Shear margins: Continent-ocean transform and fracture zone boundaries

DALE BIRD, Bird Geophysical, Houston, Texas, U.S.

Coordinated by R. Randy Ray and Lee Lawyer

As exploration extends into deeper water, it has become more important to understand the nature of the earth's crust beneath offshore sediments. That is, heat flow and related source rock potential usually require that sediments be deposited over continental crust. Hence, delineating the boundary between oceanic and continental crust becomes important. The material in this article was originally presented at the workshop "The Crust and its Structure" at SEG's recent Annual Meeting in Calgary. These results, part of a larger dissertation research project, also have been presented to several oil and gas exploration companies in Houston.

Although continental-oceanic crustal boundaries for shear margins are among the easiest to delineate, they are important to understand because their formation usually produces distinct geologic features. The remainder of this article reviews global geophysical data over several shear margins and focuses on their evolution and related structural, sedimentary, and thermal effects. These margins typically form after: (1) shearing of continental crust and complex rifting; (2) development of an active transform boundary separating oceanic and continental crust; and (3) passive margin formation along an inactive fracture zone that also separates oceanic and continental crust (Figure 1).

There are at least three significant differences between shear margins and passive margins formed by normal or near normal extension. First, the transition from continental to oceanic crust is relatively abrupt, with crustal thicknesses decreasing offshore from over 20 km to about 10 km or less over distances of 50-80 km. Second, complex rift basins develop along the continental side of the margin with structures formed by a spectrum of normal, wrench, and strike-slip faults since the dominant direction of crustal extension is subparallel to the margin. Third, highstanding marginal ridges, rising 1-3 km over the abyssal seafloor and 50-100 km wide, form along the continental side of the margin. This ridge formation is probably due to absorbed heat from juxtaposed oceanic crust as the ridge transform intersection (RTI) moves along the plate boundary; however, the structural history of some shear margins is complex, and constructional component(s) to ridge development cannot be ruled out. These ridges effectively trap prograding sediments, resulting in thick accumulations of rift and drift sequences.

Gulf of Guinea. The Côte d'Ivoire-Ghana transform margin formed by shearing along the Gold Coast related to the formation of the central Atlantic Ocean (118 million years ago). The ENE-trending transform margin intersects the NNE-trending cratonic Akwapim Fault Zone (Figure 2a), a Pan-African suture formed 600 million years ago (Edwards et al., 1997). The continental crust approaching the transform margin thins dramatically, over a distance of 20 km, from about 23 to 10 km (Figure 2b). Outboard of continental crust, typical fracture zone, and ocean crustal thicknesses, 3.5-5 km and about 7 km, respectively, have been measured by seismic refraction methods (Edwards et al., 1997). Oceanic crust is believed to be 80 million years old.

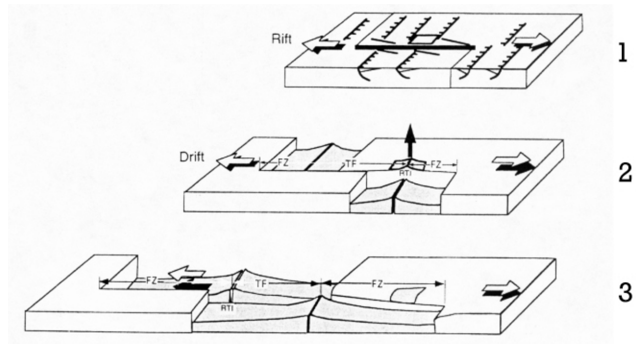


Figure 1. Generic three-stage model for shear margin formation (after Lorenzo, 1997): (1) rift: continent-continent shearing; (2) drift: continent-ocean transform boundary (active margin); and (3) passive margin: continent-ocean fracture zone boundary.

The Côte d'Ivoire-Ghana marginal ridge buttresses sediments of the deep Ivorian Basin to the north and towers 2.5 km over the abyssal plain to the south. Its overall length and width are about 130 and 25 km (Basile et al., 1993). Figure 2c shows a N-S reflection seismic line across the Côte d'Ivoire-Ghana transform margin. Ocean Drilling Program drill sites 959 and 960 (Leg 159) reveal continuous sedimentation throughout Cretaceous time—an intensely deformed deltaic-lacustrine sequence overlain by an undeformed clastic-carbonate sequence.

Figure 3 shows free-air gravity anomalies over the Gulf of Guinea (Figure 3a) as well as other shear margins reviewed here. Note that in all cases marginal ridges produce relatively high-amplitude gravity anomalies.

