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Chapter 26

Geology and tectonic history of the Gulf of California

Peter Lonsdale
Marine Physical Laboratory of the Scripps Institution of Oceanography, University of California, San Diego, California 92093

LIMITS AND LIMITATIONS OF THIS REVIEW

The Gulf of California, or Sea of Cortez, is an arm of the Pacific 100 to 150 km wide between the Mexican mainland and the 1,200-km-long peninsula of Baja California. The gulf waters flood part of a structural depression that was formed by detachment and oblique separation of the peninsula from the continent, and is occupied by the Pacific–North America plate boundary. The gulf structural province, defined as the complex trough left in the wake of the northwest-drifting peninsula, extends beyond the hydrographic limits of the gulf. In the south, the continental margin conjugate to the rifted tip of Baja California is in the vicinity of the Tres Marias Islands, well outside the gulf proper. Marine geologic and geophysical data across the East Pacific Rise in this "mouth of the gulf" region are reviewed because they prove to be critical for determining the initiation and tectonic evolution of the entire province. At the northern "head of the gulf," the delta of the Colorado River has extended across the structural depression and isolated the Salton Trough, part of the gulf province now exposed as dry land (except for the artificial Salton Sea), though much of it is below sea level. The Colorado delta is bisected by the Untied States–Mexico border; the gulf north of the "midriff islands," which congest it near lat 29°N, is politically part of the internal waters of Mexico, and the remainder is within the exclusive economic zone of Mexico.

The temporal limit for most of this chapter is the birth of the modern gulf as a plate-boundary zone between Baja California and the mainland, near the end of the Miocene, though some relevant prenatal plate interactions are also summarized. From a wider perspective, the continental crust surrounding the gulf lies near the edge of the North American craton, and basement rocks as old as early Paleozoic or latest Precambrian record a long and complex history of continental-margin sedimentation, tectonic accretion, and magmatism (e.g., Gastil and others, 1981). This history has doubtless affected the evolution of the modern province. During the Miocene, much of the future site of the gulf was occupied first by an andesitic arc overlying lithosphere subducted along the western margin of Baja California, and after subduction ceased about 12 Ma, by a belt of east-west extension marked by alkali-basalt volcanism and basin-and-range faulting. Subsidence engendered by the extensional faulting locally produced basins with access to the Pacific, and "proto-gulf" marine sediments that may be of middle Miocene age occur in the Yuma Basin, an ancestor of the Salton Trough (Lucchitta, 1979). It was into this belt of weakened attenuated crust, roughly parallel to the coastline but 250 km inland, that the shear zone marking the principal boundary between the Pacific and North American Plates shifted about 6 Ma. The transform fault connecting the early San Andreas system to the tip of the East Pacific Rise had occupied the inner slope of the former trench (Spencer and Normark, 1979), and the jump inland was precipitated by propagation of the oceanic spreading center through granitic continental crust at the mouth of the gulf. The causes and some effects of this rearrangement in the plate boundaries are controversial, and will be discussed after reviewing the known geology of the mouth of the gulf.

A crucial factor for the development of the string of oceanic basins that distinguish the gulf from a mere intracontinental transform was that the subsequent relative motion of the Pacific and North American Plates was 10 to 20° oblique to this the new inland shear zone. It therefore reorganized into several long en-chelon transform fault systems parallel to relative plate motion, linked by pull-apart basins that matured into sites of crustal accretion. Subsequent tectonic history has been complicated by reorientation and jumping of sections of the plate boundary. The precise location and width of parts of the active transform fault zones are uncertain, being poorly established by the classical method of mapping seismicity because of the lack of nearby seismometers, especially to the southwest of the gulf. The pattern must be inferred mainly from bathymetric and seismic reflection profiles, and most of these were collected on month-long reconnaissance expeditions. The closest approaches to systematic surveys of the gulf floor since the pioneering 1959 Vermilion Sea Expedition, whose results are presented in the volume edited by van Andel and Shor (1964), were a series of cruises by the University of Southern California which collected single-channel seismic profiles and superficial sediment samples (Henyey and Bischoff, 1973; Bischoff and Henyey, 1974; Niemitz and Bischoff, 1981), and a joint U.S.–Mexican geophysical survey of the southern gulf (reported in part by Ness, 1982). After summarizing the inferred

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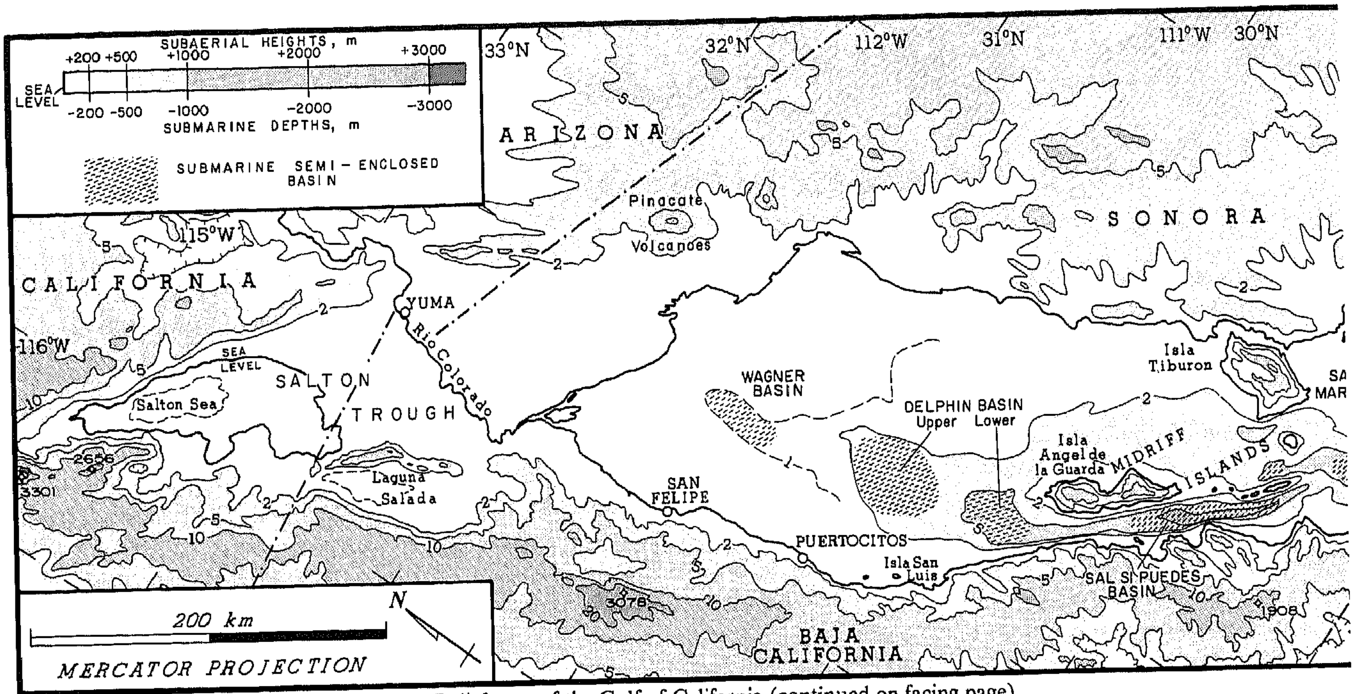


Figure 1. Relief map of the Gulf of California (continued on facing page).

pattern of presently active and recently abandoned transform faults and spreading axes, profile data are used to describe one of the major fault systems in more detail. A major limitation of this description is that very few rock samples have been collected from the widespread outcrops along submarine fault scarps. In contrast, geologic mapping of onshore outcrops has advanced rapidly in recent years.

Lack of modern marine geophysical data and drill cores is the principal limitation to comprehensive description and interpretation of the submarine basins, many of which have thick sediment fills that both record their histories and conceal basement structure. The small amounts of commercial geophysical exploration and drilling has been restricted to parts of the mainland margin, and results are proprietary. No seismic refraction results and few gravity data have been reported since the initial studies of Phillips (1964) and Harrison and Mathur (1964). Multichannel seismic profiles and drilling results are available only from Guaymas Basin (Curray and others, 1982). This part of the central gulf has also been the site of detailed heat flow studies and close-up observations from both deeply towed vehicles and submersibles, so it is much better known than basins to the north or south, and perhaps unjustifiably has come to be considered as the typical gulf basin. Guaymas Basin is used here as an example; however it should be emphasized that many of the other basins are so poorly explored that their resemblance to this "archetype" cannot be assessed properly.

