical oceanic crust.

[47] In summary, PEMEX seismic profiles show that the widespread abandonment of early-phase detachment faults was accompanied by the onset of voluminous synrift magmatism and localization of extension to its present position in the Upper and Lower Delfin basins. Therefore, we interpret the deposition of the upper sedimentary sequence to mark the onset of lithospheric rupture and birth of the Upper and Lower Delfin basins seafloor spreading system. Though acoustic basement is incompletely imaged beneath the Tiburón basin, we interpret the lateral continuity of the thick lower sedimentary sequence, along with the lack of volcanism and low seismic velocities found by *González-Fernández et al*. [2005] to preclude crustal rupture here. The axial trough of the Lower Delfin spreading center links with the Canal de Ballenas transform fault, and together these faults define the modern Pacific-North American plate margin. Farther south, the Canal de Ballenas transform steps over to the Guaymas transform fault that bounds the Guaymas spreading center, which has a much longer history of seafloor spreading than is recorded in the Upper and Lower Delfin basins [*Lizarralde et al*., 2007]. Initially, therefore, the Guaymas transform fault must have stepped northward in the area southeast of Isla Angel de la Guarda to connect with the network of early-formed detachments and their lateral basin bounding faults and accommodation zones that bracket the Tiburón basin. Subsequently, ca. 2 Ma, the Canal de Ballenas fracture zone (e.g., Volcanes fault) must have propagated tens of kilometers along strike to the northwest, connecting with faults in the Lower Delfin basin that propagated along strike to the southwest, This new, hard-linked fault system localized the majority of plate-boundary motion, detached the Isla Angel de la Guarda block from Baja California, and bypassed and abandoned extension in the Tiburón basin. It is curious that continental rupture did not occur instead within this wider rift basin, but instead occurred in the somewhat narrower Upper Delfin basin and nascent Lower Delfin basin. Therefore, other factors besides the magnitude of upper crustal thinning, such as lower crustal flow, prolonged slip in the detachment, high thermal gradient, elevated pore pressure, and possibly interbedded evaporate deposits, were more important in controlling continental rupture.

5.3. Implications for the Continent-Ocean Transition Under Thick Deltaic Sedimentation

[48] Our structural interpretation demonstrates that the Delfin and the Tiburón rift basins in the northern Gulf of California are controlled by splays of a major SE-directed detachment system and underpinned by strongly thinned continental crust. In a transport-parallel transect extending 250 km across the Gulf of California, continental crust definitively observed in PEMEX seismic profiles for 140 km (Figures 13 and S1). If the lower sedimentary sequence was deposited exclusively upon continental crust, prior to full lithospheric rupture in the Upper Delfin basin, then an additional 70 km width of continental crust may be inferred. In contrast, new hybrid crust composed of voluminous igneous intrusions and metamorphosed sedimentary rocks can only be definitively mapped over length of 25 to 40 km through the Upper Delfin-Tiburón rift segment in the northern Gulf of California. Outside of the zone of underlain new crust, the upper sedimentary sequence becomes dramatically thinner and indeed is largely absent in areas where continental basement is imaged in seismic profiles. Therefore, in a transport-parallel transect extending from the Main Gulf Escarpment in Baja California, across the Gulf and Isla Tiburón (Figure 13), our best estimate of the ratio of new hybrid crust to thinned continental crust is between 25:315 and 40:300, or 8 and 13% (Figures 13 and S1).

[49] The volume of thinned continental crust that we document to exist across the northern Gulf of California exceeds the amount that could have existed in prior to extension by more than a factor of four. *Oskin and Stock* [2003a, 2003b] demonstrated through multiple correlations of pre- and synrift tuffs that the Sonora and the Baja California margins were separated by 10–20 km. However, if the volume of existing continental basement is restored to a thickness of 35 km, the initial transport-parallel length of the rift should be >80 km. Clearly, these simple calculations require that an enormous amount of continental crust has been transported into the northern Gulf of California. The key questions are where did the crust come from and how did it get there?

[50] The excess continental crust in the northern Gulf of California is overwhelmingly lower crust. The CORTES seismic refraction profile showed that the floor of the Tiburón basin as well as the intrabasin structural high have seismic velocities consistent with lower continental crust [*González-Fernández et al*., 2005]. In fact, upper crust is largely restricted to the margins of the transect, and crude estimates of its volume suggest that the coastline restore to within 23 km of each other if the initial upper crustal thickness was ~17 km (Figure 13). Therefore, our data independently confirm the estimated 255 ± 10 km of opening that restores coastlines of the conjugate margins to within 10–20 km [*Oskinet et al*., 2001]. An inescapable conclusion of this work is that detachment faulting in the northern Gulf of California accommodated 1000% extension of the upper crust prior to lithospheric rupture.