Davie Fracture Zone. The N-S trending Davie Fracture Zone in the Mozambique Channel (Figure 3b) is a fossil transform fault that guided the southward drift of Madagascar-Antarctica-India during Late Jurassic to Early Cretaceous splitting of Eastern Gondwana, and formation of the West Somali Basin (Droz and Mougenot, 1987). The ridge longitudinally bisects the channel from the northern coast of Mozambique to the southwestern coast of Madagascar.

Based on morphology, Mascle et al. (1987) divided the channel into three regions: (1) 9-13° S, (2) 13-17° S, and (3) 17-20° S. They report that gravity data in the north indicate a strong crustal change and interpret the transition from continental to oceanic crust to coincide with this anomaly. East-dipping horst blocks in the central part of the ridge may be related to Late Cretaceous rifting and the northward drift of India. To the south in the Mozambique Upper Fan, reflection seismic data reveal disconnected NW-SE trending anticlines. The offshore Zambezi Valley

Editor's Note: The Geologic Column, which appears monthly in TLE, *is (1) produced cooperatively by the SEG Interpretation Committee and the AAPG Geophysical Integration Committee and (2) coordinated by R. Randy Ray and Lee Lawyer.*

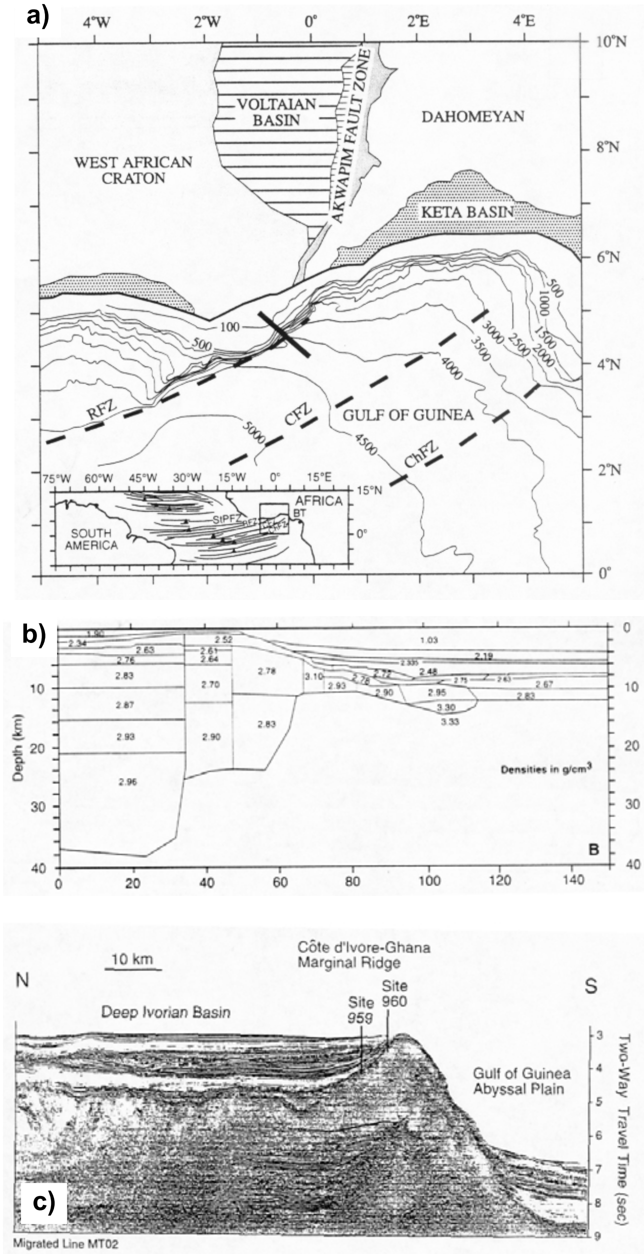


Figure 2. (a) Physiography of the Gulf of Guinea and Côte d'Ivoire-Ghana shear margin (after Edwards et al., 1997). RFZ, CFZ, ChFZ, and StPFZ are Romanche, Chain, Charcot, and St. Paul Fracture Zones, respectively; BT is Benue Trough. (b) Density model along transect shown in Figure 2a (after Edwards et al., 1997) Density units are g/cm^3. (c) Reflection seismic line over the Côte d'Ivoire-Ghana transform margin (after Clift et al., 1997.

serves as a conduit for sediment deposition SE of Mozambique, but deposition is restricted farther east by the Davie Ridge (Droz and Mougenot, 1987).

Owen Fracture Zone. The NNE-oriented Owen Fracture Zone extends from the Northern Somali Basin through the Carlsberg Ridge to the Makran Subduction Zone (Figure 3c). It records the Late Cretaceous to Paleogene northward motion of India. The Owen Basin formed in Late Jurassic to Early Cretaceous, coincident with the breakup of Gondwanaland and the formation of the Somali Basins (Minshull et al., 1992). The Owen Fracture Zone is probably a transform fault, although slip along the boundary is by far the slowest in the world: 2 mm/a right lateral motion (Gordon and DeMets, 1989). The Owen Ridge, NW of the Owen Fracture Zone, limits and traps sediment deposition from the Saudi Arabian Peninsula. Seismic refraction data indicate that continent to ocean crustal thickness decreases from about 18 to 12 km (Whitmarsh, 1979).