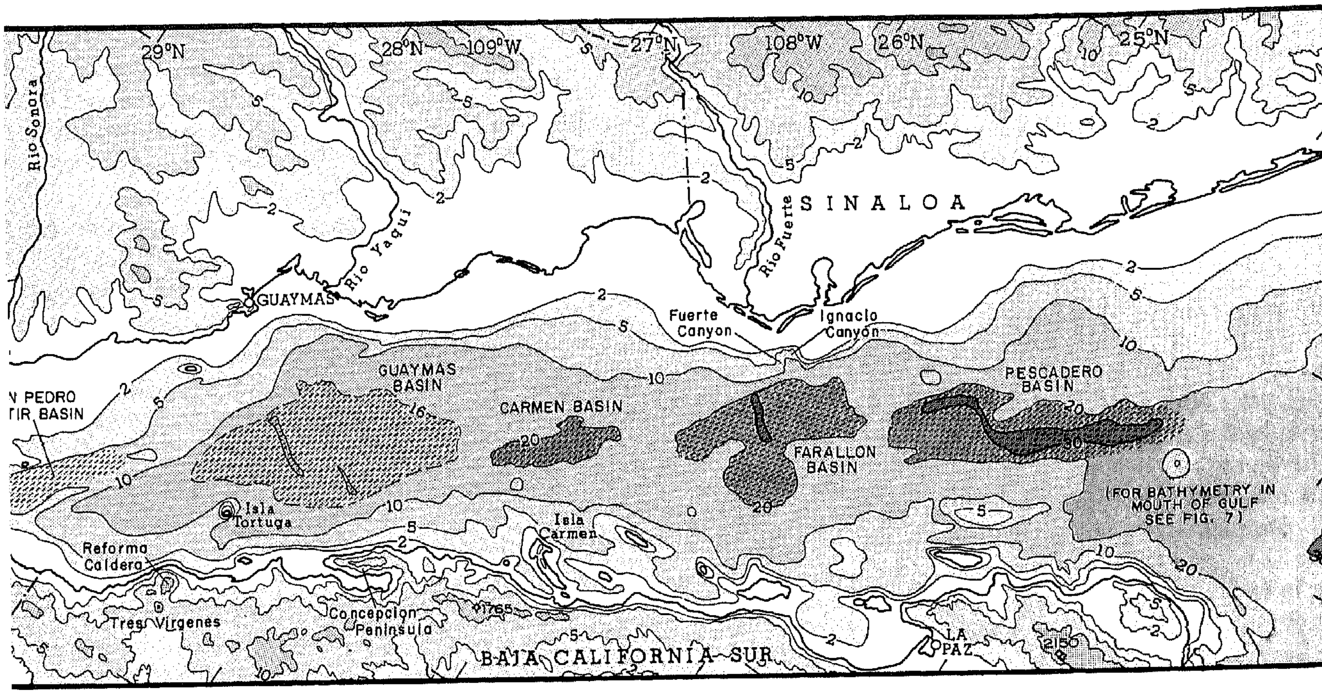
An exceptional gulf basin from the point of view of wealth of information is Salton Trough, where local seismicity studies have defined the pattern and activity of the plate boundary zone in fine detail, and the search for geothermal resources within its thick sediment fill has yielded close-spaced measurements of heat flow, gravity, magnetics, and seismic stratigraphy, as well as numerous deep bore holes. The subaerial Salton Trough is also exceptional in many aspects of its geology, but it may be somewhat representative of the poorly known basins beneath the shallow northern gulf, and comparison with Guaymas Basin may be fruitful.

The mouth of the gulf has also received considerable scientific attention, with regional geophysical surveys of bathymetry, magnetics, gravity, and sediment thickness; Sea Beam, deep tow, and submersible studies of parts of the plate boundary zone; and drilling and dredging of oceanic and subsided continental crust. Many of these studies are concerned with modern geologic processes, and their results are more at home in discussions of the East Pacific Rise (see articles by Macdonald, Fox and Gallo, and Haymon, this volume) but are probably directly applicable to the more oceanic southern part of the gulf.

OVERALL PATTERNS OF THE GULF

Bathymetry

Figure 1, adapted from the chart of Bischoff and Niemitz (1980), emphasizes the division of the gulf floor into semi-isolated basins which become shallower to the north, and the contrast between the narrow shelf bordering the mountainous Baja California peninsula and the broader shelf and coastal plain of Sonora and Sinaloa. The continental slope on the mainland side has several marginal plateaus, commonly having steep (10–15°) lower slopes to the basin floors. This relief is character-



istic of sheared (as opposed to rifted) continental margins. Especially steep slopes (>20° for a drop of up to 1,500 m) border the narrow trough between the midriff islands and the peninsula. The great amplitude, complexity, and steepness of submarine relief in the central and southern gulf, maintained despite the smoothing effects of rapid sedimentation, is a testimony to the recent and continuing relief-forming tectonism. Even some of the flat basin floors that receive the greatest sediment supply are cut by fault troughs with cliffed walls, as in Guaymas Basin. In the northern gulf much tectonic relief has been obliterated by sediment deposition, though even in Salton Trough, local crustal extension is marked by subtle depressions and marshy hollows, and there is significant erosional relief. Enclosed depressions in the gulf constriction near Isla Tiburon have been cut by tidal scour, and the relative importance of tectonics and turbidity currents for creating the shallow troughs in the floor of the northernmost part of the gulf is uncertain. Throughout the gulf, few of the continental slopes are cut by major submarine canyon systems, except around the rifted margin of the tip of the peninsula, where Shepard (1964) inferred that they originated as subaerial river valleys. Indentations of the slope off the Yaqui and Fuerte deltas (e.g., Ignacio and Fuerte canyons; Shepard, 1964) seem to be primarily structural in origin.

Sedimentation

The principal suppliers of sediment to the gulf depression are rivers draining the Sierra Madre mountains of Sonora and Sinaloa and, for the northern gulf, the Colorado River. Much less sediment comes from Baja California, where the watershed is close to the gulf coast, though extensive deep-sea fans have been built around the peninsula's tip. In the central gulf, huge populations of plankton in the highly productive surface waters provide a heavy rain of pelagic debris, especially of diatom fragments, which compose about half of the accumulated sediment in Guaymas and San Pedro Martir Basins. Ponds of relatively pure diatomaceous ooze fill some depressions in these basins. The hemipelagic muds have high organic carbon content, especially where the sea floor intersects an oxygen-minimum zone that occurs at depths of 300 to 800 m. On these parts of the continental slope, where reducing conditions prevail, diatom ooze occurs as thin laminae alternating with muddier layers (Calvert, 1966). Van Andel (1964) described the composition and distribution pattern of other sedimentary facies in the gulf.

The rate of sediment accumulation is very uneven, partly because of the distribution of sources, which favors deposition on the mainland margin and in the northern gulf, but also because of the local reworking, by mass movements and turbidity currents, from steep slopes to basin floors. Sediments cored on the floor of Guaymas Basin, which are mostly fine-grained mud turbidites (Einsele and Kelts, 1982) accumulated at about 1 m/1,000 yr, but rates several times greater prevail in the local depressions opened by tectonism at the basin's axis.

Structure

The location of the first-order structural boundary, between old continental and young oceanic crust, is uncertain throughout much of the gulf; some of this uncertainty may be caused by the presence of an intermediate type of crust (with continental slivers invested with magmatic intrusions), not just by the lack of data. The boundary is well defined at some sheared continental margins, where there is a sharp drop in topography and the gravity field across a narrow fault zone, and at the rifted tip of Baja

California, where subsided granitic rocks under a thin and patchy sediment cover abut a typical East Pacific Rise flank with lineated abyssal hills and magnetic anomalies. At the rifted margins of the basins within the gulf, thickly buried by sediments, gradients in depth, gravity, and magnetics are more gradual. Lacking multichannel seismic profiles or high resolution refraction studies (except for parts of Salton Trough), the extent of oceanic crust indicated in Figure 2 is deduced mainly from gravity data.

"Oceanic crust" in this context includes whatever newly accreted materials have filled the gaps caused by separation of continental crust. A typical oceanic stratigraphy of gabbros (seismic layer 3), dikes (2b), and lavas (2a) overlain with a sediment blanket (layer 1) that thickens gradually with age is found only in the mouth of the gulf. In the central gulf, sediments play a major role in filling the ever-widening gap from above, at the same time as major intrusions fill it from below. The result is a thick dike and sill complex containing intercalated sediment. Refraction studies in Guaymas Basin (Phillips, 1964) indicate that this type of crust, in which the standard crustal layers are jumbled, may be 6 to 7 km thick. It produces low-amplitude magnetic anomalies that are lineated parallel to spreading axes but cannot be matched to the reversal time scale; as a result, all estimates of spreading rate in the gulf are based on extrapolation for the rate recorded by oceanic crust at its mouth (an average of 54 mm/yr for the past 3.5 m.y.). It has been argued that, in Salton Trough the sedimentary contribution to crustal accretion is overwhelming, and an igneous crust is essentially absent; the metamorphosed sediments rest directly on a mantle exposed by continental separation (Nicolas, 1985).

Continental crust at the rifted margins is inferred, from model studies, seismic profiles, and samples (e.g., from the tip of Baja California), to have been extended by listric faulting and injected by dikes as it subsided to basin-floor depths. Good subaerial exposures of attenuated continental crust occur in the Puertocitos region of the northern gulf coast, where Pliocene strata and lavas are dissected by an intricate pattern of synthetic and antithetic faults, but most of the (east-west) crustal extension in this area predates formation of the gulf (Dokka and Merriam, 1982).