[51] The excess lower crust in the northern Gulf of California must have been derived from the rifted margins through detachment faulting and lower-crustal flow [*Wernicke*, 1985]. The unextended Baja California microplate has a crustal thickness that reaches 40 km [*Lewis et al*., 2001], which suggests that the lower crust has not been extensively mobilized from this margin. Nonetheless, immediately adjacent to transect, the lower crust thins and the highest mountains of the Sierra San Pedro Mártir along the rift flank lack deep isostatic roots [*Lewis et al*., 2001; *Persaud et al*., 2007]. Thus, flow of lower crust across the Baja California rift flank likely contributed a minor amount (<10%) of the excess lower crust within the rift.

[52] In contrast, the Sonora margin has been the site of large-magnitude extension for much of the Neogene, with large-offset detachment faults that have unroofed midcrustal rocks [*Nourse et al*., 1994; *Wong and Gans*, 2008]. Lower crustal flow is required to maintain high mean elevations and relatively thick crust after large magnitudes of extension (hundreds of percent) and the thinning to near-complete removal of the upper crust above detachment fault systems [*Block and Royden*, 1990]. A low-viscosity lower crust is also required to decouple localized detachment faulting in the upper crust from distributed thinning in the lower crust [*Buck*, 1991]. We suggest, based on the large excess of lower crust imaged within beneath Upper Delfin-Tiburón basins, that such decoupling took place over entire width of the Gulf Extensional Province up until crustal rupture within the past two million years. Beneath the Tiburón basin, the PEMEX seismic profiles demonstrate that a midcrustal detachment system, the AGD, rooted under the Sonoran margin and facilitated the unroofing of its lower crust (Figure 13). This flow of lower crust from beneath Sonora was maintained while upper crustal extension was localized into the Gulf of California [*Oskin and Stock*, 2003a, 2003b; *Oskin et al*., 2001]. In order to provide sufficient material, lower crust must have been mobilized from a wide swath of the Sonora margin and moved laterally toward the Gulf of California via Poiseuille flow (channel flow). We conservatively estimate that more than 90% of the excess lower crust in the Delfin-Tiburon transect was derived by deflation of the Sonoran margin through channel flow and unroofing in the footwall of the Angel de la Guarda Detachment fault system.

5.4. A Sediment-Enhanced Core-Complex Mode of Continental Extension?

[53] The orogen-scale structural relations documented indicate an unusual mode of continental extension took place in the northern Gulf of California—an area characterized by an overwhelming input of sediment from the Colorado River [*Dorsey*, 2010]. Our work confirms the general scenario of a late transition from core complex to narrow-rift mode of continental extension in the Tiburon-Delfin segment as was first proposed by *González-Fernández et al*. [2005]. Either a single detachment fault with splays (San Pedro Martír - AGD) or, more generally, a system of detachment faults that rooted into a zone of distributed lower crustal thinning, decoupled the upper, predominantly sediment-derived crust of the northern Gulf of California from a lower crust unroofed largely from the Sonora continental margin. Decoupling of upper- and lower-crustal extension is the defining characteristics of core-complex mode of continental extension [e.g., *Block and Royden*, 1990; *Buck*, 1991]. In the case of the Gulf of California, upper crustal extension localized along a narrow zone ca. 6 Ma [*Oskin et al*., 2001], while detachment faulting permitted the influx of lower crust into the rift. However, upper crustal extension did not remain focused in a narrow region as is envisioned for a rolling-hinge style of core-complex development [*Buck*, 1991; *Wernicke and Axen*, 1988]. Instead, the initially narrow upper-crustal rift that existed at 6 Ma was supplanted by widely distributed upper crustal thinning as the lower crust was unroofed via the Angel de la Guarda and San Pedro Mártir-San Felipe detachment systems, and the upper crust grew by the influx of Colorado River-derived sediment, which first entered the Salton Trough and northern Gulf of California at about 5.3 Ma [*Dorsey et al*., 2011]. This sediment-enhanced core-complex mode of continental extension allowed both the Tiburón and Upper Delfin basins to simultaneously lengthen by tens of kilometers and absorb the majority of the ~5 cm/yr oblique divergence between the Pacific and North America plates. After approximately 1000% extension of the upper crust, rifting evolved back to a narrow mode and proceeded to rupture the lithosphere in the Upper Delfin basin. However, our work shows that this transition occurred much later than previously thought [e.g., *González-Fernández et al*., 2005]. The portion of the Upper Delfin basin marked by a dramatic subsidence and thickening of the upper sedimentary sequence is only 70 km wide, and only 25–40 km of new hybrid crust has formed since rupture. Given relative plate motion of 47 mm/yr [*Plattner et al*., 2007] the transition to narrow rifting and continental rupture should have occurred less than 1 Myr ago.