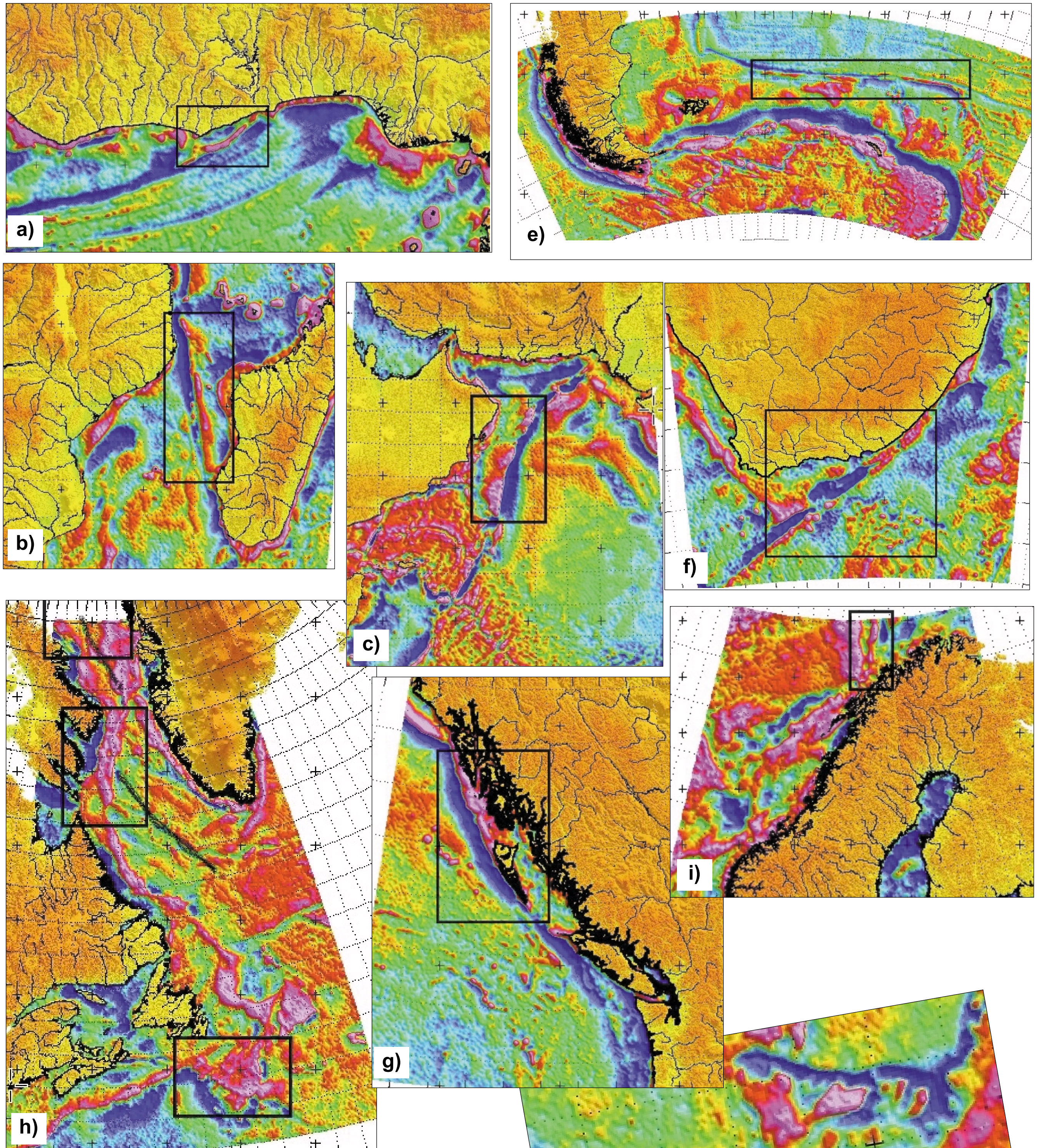
Southern Exmouth Plateau. Lorenzo et al. (1991) proposed a two-stage model for continent-ocean transform boundary formation south of the Exmouth Plateau off northwestern Australia (Figure 3d). The Exmouth Plateau is a continental block that was deformed during Jurassic rifting prior to Early Cretaceous Indian Ocean seafloor spreading. During the rift stage detachment surfaces formed and were then sheared by right lateral strike-slip motion and fault block rotation. In the drift stage thermal conditions resulted in magmatic underplating beneath the continental side of the margin. Lorenzo et al. (1991) have mapped a prominent basement ridge (marginal) and suggest that it is a zone of igneous intrusion. Lorenzo and Vera (1992) estimate marginal ridge uplift lead to erosion of up to 3.5 km of sediments and that 1000 km^3 of sediments are eroded for every 10 km of transform length.