Tectonics and Volcanism

The principal strike-slip fault zones and linking spreading centers that are inferred to be active traces of the present plate boundary are identified in Figure 2. In some places the Pacific-North America plate motion is shared between two or more overlapping zones. This is best documented within continental crust at the head of the gulf, where widely separated faults of the San Andreas system are simultaneously active. Such overlap is unusual in oceanic crust, and could be interpreted as evidence for a more diffuse plate boundary in continental situations. A slightly different explanation is that there has been gradual shifting of the plate boundary from one site to another. In the north, for example, initiation of the San Andreas, San Jacinto, and Elsinore fault zones occurred at successively later times (Crowell, 1981), marking the gradual migration of the plate boundary back toward the ocean. Many of the fossil transform fault zones indicated in Figure 2 may have residual seismic activity. Indeed, scattered earthquakes and clear geomorphic evidence of recent movement mark much of the San Isidro, San Benito, and Tosco-Abreojos fault zones, supposedly abandoned at the birth of the gulf.

Though earthquake epicenter determinations are too imprecise in most of the gulf to be of much help in defining the fault zone locations (except where special local arrays of instruments have been set up to monitor aftershocks), focal mechanism studies have been valuable for confirming the direction of plate motion and thus the likely orientation of transform fault zones. Calculated fault planes for most of the large right-lateral strike-slip events in the gulf are within 10° of the directions predicted by plate motion models (Sharman and others, 1976). Bathymetry suggests that near lat 28°N there is an abrupt 6 to 7° change in azimuth, more than can be explained by a changing plate longitude, with fault zones to the north striking more northerly (312°) than those to the south (305°). The difference seems to have significant structural effects, as discussed below.

Some of the 15 to 20 en enchelon spreading centers in the gulf are orthogonal to the transform faults and to inferred plate motion, and some are at least 30° oblique to this direction (Fig. 2). The oblique examples include very short spreading axes between major transform faults, where (as in similar situations on mid-ocean ridges) axes of extension are diverted by the strike-slip shear couple, and the relatively long (but poorly mapped) spreading centers beneath the northern gulf.

Geophysical and visual observations, of faulted Holocene sediments, for example, imply that the spreading centers also have a high level of seismic activity, though they do not produce large earthquakes. A characteristic mode of activity is a swarm of small events, perhaps caused by movement of magma (Reichle and Reid, 1977). Other earthquakes and neotectonic deformation are not directly related to the plate boundary. A good example is at the Reforma resurgent caldera, on the peninsula coast of the central gulf, where Pleistocene marine terraces record a local uplift rate of 1 m/1,000 yr (Ortlieb, 1980).

Quaternary volcanism is likewise widespread in the gulf province, through concentrated at the accreting parts of the plate boundary. Eruptions of tholeiitic lava are characteristic of the spreading centers at the mouth of the gulf, but farther north most or all of the axial magmatism is manifested as dike and sill intrusions into young sediment. In Salton Trough, fractionated blobs of low-density silicic magma (containing tholeiitic xenoliths) have risen to the surface through several kilometers of sediment to form small rhyolite domes (Robinson and others, 1976). The extent of volcanism along the gulf's transform faults is poorly determined because of lack of samples. Seismic profiles show no evidence for volcanism at these sites in the central and southern gulf, but tholeiitic pillows have been dredged from a fault zone in the midriff, close to Isla Raza (Fig. 3), which is itself made of young basalt flows. The fracture-zone extensions of several transform faults have clusters or chains of volcanoes, including re-

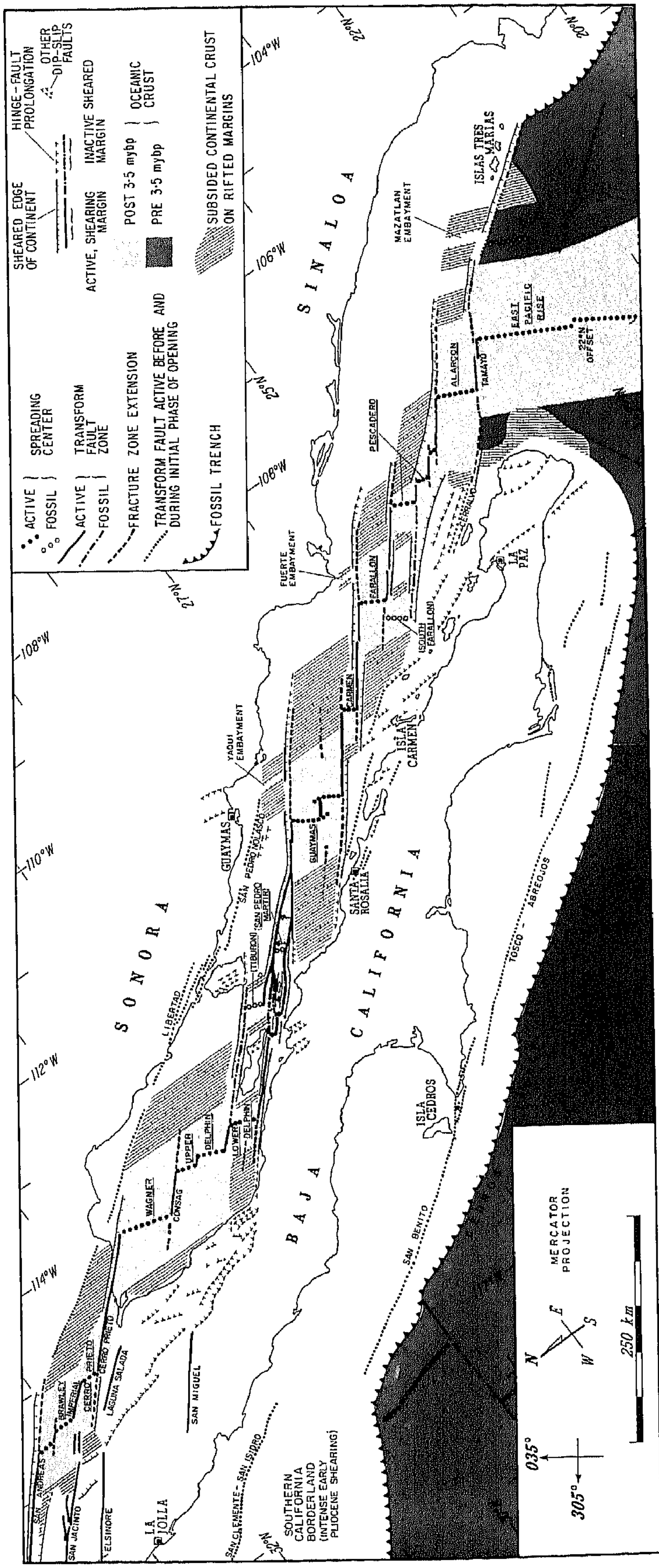


Figure 2. Structural interpretation of the gulf province. The extent of newly accreted (oceanic) crust within the gulf is poorly determined. Spreading-center names are underlined, and in brackets if they are no longer active.