[54] *Bialas and Buck* [2009] developed a mechanical model to show that thick deltaic sedimentation should enhance narrow-rift mode of continental extension by reducing the buoyancy force difference that inhibits the focusing of lithospheric extension, and narrow-rift mode of continental extension is thought to lead rapidly to lithospheric rupture because of the coupling of extension in the crust and upper mantle [*Buck*, 1991]. *Bialas and Buck* [2009] used along-strike variations in rift style in the Gulf of California to support their model and reported that the northern Gulf of California was a good example of the association of thick deltaic sedimentation and narrow-rift mode of continental extension. However, our work shows that the heavily sedimented Tiburon-Delfin transect was probably one of the very last rift segments to transition to narrow rifting and continental rupture. This contrasts with Guaymas rift segment, which is located beyond the southern limit of the Colorado River delta (Figure 12). The Guaymas segment is associated with modest sedimentation [*Aubry et al*., 1982] and probably the earliest rupture of any rift segment within the Gulf of California, with 280 km of mafic crust [*Lizarralde et al*., 2007]. This is the only segment in the Gulf of California that may have an association of sedimentation and the early onset of narrow mode rifting. Therefore, we contend that the *Bialas and Buck* [2009] model does not adequately capture the processes that led to continental rupture in the northern Gulf of California. We find that contrary to their model results, the most consistent association of thick deltaic sedimentation is with detachment faulting and delayed lithospheric rupture.

[55] Regional systems of low-angle detachments that control vast rift basins are exposed throughout both margins of the Salton Trough and northern Gulf of California. Deltaic deposits of the Colorado River fill at least three major rift segments defined by changes in polarity of normal faulting [*Axen*, 1995]. In each segment, detachment faults are widely exposed on the margins [*Axen and Fletcher*, 1998; *Bennett et al*., 2013; *Bryant*, 1986; *Seiler et al*., 2010; *Siem and Gastil*, 1994] and also imaged in the subsurface across the extensional province [*González-Fernández et al*., 2005; *González-Escobar et al*., 2012; *Pacheco et al*., 2006; *Gallardo-Mata*, 2013]. Conversely, detachment faults are not recognized around the rest of the Gulf of California, where there are no thick sequences of deltaic sedimentation. However, this spatial association need not imply a genetic relationship because, in general, the onset of

detachment faulting predated the onset of thick deltaic sedimentation estimated at 5.3 Ma [*Dorsey et al*., 2011]. Moreover, rift segments dominated by late Miocene to recent detachment faulting restore to a position adjacent to areas of large-magnitude extension within the Sonoran margin. Therefore, it is likely that continental lithosphere in this region was predisposed to have a highly mobile lower crust prior to the onset of the opening of the Gulf of California. Nonetheless, the scale of detachment faulting evident beneath the northern Gulf of California appears to have been strongly influenced by the input of large volumes of sediments into the widening rift.

[56] Several complimentary mechanisms related to thick and rapid sedimentation could have played an important role in maintaining the stability of detachment faults beneath the Gulf of California that opened the Upper Delfin and Tiburón basins by ~60 to 80 km and ~100 km, respectively, prior to lithospheric rupture. First, the sediment input maintained upper-plate thicknesses, preventing the formation of a typical rolling-hinge system, and reducing the amount of crustal volume that needed to be filled by the inflow of lower crust [*Gans*, 1987]. Lower crustal doming appears to have occurred only at the intrabasin structural high. Second, the sediment-filled basin reduced the buoyancy contrast with the adjacent rift margins, and prevented upward flexure of the detachment fault footwall—both processes that tend to cause rifting to migrate into less extended areas [*Buck*, 1991; *Forsyth*, 1985]. Third, blanketing by thick sediments maintains higher temperatures at the basin floor, where we infer juxtaposition of sediments against warm, exhumed lower crustal rocks across detachment-fault controlled contacts. Similar contacts have been imaged elsewhere in the northern Gulf of California [*Pacheco et al*., 2006] and are inferred to be forming today in the Laguna Salada basin [*Fletcher and Spelz*, 2008; *Spelz et al*., 2008]. Fourth, rapid sedimentation (>1 km/Myr) of fine-grained sediments (silt and clay) can lead to over-pressurization of sediment pore water as the sedimentary column undergoes compaction [*Audet and Fowler*, 1992]. Both the lithology [*Helenes et al*., 2009] and sedimentation rate in the northern Gulf of California [*Dorsey*, 2010] were sufficient to generate overpressure. This could have driven the effective stress state partially into the tensile regime, where slip on gently dipping normal faults becomes mechanically feasible [*Axen*, 1992; *Axen and Selverstone*, 1994].