Agulhas-Falkland Fracture Zone. The Agulhas-Falkland Fracture Zone is one of the earth's most spectacular transform/fracture zone systems. Its Early Cretaceous 1200-km offset, coinciding with the breakup of West Gondwanaland, made it a giant class transform fault, similar to the San Andreas and Dead Sea transforms (Ben-Avraham et al., 1997). Ben-Avraham et al. (1997) also report that this offset endured for about 65 Myr (from 130 to 65 million years ago) until a major ridge jump reduced its size to about 180 km.

The Falkland Plateau and Basin is a foundered complex of oceanic and continental blocks that traveled along the Algulhas-Falkland Fracture Zone after Middle Jurassic Gondwanide breakup of Antarctica from Africa and South America (Lorenzo and Wessel, 1997). Along the northern edge of the plateau a prominent marginal ridge forms the Falkland Escarpment and rises as much as 2 km over the South Atlantic Ocean (Figure 3e). Lorenzo and Wessel (1997) report that the transition from oceanic (~14 km thick) to continental crust (~25 km thick) is less than 50 km wide. They have suggested that mechanical coupling and thermal subsidence of oceanic and continental crust after the ridge segment passed caused the continental side of the margin to bend down, while forcing the oceanic side to bend upward.

SE of the Agulhas Bank and Mallory Trough, offshore South Africa, the Agulhas Marginal Fracture Ridge and Diaz Ridge (Figure 3f) form an overlapping, en-echelon trap for sediment deposition to the NW (Ben-Avraham et al., 1997). Lower units in the Mallory Trough and Southern Outeniqua Basin (NW of Diaz Ridge) are deformed, reflecting rotated blocks related to transverse rifting and formation of the continent-ocean shear margin.

Queen Charlotte Transform Margin. The Queen Charlotte Transform Margin (Figure 3g) extends from the Queen Charlotte triple junction (Pacific, Juan de Fuca, and North American Plates) to the south Alaskan subduction zone and has been stable for 40 million years (Prims et al., 1997). Relative motion along the boundary is right-lateral at 50 mm/a. Discrepancies in the relative directions of plate



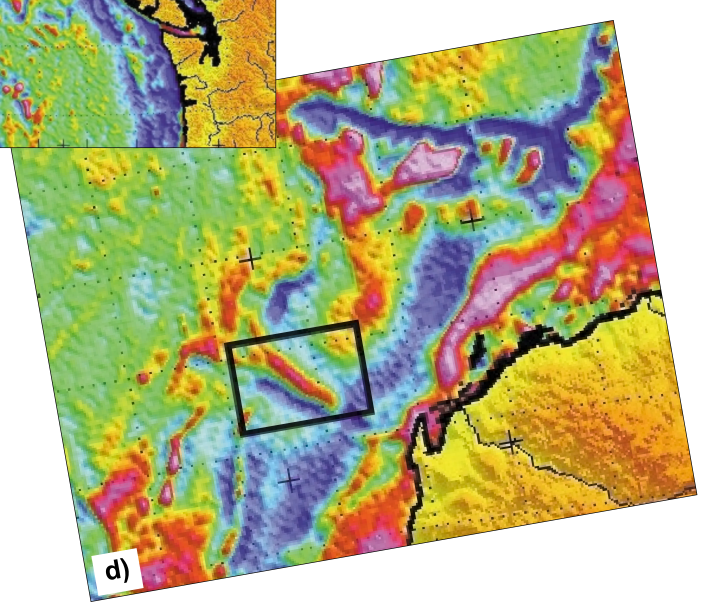


Figure 3. Onshore and offshore data are topography and satellite-derived free-air gravity anomalies with boxes around marginal ridges. Shear margins are (a) Côte d'Ivoire-Ghana; (b) Davie Ridge; (c) Owen Fracture Zone; (d) Southern Exmouth Plateau; (e) Falkland Plateau and Maurice Ewing Bank; (f) South Africa; (g) Queen Charlotte Transform; (h) Newfoundland Transform Margin (southern area), Ungava Transform Margin (central area), and northern Baffin Bay margin (northern area); and (i) Senja Fracture Zone.