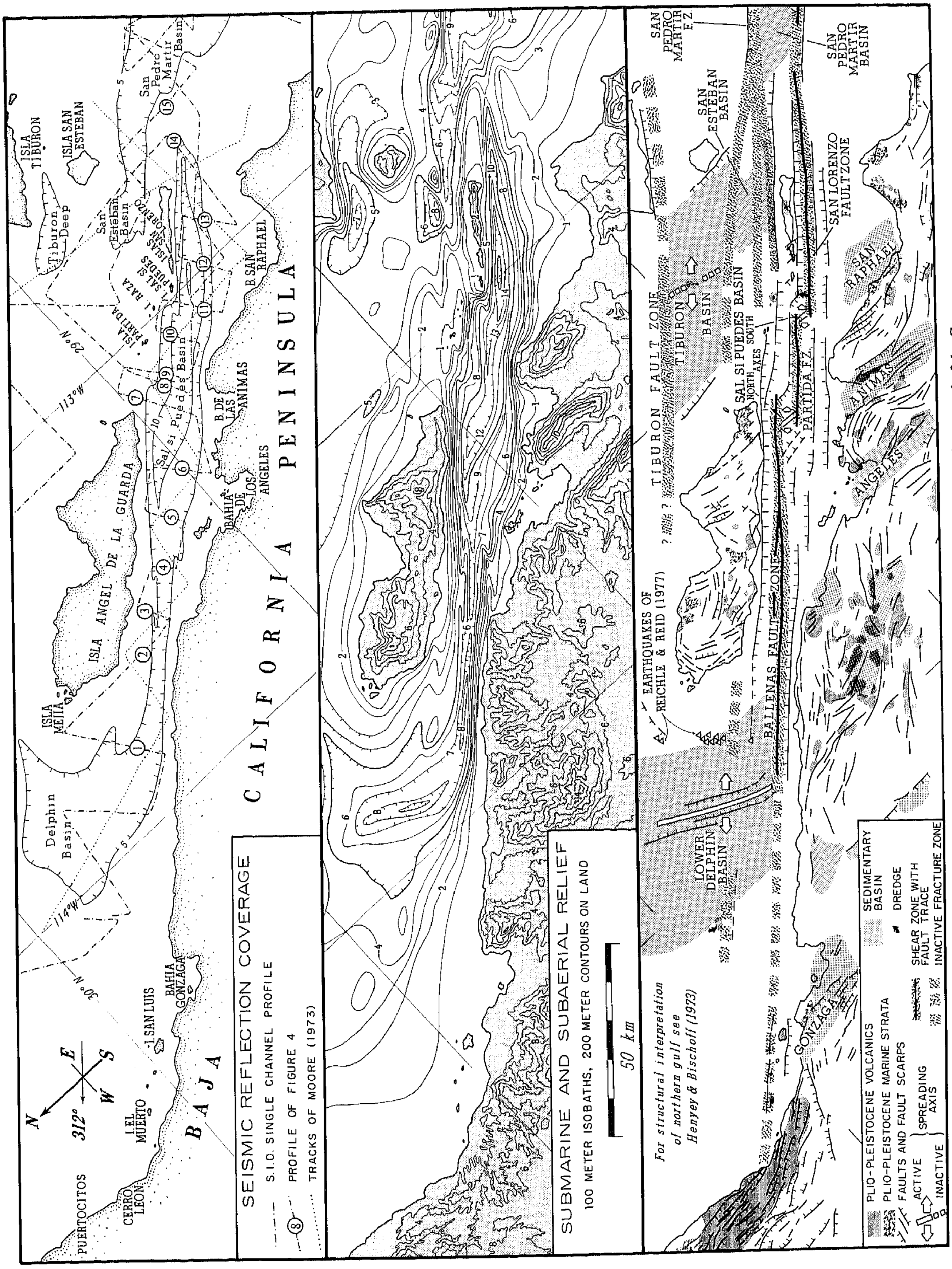


Figure 3. Location map, bathymetry, and structural interpretation of the northwest end of the Guaymas fault system.

cently active tholeiitic shields, as at Isla Tortuga in Guaymas Basin (Batiza, 1978), and obsidian domes as in the Islas San Luis (Fig. 3). Some of the oceanic basins, especially in the mouth of the gulf but including Guaymas Basin, also have submerged off-axis volcanoes (seamounts). Measurements of unusually high geothermal flux in Farallon Basin (Lawver and others, 1973) may record a modern off-axis intrusion there.

Quaternary subaerial volcanism into continental crust has included many small alkali basalt flows in Baja California, especially in the western half of the peninsula, which represent the most recent products of an eruptive episode that has persisted for about 10 m.y. A few other small, young basalt flows occur on the mainland margin, for example on the Fuerte delta (Gastil and others, 1979), and the major Pinacate volcanic region in northwestern Sonora may also be related to gulf tectonics.

A GULF TRANSFORM FAULT: THE GUAYMAS FAULT SYSTEM

The strike-slip fault zones that compose the Guaymas fault system act as the Pacific–North America plate boundary for 325 km between oceanic spreading centers in Lower Delphin Basin and Guaymas Basin. The central part of the system has several fault zones that branch and overlap around the margins of San Pedro Martir and San Esteban Basins, which are probably fault-wedge basins resembling some in the California continental borderland. The southeast and northwest ends of the system, where the plate boundary has a simpler geometry, are better known and represent good examples of a shearing continental margin and an intracontinental transform at the early stages of ocean-basin formation.

For about 65 km at the southeast of the fault system, the Guaymas fault zone separates continental and oceanic crust at the shearing northern margin of Guaymas Basin (Lonsdale, 1985). A salient feature of the fault zone is a transform ridge formed by uplift of sheared and perhaps serpentinized oceanic crust. The height of this ridge increases away from the right-angle spreading center–transform intersection as the length of time that the oceanic crust has been exposed to strike-slip faulting increases. On seismic profiles the ridge is recognizable about 5 km from the spreading axis as a small subbottom structure at the 2,000-m-deep foot of the continental slope. At 65 km from the axis its crest is as shallow (750 m) as the surface of the adjacent marginal plateau. Between these sites the ridge is part way up the lower slope, forming a protective dam for a thick sequence of sediments on the marginal plateau. A detailed near-bottom study (Lonsdale, 1985) showed that the transform fault zone is only 1 to 1.5 km wide, even where the fault has overlapping strands around small pull-apart basins. Within this zone, young slope sediments are intensely deformed by folding and faulting accompanied by local erosion of anticlinal crests; beyond this narrow zone, superficial strata have only minor en enchelon folds and faults. The crest of the transform ridge forms an inlier of tightly folded sedimentary rock which leaks plumes of hydrocarbons, streams of small bouyant droplets (probably composed mainly of methane) that have recently been observed from a submersible. There has been no eruptive volcanism along this basin-margin shear zone, except at its spreading-center intersection, where the continental crust is probably injected with overshooting dikes that cause rapid uplift of the rim of the continental crust. Basaltic rocks have been dredged from the steep basin wall at the opposite intersection on the south side of Guaymas Basin.

The northwestern part of this fault system includes three en enchelon fault zones which share a complex rift valley between Baja California and the midriff islands (Fig. 3). Where the valley broadens at pull-aparts between the fault zones it is known as Sal si Puedes Basin. Profiles that directly cross the north-south axes of the pull-aparts (e.g., Bischoff and Henyey, 1974, Fig. 8a) show small buried basement ridges that are probably igneous intrusions representing incipient spreading centers. However, the heat flow (3.4 μ cal cm^{-2} sec^{-1}) calculated from the single thermal gradient measurement made near this axis is much lower than over shallow intrusions at other gulf spreading centers. The strike-slip fault zones are about 7° oblique to the direction of spreading in Guaymas Basin, and a component of extension across this part of the transform is probably responsible for the deep rift valley. The rift is closed off at its southwestern end by a shallow sill (400 m) where the San Lorenzo fault zone veers to a direction parallel to the inferred plate motion. Despite its situation as a deep trough within a semiarid mountainous terrains, much of the rift valley, where it is occupied by the San Lorenzo and Ballenas fault zones, has very little sediment fill recognizable on seismic profiles (Fig. 4). This might be a result of volcanism along its axis, but strong bottom currents (as well as the youth of the structure) could also account for the dearth of sediment in the most constricted parts of the valley.

Although Ballenas fault zone intersects a spreading-center trough in Lower Delphin Basin, only a short section of its northeast margin is newly accreted oceanic crust. Within 30 km of the axial trough, continental basement cut by faults and dikes that parallel the spreading center is exposed on Isla Mejia and Isla Angel de la Guarda; this extensionally faulted basement can be traced on seismic profiles to a buried continental slope about 15 km from the spreading center. Reichle and Reid (1977) located an off-axis earthquake swarm, characterized by normal faulting events, along this most likely position for a continental-oceanic crustal boundary. Alongside this region the thick sediment fill which has lapped into the Ballenas fault zone rift valley from Delphin Basin is tilted toward the base of the steep Baja California slope, the inferred site of the strike-slip fault (Fig. 4, profile 15). The steepening dip with increasing subbottom depth demonstrates continued subsidence and tilting toward the transform of the oceanic and thinned continental crust between Isla Angel de la Guarda and the spreading center. To the southeast, the rift valley of the San Lorenzo fault zone has the opposite sense of asymmetry, and the sediment fill tilts away from the islands (Fig. 4, profile 4). These relationships are consistent with an uplift of this part of the offshore block, also recorded by marine Plio-