6. Conclusions

[57] Analysis of PEMEX seismic reflection data collected in the 1980s combined with geological constraints from the rifted margins indicates that most of the history of rifting between San Felipe and Isla Tiburon was dominated by detachment faulting. Extreme crustal thinning associated with ~1000% extension was compensated by lower crustal flow from below and thick deltaic sedimentation from above. This phase of sediment-enhanced core-complex mode extension was associated with deposition of a lower sequence of late Miocene to Pliocene strata in both the Tiburón and Upper Delfin basins. The transition to deposition of thick upper sedimentary sequence in the upper Delfin basin marks the initiation of a narrow-rift mode that led to full lithospheric rupture in the northern Gulf of California. We estimate that between 25 and 40 km of new hybrid crust has formed in the Upper and Lower Delfin basins since full continental rupture.

[58] The structure of the Tiburon and Upper Delfin basins in the northern Gulf of California reveals key observations about the earlier, core-complex rifting mode. Strain was efficiently partitioned along shear zones linked to extensional domains within rift segments. Thinning of the crust occurred in the Upper Delfin and Tiburón basins controlled by detachment faults that exhumed continental basement from beneath the rift margins. This exhumed lower continental crust is directly imaged from basement acoustic reflectors under at least 65% of the Tiburon-Delfin rift segment and forms the core of a basement dome—the Intrabasin Structural High, that separates the Tiburon and Upper Delfin basins. The concomitant relationship between strike-slip faults and extensional dip-slip faults documented at specific locations in northwestern Baja California, the southwestern Salton Trough and northwestern Sonora, is clearly imaged offshore in the Tiburon-Delfin segment, and thus illustrates an efficient partitioning of strain in highly oblique rifts likely under rapid strain rates.

[59] Our crustal estimates based on mapping the acoustic basement constrain maximum possible closure of the Tiburon-Delfin rift segment to 80–90 km between shorelines in Baja California and Sonora starting with a 35 km thick continental crust. These results strongly suggest flow of lower crust beneath the thick sedimentary deposits in narrow-rift basins and allows continental crust to have accommodated >1000% of extension prior to rupture of the continental crust in the Upper Delfin basin in latest Pliocene time.

[60] The extreme degree of extension and unroofing of lower crust to form the basement of the northern Gulf of California was likely promoted by thick deltaic sedimentation from the Colorado River. Though this sediment input may have allowed rifting to remain localized within the Gulf of California, as predicted by the *Bialas and Buck* (2009) model, continental rupture here was delayed by several million years compared to basins farther south and away from the influence of the voluminous sediment. Based on the history of extension revealed by the seismic reflection data, we infer that sedimentation promoted the longevity of detachment faulting beneath the Tiburón and Upper Delfin basins, and that several complimentary mechanical effects of the thick sedimentary lid allowed the zone of crustal extension to broaden as the Gulf of California widened. These include the reduction of buoyancy contrasts, inhibition of crustal doming and flexure of normal-fault footwalls, thermal blanketing, and possibly the generation of overpressure by the rapidly compacting sedimentary column. Only very recently, within the past one million years, has rifting proceeded to crustal rupture and formation of new hybrid mafic-sedimentary crust beneath the Delfin basins. Based on similar patterns of faulting [*González-Fernández et al*., 2005; *Pacheco et al*., 2006] and late strain localization [*Aragon-Arreola and Martín-Barajas*, 2007], we propose that detachment faulting and delayed continental rupture occurred throughout the northern Gulf of California, which formed adjacent to already thinned and warm crust in the actively extending Sonoran basin and range province, and was everywhere subject to rapid and thick sedimentation from the Colorado River. This sediment-enhanced core-complex mode of extension may characterize other areas of continental breakup, especially where major river systems become funneled into narrow-rift basins.

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