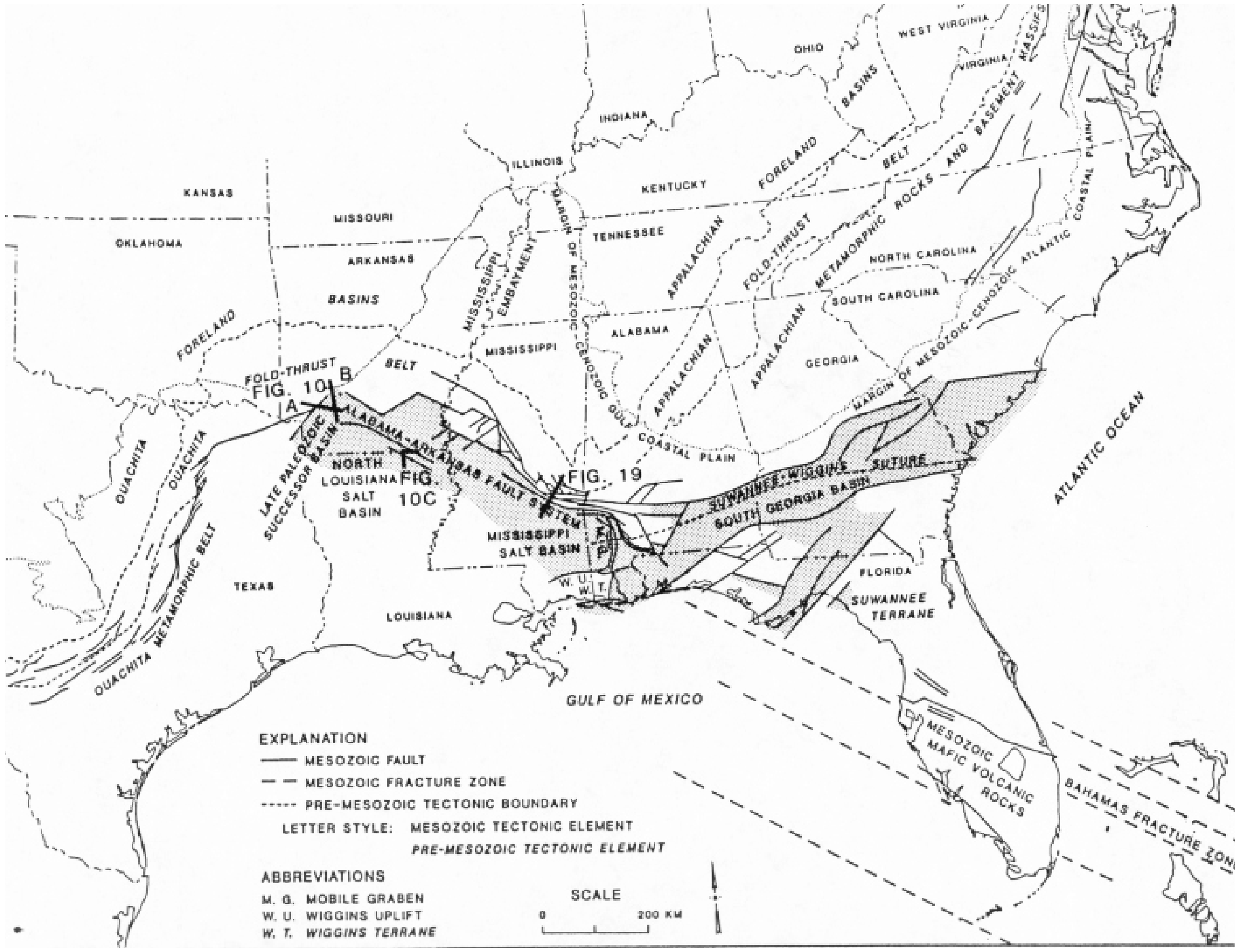


Figure 4. Early Mesozoic transform fault system (dashed lines) and regional tectonic elements related to the formation of the Gulf of Mexico (after Buffler and Thomas, 1994).

motions imply a component of convergence along the boundary. Hence, Prims et al. (1997) suggest that the Queen Charlotte Trough formed due to transpressional flexure along the margin over the last 5 million years from 10-15 km of Pacific Plate underthrusting. The marginal ridge along the boundary is the Queen Charlotte Islands and Terrace.

Mackie et al. (1989) proposed two evolutionary models including possible oblique Pacific Plate subduction. One model assumed oblique subduction and the other assumed only dextral slip along the boundary. They preferred oblique subduction but noted that crustal thickening and lateral distortion are also possible. Refraction experiments indicate: (1) anomalous crustal velocities west of the Queen Charlotte Terrace and above the mantle; (2) 21-27-km thick crust beneath Queen Charlotte Islands; and (3) gentle crustal thickening toward the mainland. Finally, they report that an obliquely subducting slab would extend no farther than the 30-km thick crust of the mainland.