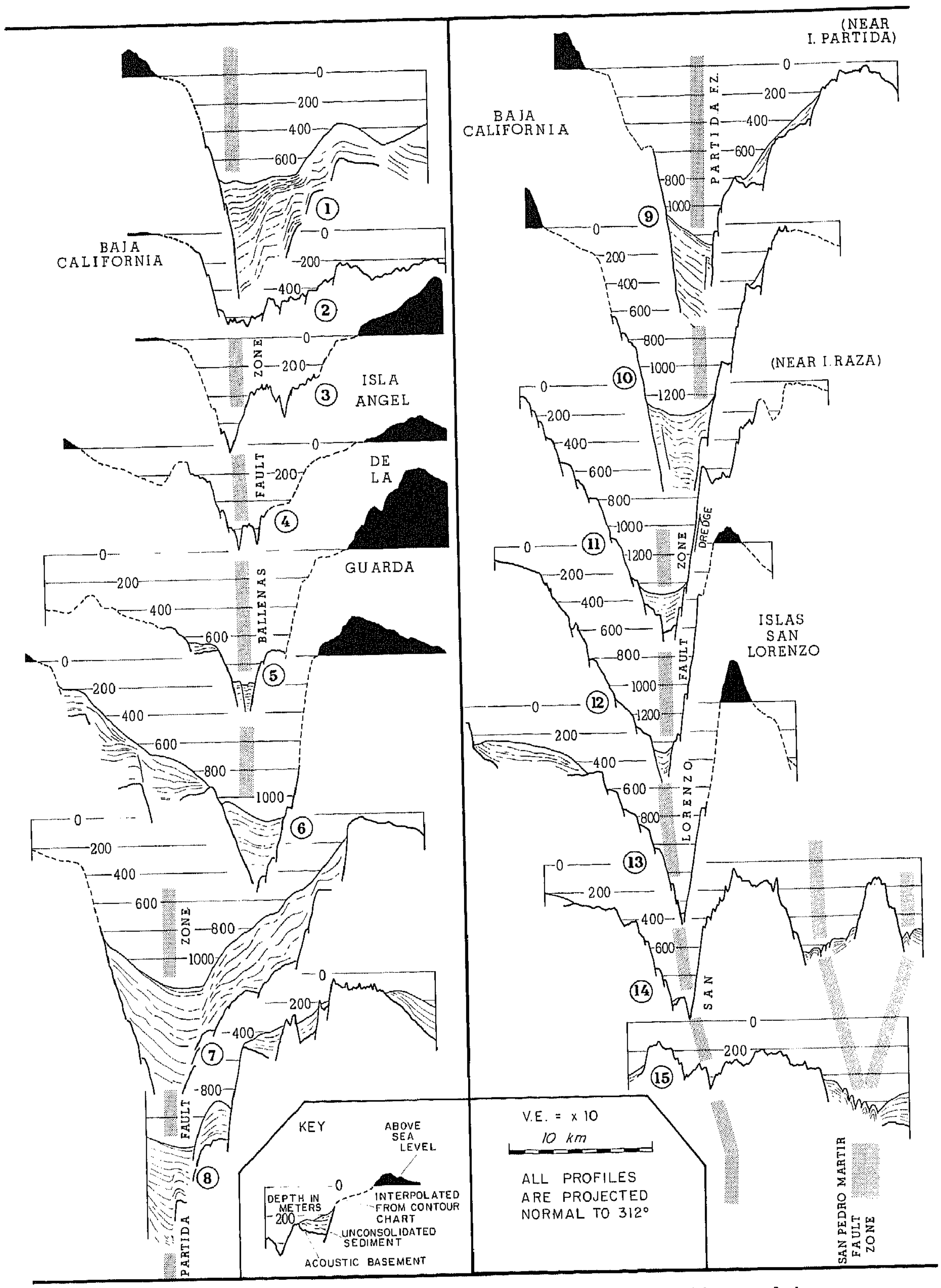


Figure 4. Line drawings of seismic reflection profiles across the northwest end of Guaymas fault system (located in Figure 3). These single-channel airgun profiles have been projected normal to the 312° azimuth of the fault zones.

cene strata several hundred meters above sea level on Islas San Lorenzo. The pattern of the plate boundary provides an explanation for this uplift; in this region, right-lateral motion on the San Pedro Martir branch fault is tranferred into Sal si Puedes Basin by a left step of 10 km across the San Lorenzo block, a geometry that is conducive to compression and horst formation between the fault zones.

Some of the right-lateral shear stress of this part of the transform fault system is also distributed into the continental margin of Baja California, where its effects are well exposed subaerially. For 30 km inland from the principal (submarine) transform faults, the crust has been dissected by families of faults with average trends of 000° and 312° (Fig.3), appropriate directions for tension and strike-slip faults within a broad plate-boundary zone. An important result is formation at the outer margins of the shear zone of continental fault-wedge and pull-apart basins, which have intercepted terrigenous sediment that might otherwise have filled Sal si Puedes Basin. Alongside the axes of that "oceanic" pull-apart, most of the fractures mapped on land have the 000° trend and bound grabens that strike obliquely into the continent for 40 km. San Raphael Basin is mainly on the shelf and inadequately surveyed, but Animas and Angeles basins are mainly subaerial, and were mapped by Gastil and others (1975). Their role as sediment traps is enhanced by basement ridges, parallel to the transforms, that truncate their northern ends and are best exposed in the line of islands across the mouth of Bahia de los Angeles. Continuing slow uplift of these dams is shown by the slightly elevated wave-cut terraces and marine Pleistocene deposits that occur on the headlands between the bays. Thickness of the Pliocene-Pleistocene basin fills is unknown, though large negative Bouguer gravity anomalies (down to −60 mgal in Angeles Basin) indicate substantial volumes of unconsolidated deposits. Igneous rocks, principally fissure basalts from the extensional faults, have contributed to basin filling; continued dilation of the basins is attested by the youth of some of their lava flows and fault scarps. Gonzaga Basin, closed by a partly submerged granitic ridge (Gastil and others, 1975), resembles Angles Basin and may once have been alongside the Lower Delphin spreading center, but it has been transported northwest so that it now lies alongside the inactive fracture-zone extension of the transform fault system. These small truncated grabens on the Baja California margin resemble those described from the margin of the Gulf of Aden by Tamsett (1984), and are interpreted by his model of precursor rifts, i.e., formed in continental crust as the pattern of transform faults linked by oceanic spreading centers was being established. Larger grabens intersecting sheared continental margins on the mainland side of the gulf (the Yaqui, Fuerte, and Mazatlan embayments of Fig. 2) are believed to have a similar origin.

A PAIR OF GULF SPREADING CENTERS IN GUAYMAS BASIN

Near the center of Guaymas Basin in the central Gulf of California is a pair of fault troughs, 3 to 4 km wide and up to 200 m deep. The role of the troughs as axes of plate separation and crustal accretion was initially deduced from seismic profiles showing recent extensional faulting (Moore, 1973) and from measurements of high thermal gradients in their floors (e.g., Lawver and others, 1973). Submersible observations (Lonsdale and Lawver, 1980) confirmed that the trough walls are fresh fault scarps exposing semilithified diatomaceous muds, and that ponds of Recent sediment within the troughs are cut by normal faults; drilling has sampled basaltic sills recently emplaced less than 100 m beneath the trough floors (Curray and others, 1982). In plan (Fig. 5), the northern and southern troughs overlap and veer toward each other, much as rift zones do at nontransform offsets on the East Pacific Rise (Macdonald, this volume), but between the overlapping troughs there is a low ridge which parallels plate motion, and is probably the trace of a transform fault that links the pair of spreading axes; the veering segments of overlapping troughs probably result from "overshoot" of the crustal extension and dike injection past this central transform fault. Where the troughs are not overlapped, their walls strike 035°, normal to the spreading direction, except in the immediate vicinity of the transform faults along the basin's margins. There, as at comparable intersections at the Tamayo transform (Gallo and others, 1984) and many other ocean ridges, the walls at the angles between the active transform faults and the spreading axes strike almost 45° oblique to the spreading-normal (Lonsdale, 1985). Another similarity to rifted mid-ocean ridges is that the trough floors plunge toward the marginal transform faults, though the bathymetric expression of this phenomenon is muted by ponding of Recent unconsolidated sediment.

The similarities in structural pattern to the axial rift valleys of mid-ocean ridges suggest that the axial troughs of Guaymas Basin have a similar origin, namely steady-state regenerating rift valleys in which material is accreted in the rift floor and uplifted at the rift walls. An alternative interpretation, that the troughs are simple grabens with down-dropped floors that were formerly part of a flat basin floor (Moore, 1973), is not supported by detailed acoustic stratigraphy of the trough walls, which include uplifted sections of trough-floor turbidite ponds (Lonsdale and Becker, 1985). Discriminating between these two alternatives is important not only because they would produce very different distributions of sediment (and mineral) facies, but because of their implications for the stability of the spreading center troughs. If the troughs merely represent down-dropped parts of a basin in regional extension, then the present pattern might be temporary, being replaced by a new arrangement after a further episode of sediment infilling; over the long term, magmatic accretion might occur diffusely throughout the basin, even if it is concentrated in the trough floors. The systematic changes along the marginal transform faults as the present axial troughs are approached (e.g., the change in height of the transform ridge), as well as the observed structure of the troughs and their position near the center of a strip of accreted crust with very uniform heat flow, argues instead for their long-term persistence as bona fide spreading centers. The best evidence for diffuse magmatic accretion in