Northeastern Canada. The Southwest Newfoundland Transform Margin (Figure 3h, southern area) developed in response to Mesozoic separation of North American and African Plates. Continental crust thins from just over 20 km to about 6 km beneath an apparent slice of obducted oceanic crust at the transform margin (Reid and Jackson, 1997). A ridge does not exist along this margin, probably due to tectonic processes different from other shear margins since obducted oceanic crust exists on the island.

Since deep seismic data do not exist across the Ungava Transform Margin (Figure 3h, central area), regional crustal thicknesses were estimated by inversion of gravity data (Reid and Jackson, 1997). Crustal thinning of continental to oceanic crust (35-12 km thick, respectively) spans 50 km. The inversion model reveals only a slight expression of a marginal ridge, but Reid and Jackson note that the margin is oblique to the spreading direction. Heavy lines sketched in Figure 3h approximately coincide with seafloor spreading centers.

The northern Baffin Bay margin (Figure 3h, northern area) is complex and affected by transcurrent, extension, and compressional forces related to interaction between Greenland and North American Plates. Offshore basement structures reveal basin-forming normal faults, flower structures, and folding. Continent-ocean crustal thinning (28-10 km) occurs over 60 km. The existence of a marginal ridge cannot be confirmed for this complex area.

Senja Fracture Zone. The Senja Fracture Zone (Figure 3i) formed in response to the formation of the Norwegian

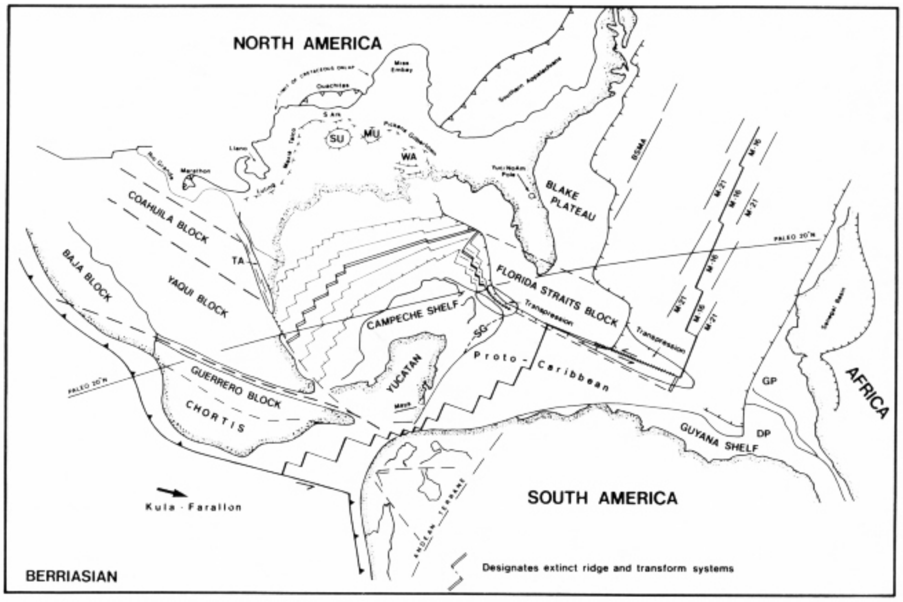


Figure 5. Berriasian (Early Cretaceous) paleogeography of the Gulf of Mexico and Caribbean region about 140 million years ago (after Pindell, 1985).

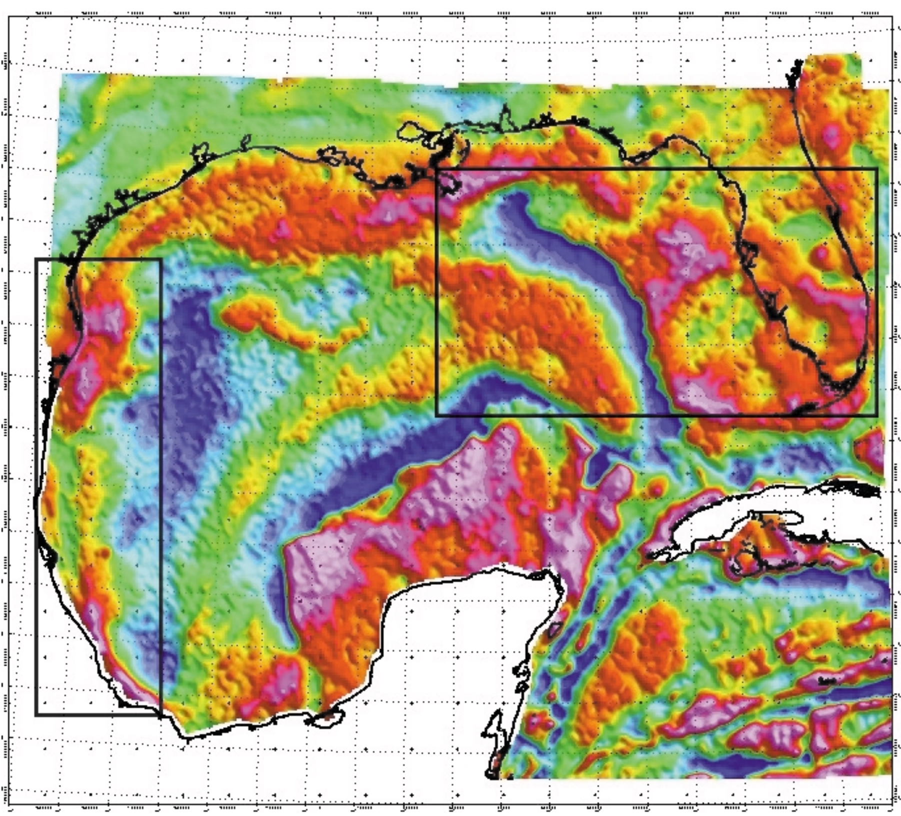


Figure 6. Gravity anomalies (SEG Bouguer onshore and satellite-derived free-air gravity offshore) over the Gulf of Mexico. Boxes show areas that should exhibit marginal ridges according to both models for the tectonic formation of the Gulf of Mexico.

Greenland Sea (Vågnes, 1997) beginning 57 million years ago (Paleocene-Eocene boundary). Seafloor extension was nearly parallel to the coast but shifted to nearly E-W 35 million years ago (Eocene-Oligocene boundary). Then, due to oblique rifting, the active transform became part of the present Knipovich spreading axis, so the margin was active for about 22 million years. This timing and preservation of predrift sediments along the margin provide good constraints for estimating the amount of erosion. Vågnes reported that uplift began after the initial formation of the Senja Fracture Zone and lasted until Middle or Late Eocene and further estimated the maximum amount of erosion near the transform to be 1.5 km.

Thermal models. Vågnes compared thermal models based on conduction only with combined conduction and advection due to viscous coupling of lower, ductile lithosphere. Results of these experiments show that more heat is predicted from the combined model, but uplift is only half that predicted by the conductive-only model. Vågnes compared model results with erosion estimates from the Senja Transform margin and found that predicted uplift from the combined model corresponds best to erosion estimates.

Gadd and Scrutton (1997) calculate 1300-1400 m of uplift from thermal effects for a 900-km-long transform segment but note that it is reduced to 335-470 m when considering regional isostatic effects. They also report that the amount of uplift depends on the degree of ocean-continent coupling. Frictional heating is negligible, contributing only 5% of that from conduction (Gadd and Scrutton, 1997). Todd and Keen (1989) modeled thermal effects of a 500-km-long transform segment with spreading half-rates of 1.0 and 4.0 cm/a and report that over 2 km of crustal uplift may occur at the margin and decreases over a distance of 60-80 km away from the margin.

Discussion. Figures 4 and 5 show two suggested models for the tectonic formation of the Gulf of Mexico (Buffler and Thomas, 1994; Pindell, 1985). Mesozoic extension from NNE- to NE-oriented spreading centers (Figure 4), originally postulated by Klitgord et al. (1984), requires NW- to WNW-oriented transforms. Transform faults in this model are subparallel to Late Precambrian-Early Paleozoic transform faults that guided the opening of the Iapetus Ocean, which "produced the North American continental margin along which the late Paleozoic Appalachian-Ouachita orogenic belt subsequently formed" (Buffler and Thomas, 1994). If the directions of Mesozoic and Late Precambrian-Early Paleozoic extension are similar, then this model seems reasonable for the formation of the Gulf of Mexico.

An alternative model for its formation (Figure 5) requires SSE extension, that is, counterclockwise rotation about a Euler pole in northern Florida (Pindell, 1985). Hall and Najmuddin (1994) have suggested a similar model with the pole of rotation about 130 km south of Florida. A noteworthy point regarding all these models, especially when considering the review of shear margins above, is that each requires a shear margin for the formation of the Gulf of Mexico. NNE-NE extension requires a shear margin oriented subparallel to the Texas-Louisiana-Florida coast, and SSE extension requires a shear margin along the coast of central Mexico.

Comparison of the model in Figure 4 with Figure 2a reveals that the model is essentially a mirror of the fracture zone pattern displayed offshore Gulf of Guinea. With this in mind, one would expect to see similar tectonic features such as a ridge and abrupt crustal thinning. Extensive transitional crust, or gradual SSE-thinning of continental crust over as much as 700 km (Buffler and Thomas, 1994), seems inconsistent with expected crustal structure for a shear margin produced by this model.