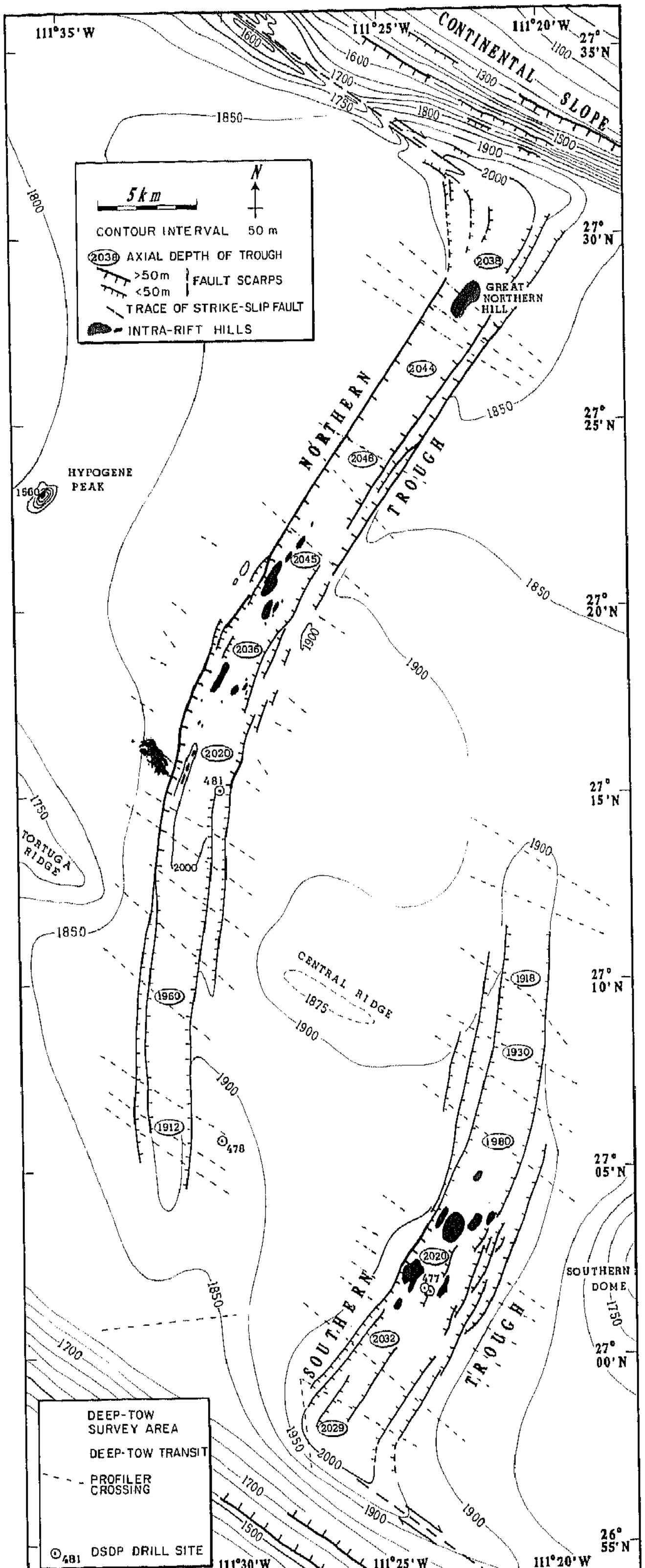


Figure 5. The spreading-center troughs of Guaymas Basin, mapped by a deep tow survey system and conventional seimic profiles. Note the overlap of curving sections of the troughs.

Guaymas Basin, other than a few small seamounts, is an anomalously young sill sampled at Deep Sea Drilling Site 478, 12 km away from the southern trough; however, this site is very close to the extension of the northern trough (Fig. 5), and may be vulnerable to intrusions overshooting from that axis.

Being the deepest parts of the basin and thereby acting as settling ponds for density flows from the continental margins is not the only reason that the trough floors accumulate sediment rapidly. Most of the basin floor is swept by tidal currents that flow up and down the gulf fast enough to entrain diatom tests, and preferential fall-out in the more tranquil bottom waters contained within the axial troughs may account for some of the ponds of ooze on the trough floors. In addition, there is major recycling of sediment that slumps and is seismically shaken off the trough walls, being transported back into the axes by rockfalls and debris flows. An important result of the influx of low density sediment is complete suppression of extrusive volcanism at the spreading axes; rising magma spreads out and solidifies as sills within the young sediments, rather than as flows at the sediment-water interface (Lonsdale and Lawver, 1980; Einsele, 1982). Intrusion of these sills has little or no bathymetric effect, because space is made available in the sea bed by expulsion of pore water, but narrow ridges mapped by near bottom sonars in the floor of the northern trough are interpreted as uplifts over recent dikes; fault-bounded hills of uplifted, semilithified sediments with flat summits up to 120 m above the floors of both troughs were probably raised above massive pluglike magmatic intrusions. Injection of magma into young, saturated, organic-rich sediments has major diagenetic effects, and greenschist-facies metamorphism prevails within 150 m of the sea floor. Among the more dramatic diagenetic changes are conversion of diatom-derived opaline silica to quartz (Kastner and Siever, 1983) and rapid maturation of organic matter to petroleum (Simoneit and Lonsdale, 1982). The petroleum is transported within the sea floor by a hydrothermal circulation initially inferred from the spatial distribution of heat flow, which has extreme small-scale variation with some very high (>1 W/m^2) values (Williams and others, 1979).

The hydrothermal circulation in the spreading-center trough discharges to the bottom water at high-velocity, high-temperature (270–314 °C) springs through mineralized pipes, and more diffusely as lower temperature seepage through the surrounding mud (Lonsdale and Becker, 1985). The local distribution of vents has a tight structural control: many of them overlie fractures in the shallowest sills, which act as cap rocks for the hydrothermal circulation, or are at the periphery of such sills. The recent shallow intrusions are not the heat source for the primary circulation, though their injection must cause short-lived discharge of heated pore water; only a more massive, deeper magma body could sustain the rapid conductive and convective heat loss that has been observed.

Geologic features at the sea-floor vents include mineralized veins lining conduits through the surface muds, and petroleum-soaked mounds, chimneys, and columns of hydrothermally deposited sulfides, sulfates (anhydrite, barite), carbonates (calcite),

silicates (talc), and opaline silica (Koski and others, 1985). These mineral deposits are commonly 20 to 100 m in diameter and 10 to 25 m high; in the southern trough, actively growing examples (a few of them discharging black smokers, which spew particulate sulfides into the bottom water) occur across almost the entire 3-km width of the trough floor, not just at the axis as on many mid-ocean ridges. Similar but inactive deposits have been found on the trough walls and intrarift hills, tectonically raised above the preferred discharge sites and flood of turbidites that rapidly bury them if they remain on the trough floor. No actively growing deposits have been located during extensive manned and unmanned searches of the floor of the northern trough, though dead sulfide mounds and ledges of talc have been found on uplifted ridges and hills within that rift valley. The paired spreading centers of Guaymas Basin are not though to be fundamentally different in their hydrothermal activity; they are just at different stages in a cycle (lasting perhaps 10,000 yr) in which brief episodes of profligate heat loss associated with freezing of a crustal magma chamber alternate with long periods in which growth of the magma chamber replenishes the heat supply.

There is no better illustration of the patchy nature of the exploration of the gulf floor than the fact that none of the other spreading centers outside of Guaymas Basin have been examined with the equipment (near-bottom sonars and cameras) needed to find similar mineral deposits, let alone with the submersibles needed for adequate sampling of the discharges, condensates, and precipitates. However, vents as energetic as those now active in the southern trough of the Guaymas Basin inject enough dissolved hydrothermal tracers (manganese, silica, methane, helium) into the bottom water that their presence can be detected by analyses of water collected in standard hydrographic casts. Incomplete results so far indicate that the present distribution of these tracers throughout the gulf's basins can be explained by transport from a single source in the southern trough. Of course, mineralizing hydrothermal systems that are contained within the sediments have no such geochemical markers; they have been adequately explored, by drilling, only in Salton Trough.

SALTON TROUGH: A COMPARISON WITH THE SUBMARINE BASINS

In Salton Trough, most of the gap between the obliquely separating continental blocks has been filled with sediment, mainly exotic detritus delivered by the Colorado River, which has been building its delta here for about 5 m.y. Lower Pliocene sandstones and mudstones and Upper Miocene beds that may have been deposited before growth of the delta began are mainly shallow marine; later silts and clays are mainly fluviatile and lacustrine. Almost all of them were deposited within 100 m of sea level, as sediment accumulation kept pace with rapid tectonic subsidence. Levelling surveys confirm that subsidence continues in the central part of the trough, but many marginal areas alongside active strike-slip faults have had a reversal in the past 2 m.y. to rapid uplift, causing erosion and exposure of early trough-fill sequences up to several kilometers in stratigraphic thickness. In the central parts of the valley, where drill cores have not penetrated beyond the Pleistocene, estimates of total sediment thickness rely on refraction measurements: in the U.S. part of the trough (north of the thickest part of the delta) sedimentary rocks 3.7 to 4.8 km thick (Fig. 6) overlie about 10 km of basement crustal rocks, which Fuis and others (1982) inferred to be mainly young (i.e., post-middle Miocene) sediments metamorphosed to lower greenschist facies at temperatures of 300°C or more. However, a significant fraction of this layer might be basaltic sills and dikes, several of which have been sampled by drilling in the overlying sedimentary layer (Elders, 1979). The composition of an underlying "subbasement" layer, of high velocity (7.2 to 8.0 km/s) but with a base undefined by seismic refraction, is even more uncertain. Fuis and others (1982) identified it as an igneous crustal layer, composed of basaltic sills and dikes in a 1-km-thick "transitional layer," that overlies gabbroic rocks more than 10 km thick. Nicolas (1985) reinterpreted it as an altered part of the upper mantle, similar to that beneath many mid-ocean ridges and composed of partly serpentinized peridotite. Neither interpretation explains the presence in rhyolite domes near the trough's axes of granitic xenoliths (Robinson and others, 1976), but these may have been derived from islands of continental crust scattered within the basement layer.