The high-amplitude gravity anomaly, subparallel to the coast of central Mexico, is similar to gravity anomalies produced by ridges described here; however, sparse refraction data do not provide compelling evidence for the existence of a marginal ridge nor abrupt crustal thinning (Ibrahim et al., 1981). Figure 6 shows gravity anomalies, SEG Bouguer onshore and satellite-derived free-air offshore, over the Gulf of Mexico with areas of expected shear margin formation according to both models outlined.

Conclusion. The evolution of shear margins typically involves continental rifting and intensely deformed rift sequences over rotated basement blocks. As the seafloor spreading axis moves along the margin thermal uplift probably produces a ridge that traps sediments allowing thick sequences to accumulate. After the ridge axis passes, the margin is characterized by normal tectonic and thermal subsidence.

Suggested reading. "The Ivory Coast-Ghana transform margin: A marginal ridge structure deduced from seismic data" by Basile et al. (*Tectonophysics*, 1993). "Structure and tectonics of the Agulhas-Falkland fracture zone by Ben-Avraham et al. (*Tectonophysics*, 1997). "Crustal structure and evolution of the southeastern margin of North America and the Gulf of Mexico basin" by Buffler and Thomas (in *Phanerozoic Evolution of North American Continent-Ocean Transitions*, Geological Society of America, 1994). "Transform tectonics and thermal rejuvenation on the Côte d'Ivoire-Ghana margin, west Africa" by Clift et al. (*Journal of the Geological Society of London*, 1997). "Mozambique Upper Fan: Origin of depositional units" by Droz and Mougenot (AAPG *Bulletin*, 1987). "Synthesis of the crustal structure of the transform continental margin off Ghana, northern Gulf of Guinea" by Edwards et al. (*Geo-Marine Letters*, 1997). "An integrated thermomechanical model for transform continental margin evolution" by Gadd and Scrutton (*Geo-Marine Letters*, 1997). "Present-day motion along the Owen Fracture Zone and Dalrymple Trough in the Arabian Sea" by Gordon and DeMets (*Journal of Geophysical Research*, 1989). "Constraints on the tectonic development of the eastern Gulf of Mexico provided by magnetic anomaly data" by Hall and Najmuddin (*Journal of Geophysical Research*, 1994). "Crustal structure in Gulf of Mexico from OBS refraction and multichannel reflection data" by Ibrahim et al. (AAPG *Bulletin*, 1981). "Florida, a Jurassic transform plate boundary" by Klitgord et al. (*Journal of Geophysical Research*, 1984). "Sheared continent-ocean margins: an overview" by Lorenzo (*Geo-Marine Letters*, 1997). "Development of the continent-ocean transform boundary of the southern Exmouth Plateau" by Lorenzo et al. (*Geology*, 1997). "Thermal uplift and erosion across the continent - ocean transform boundary of the southern Exmouth Plateau" by Lorenzo and Vera (*Earth Planetary Scientific Letters*, 1992.). "Flexure across a continent-ocean fracture zone: The northern Falkland/Malvinas Plateau, South Atlantic" by Lorenzo et al. (*Geo-Marine Letters*, 1997). "The Queen Charlotte Islands refraction project. Part II. Structural model for transition from Pacific plate to North American plate" by Mackie et al. (*Canadian Journal of Earth Science*, 1989). "African transform continental margins: examples from Guinea, the Ivory Coast and Mozambique" by Mascle et al. (*Geol. J. Thematic Issue*, 1987). "Deformation at plate boundaries around the Gulf of Oman" by Minshull et al (*Marine Geology*, 1992). "Alleghenian reconstruction and subsequent evolution of the Gulf of Mexico, Bahamas, and Proto-Caribbean" by Pindell (*Tectonics*, 1985). "Lithospheric structure along the Queen Charlotte margin in western Canada: Constraints from flexural modeling" by Prims et al. (*Geo-Marine Letters*, 1997). "A review of three transform margins off eastern Canada" by Reid and Jackson (*Geo-Marine Letters*, 1997). "Temperature effects and their geological consequences at transform margins" by Todd and Keen (*Canadian Journal of Earth Sciences*, 1989). "Uplift at thermo-mechanically coupled ocean-continent transforms: Modeled at the Senja Fracture Zone, southwestern Barents Sea" by Vagnes (*Geo-Marine Letters,* 1997). "The Owen Basin off the south-east margin of Arabia and the evolution of the Owen Fracture Zone" by Whitmarsh (*Geophysical Journal of the Royal Astronomical Society*, 1979). LE

Corresponding author: D. Bird, dale@birdgeo.com