No close comparison is possible between such inadequately known crustal sections as those in Salton Trough and Guaymas Basin. If the subbasement of the former is mantle, so that the accreted crust is 10 to 16 km thick, then it is about twice as thick as in Guaymas Basin. This would be consistent with a greater fraction of the basement originally being low density sediments. Because of the greater role of magmatic accretion in Guaymas Basin, and because of a more active hydrothermal circulation under marine conditions, greenschist metamorphism occurs at much shallower levels. In the northern gulf the crustal section (Phillips, 1964) is much more like Salton Trough, with a relative low velocity (5.4 km/s) basement at 5 to 10 km depth that may be intercalated greenschist-facies rocks and magmatic intrusions, and a 6.7 km/s underlying layer that may correspond to the trough's transitional layer; as in Salton Trough, the depth to mantle is not well resolved by existing refraction measurements.

Closely related to the question of similarlity in crustal structure is whether there are true spreading centers acting as the foci of accretion in Salton trough. To the extent that the crust is of sedimentary origin, accretion occurs by deposition across most of the trough floor; if the magmatic contribution to crustal growth is negligible, as in Nicolas's (1985) model, then the concept of a spreading center must be invalid. Even if basaltic intrusion is a major accreting process in the lower crust, it may not be concentrated at well-defined, long-lived axes. Some of the young sills that have been sampled by drilling in the upper crust were clearly emplaced recently at off-axis locations. Nevertheless, "spreading centers," perhaps less stable than those in more oceanic parts of the gulf, and certainly having less topographic expression, have long been recognized in the trough. Lomnitz and others (1970)

and Elders and others (1972) identified the Cerro Prieto, Brawley, and Salton Buttes spreading centers on the basis of their locations at right steps in the right-lateral transform fault system and their superficial volcanic and hydrothermal phenomena, including rhyolite domes and historically active boiling mud pots at Salton Buttes, and a young dacite volcano, perhaps formed by remelting of adjacent continental rocks, at Cerro Prieto. Intensive geothermal exploration has confirmed that high-temperature (300 °C or more) hydrothermal systems in the upper crust are confined to these three spreading-center sites, though there are several off-axis areas with geothermal resources of 150 to 250 °C. The high-temperature hydrothermal circulations resemble those

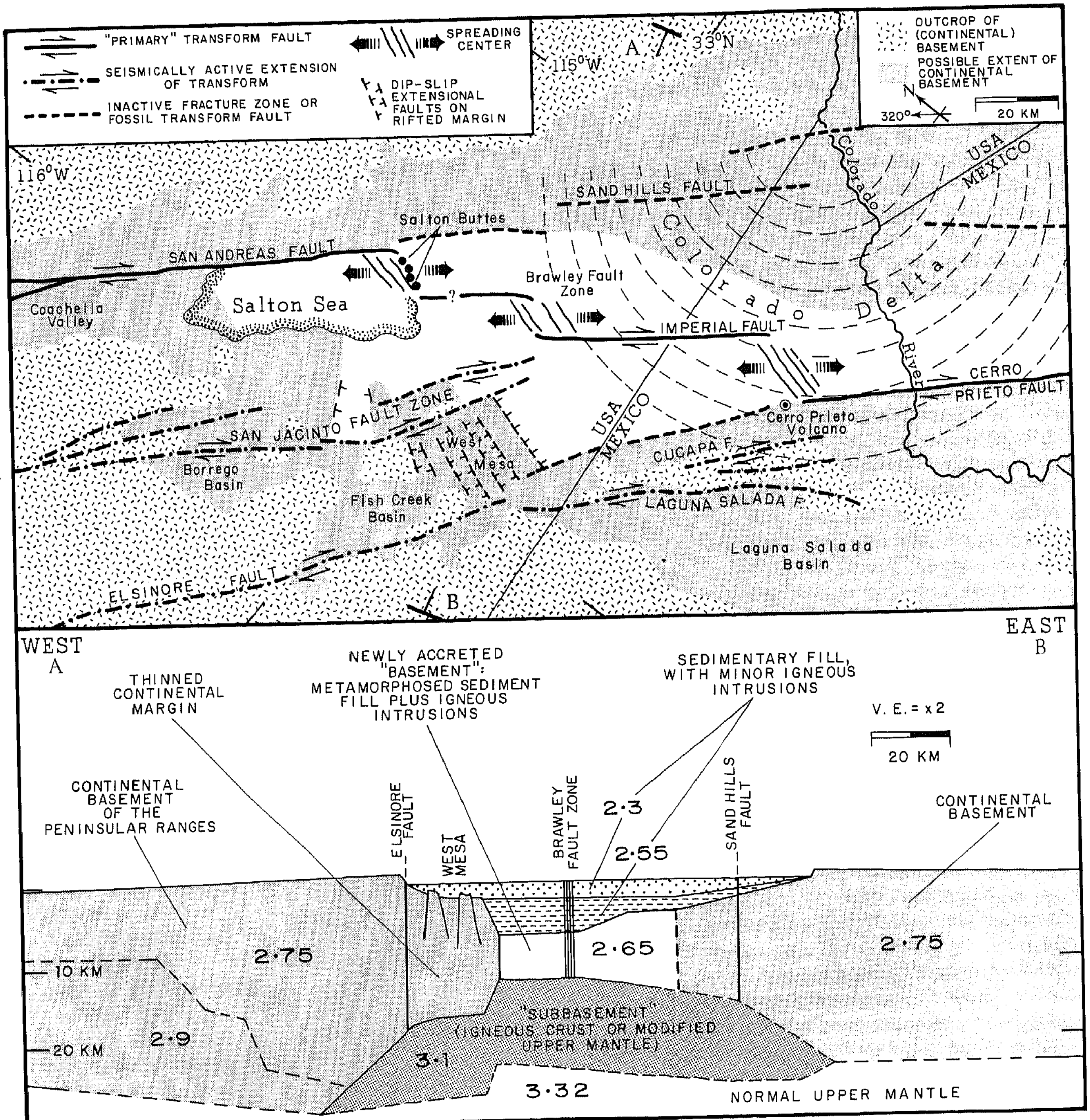


Figure 6. Sketch map and crustal section of Salton Trough (after Fuis and others, 1982). Dashed boundaries in the section are controlled by gravity modeling only (not by refraction). Numbers are estimated densities (g/cm^3).

at submarine Guaymas Basin spreading centers, even though the fluid is meteoric water, in depositing sulfide minerals (albeit within the sediment fill, rather than as superficial mounds) and, in the case of the Salton Buttes system, in having a sodium-chloride brine perhaps derived from evaporite dissolution. Their cap rocks usually seem to be impermeable lacustrine clays or self-sealed hydrothermally silicified strata (Elders, 1979), rather than igneous sills.

Recent geologic mapping, seismicity studies, and neotectonic observations have refined the fault pattern, orientation, and kinematics of these zones of crustal extension. Both the Cerro Prieto and Brawley zones have active normal faults that strike about 005°, at right angles to the maximum tensional stress imposed by the right-lateral shearing, and seismicity is characterized by swarms of small earthquakes that may be caused directly or indirectly by dike injection in the same 005° direction (Weaver and Hill, 1978). The five Salton Buttes are aligned on a similar trend, and boreholes drilled between them intercept numerous young sills and dikes (Robinson and others, 1976). These short spreading axes are thus highly oblique to plate motion, as are those bathymetrically defined in the northern gulf. Another distinctive feature is that they do not relay all of the plate motion from one transform fault to the next in the right-stepping system. Some of the strike-slip motion of the Cerro Prieto and Imperial faults continues to the northwest past their spreading-center intersections, where the active Elsinore and San Jacinto fault zones (Fig. 6) take the place of the aseismic fracture-zone extensions of a normal oceanic transform-fault system. Rupture of these fracture-zone faults can sometimes occur as an immediate consequence of an earthquake along a primary transform fault, such as the magnitude-6.5 event that broke the Imperial fault and part of the San Jacinto fault zone in October 1979, and caused dip-slip displacement at the Brawley spreading axis. An important result of this complexity in the plate boundary is that the spreading axes farthest to the northwest should have a slower spreading rate, and should therefore have accreted a narrower strip of crust. The rifted margin on the west side of the Salton Sea is only about 30 km from the Brawley spreading axis, whereas the rifted margin of West Mesa is about twice as far from the Cerro Prieto axis, which itself loses some of the plate motion to the Elsinore and Laguna Salada faults. However, poor definition of the oceanic/continental boundary in the southeast part of Salton trough prevents full confirmation of this pattern and prevents resolution of whether the present spreading axes are symmetrically disposed between rifted margins (which, as at Guaymas basin, might suggest some long-term stability).

The rifted margin of West Mesa (Fig. 6), well defined by seismic refraction (Fuis and others, 1982), is cut by normal faults approximately orthogonal to crustal separation, and underwent rapid subsidence early in the history of the trough. Even the continental rim, the top of the original continental slope, has granitic rocks now more than 1 km below sea level. A tectonic subsidence rate of 1.5 to 1.0 mm/yr documented for the interval from 4.3 to 4.0 Ma by Johnson and others (1983) is similar to that estimated by Curray and others (1982) for rifted continental crust at the mouth of the gulf. As is true throughout the gulf, a greater length of the trough's margins is of the sheared rather than the rifted variety. Some of the sheared margins have parallel fault zones isolating crustal slices that resemble marginal plateaus, now submerged by the trough fill (e.g., Sylvester and Smith, 1976).

As noted earlier, many of the marginal strike-slip faults that cut continental rocks bound areas of rapid uplift. Reversal of the general tendency of the trough floor to sink is caused by a component of compression across the fault zones. It has been suggested that this transpression, which locally causes intricate folding of the sedimentary section (Sylvester and Smith, 1976), marks lack of adjustment of the azimuth of the continental fractures to the 320° direction of recent relative plate motion (Fuis and others, 1982). This direction is followed by the Imperial fault, wholly contained in newly accreted crust, and by those short segments of the southern San Andreas fault that have not caused adjacent uplifts (Bilham and Williams, 1985). If this theory is correct, then the San Jacinto and Elsinore fault zones, which strike 315–290° and 295°, respectively, may have been born maladjusted, because uplift along the western margin of the trough began soon after their initiation as major components of the plate boundary (e.g., Johnson and others, 1983). Whatever the cause of the variable orientation of the trough's transform faults, the pattern is in striking contrast to the Guaymas fault system, where the intracontinental fault zones have a more northerly trend than those involving oceanic crust, and their confinement in deep, narrow rift valleys is indicative of transtension rather than transpression.

The timing and net amount of strike-slip motion on the several fault zones of the San Andreas system that enter Salton Trough can be determined from the amount of offset of dated strata that they displace. Crowell (1981) estimated about 30 km of slip on the Elsinore fault zone, 24 km on the San Jacinto (both beginning in the late Pliocene), and perhaps as much as 250 km on the San Andreas, beginning at 4 Ma. Before initiation of the modern San Andreas fault in this area, there was about 50 km of right-lateral motion, probably along the northeast side of Salton Trough, on the southern extension of the San Gabriel fault zone. This now-inactive fault zone was the earliest component of the plate boundary in the northern part of the gulf province, so its birth near the end of the Miocene, 5–6 Ma (Ehlig and others, 1975), dates the beginning of the entire inland transform boundary. The other critical data on the timing of the detachment of Baja California come from oceanographic studies at the mouth of the gulf.

GEOLOGY AND GEOPHYSICS AT THE MOUTH OF THE GULF

The ocean floor at the entrance to the gulf is occupied by two ordinary segments of the East Pacific Rise, linked by the 70-km-long Tamayo transform fault. This fault zone, which for the past 1 m.y. has been entirely contained within oceanic crust,

has many characteristics of mid-ocean ridge transforms, including a transverse ridge that may be a serpentinite intrusion (Kastens and others, 1979). The rise crest north of the Tamayo fault zone has a low axial ridge that makes a T-junction with the transverse ridge. The flanks of this northernmost section of the East Pacific Rise (which has also been called the Gulf Rise and Alarcon Rise) have low lineated abyssal hills and clear sea-floor-spreading magnetic anomalies on crust as old as 2 Ma (and less convincingly to 3.5 Ma), though the lineated pattern is disrupted on the west flank by a large extinct volcano, Alarcon seamount (Fig. 7). South of the Tamayo fault zone the rise crest strikes at 215° for 125 km to a short left offset at lat 22°N. The central part of this segment has an axial volcanic ridge, but at both ends, especially at the Tamayo intersection, the spreading axis lies within a rift valley. This pattern, with ~100 km long linear volcanoes separated by left offsets, is continued as far south as the Rivera transform fault, though south of lat 22°N the rise can hardly be considered to be in the mouth of the gulf. Sea Beam bathymetric swaths across the offsets suggest that none of them are true transform faults having strike-slip faults parallel to spreading, though they are seismically active. A survey of the lat 22°N offset (Fig. 7, inset) indicates that this example is migrating southward, probably in the same way that offsets migrate west on the similar Cocos-Nazca spreading center (Hey and others, 1980). Rise-flank magnetic anomalies (Fig. 8) show that the left offsets originated 1.7 to 1.0 Ma, between the times of Anomaly 2 and the Jaramillo event, when the spreading axis and presumably the spreading direction rotated clockwise by 10 to 15°. This rotation brought the rise crest parallel to Pacific–North America spreading centers within the gulf (e.g., in Guaymas and Farallon Basins), and is most readily explained by the plate that formed the east flank of the rise changing its motion to that of the North American plate. Previously it had moved as the independent Rivera plate, a fragment of the ancestral Farallon Plate. A trench extending northwest to the Tres Marias Islands and a belt of calc-alkaline volcanism are the legacy of the former convergence of this small plate with North America, and there is still a low level of modern seismicity extending along the trench to the Tamayo fracture zone.

Involvement of a third lithospheric plate, in addition to the Pacific and North American, has not been the only tectonic complication at the mouth of the gulf, as evidenced by the eccentric position of the spreading axis (Fig. 7). The western flank of the rise has a maximum age near lat 23°N of about 3.5 Ma (just older than Anomaly 2A), and laps against subsided crust of the rifted margin of Baja California about 90 km from the present rise crest. Drilling onto the continental crust near this boundary established that it has accumulated marine hemipelagic muds since at least 4.5 Ma (Curray and others, 1982). In the more accessible onshore sections within the San Jose del Cabo fault trough, hemipelagic deposition began in the late Miocene (i.e., pre–5 Ma), following a period of shallow marine conditions that may have begun as early as the middle Miocene (McCloy, 1984). On the eastern flank of the East Pacific Rise, Anomaly 2A occurs at almost the same distance off-axis (Fig. 8), but between it and the continental slope of Islas Tres Marias (where upper Miocene hemipelagic muds also crop out) is a 70 to 100-km-wide area of rugged deep-sea floor known as the Maria Magdalena Rise. For about 20 years it has been recognized that this small area is a key to understanding the initiation and early history of the gulf, but there is still not enough marine geophysical data for a complete structural interpretation, and there are no relevant geologic samples. Recent bathymetric and magnetic profiles, including a Sea Beam traverse (Fig. 9), support the hypothesis that most of the rise is oceanic crust that accreted before 3.5 Ma at a spreading center that was abandoned at that time in favor of the present axis (Larson, 1972; Mammerickx, 1980). The relief is composed of highly lineated fault blocks and volcanic ridges that have axes of symmetry which strike in a plausible direction (025°) for a former spreading center, and there are lineated magnetic anomalies with wavelengths and amplitudes characteristic of oceanic crust; a refraction line located in Figure 7 shows a typical oceanic section (Phillips, 1964). These facts are difficult to reconcile with the alternative hypothesis, that the Maria Magdalena Rise is a block of foundered continental crust (Curray and others, 1982). The best candidate for a detached fragment of preexisting continent is a small (600 km^2) plateau with a 2,000-m-deep summit and up to 500 m of sediment cover, immediately west of Islas Tres Marias. The distance across the mouth of the gulf from the western edge of this plateau to the continental margin of Baja California is 280 km, a little less than the total right-lateral displacement across the gulf transform system (estimated as 300 km by Gastil and others, 1981). However, even if most of the Maria Magdalena Rise is accepted as accreted oceanic crust, competing hypotheses for its age and the origin of its relief cannot be fully tested because the magnetic anomalies over the rise cannot be unambiguously identified with the reversal time scale. Reasons for this difficulty include the shortness of the magnetic sequence, the likelihood that the crust was accreted at short, laterally offset spreading segments (Fig. 9), and, perhaps, the low fidelity of anomalies over crust that accreted near a sediment-shedding continental margin. Inability to identify oceanic magnetic anomalies adjacent to the continent slope, except where old crust is being subducted at a trench, is not limited to the Maria Magdalena Rise; it is the general rule throughout the area shown in Figure 8, with the exception of the oceanic crust east of the tip of Baja California. Ness and others (1981) proposed that this exceptional area also had a trench, at least 8 m.y. old, that consumed west-flank crust conjugate to the Maria Magdalena Rise and had a subduction zone dipping northwest under the tip of Baja California; in this scheme, the Maria Magdalena Rise is merely the old (pre–3.5 Ma) east flank of the East Pacific Rise, deformed by plate interactions at the Rivera–North American boundary. This radical suggestion, poorly supported by magnetic data, can be rejected as inconsistent with the structural geology of the Baja California margin (Curray and others, 1982). A preferred interpretation that better fits into the spreading history revealed by anomaly patterns beyond the immedate mouth of the

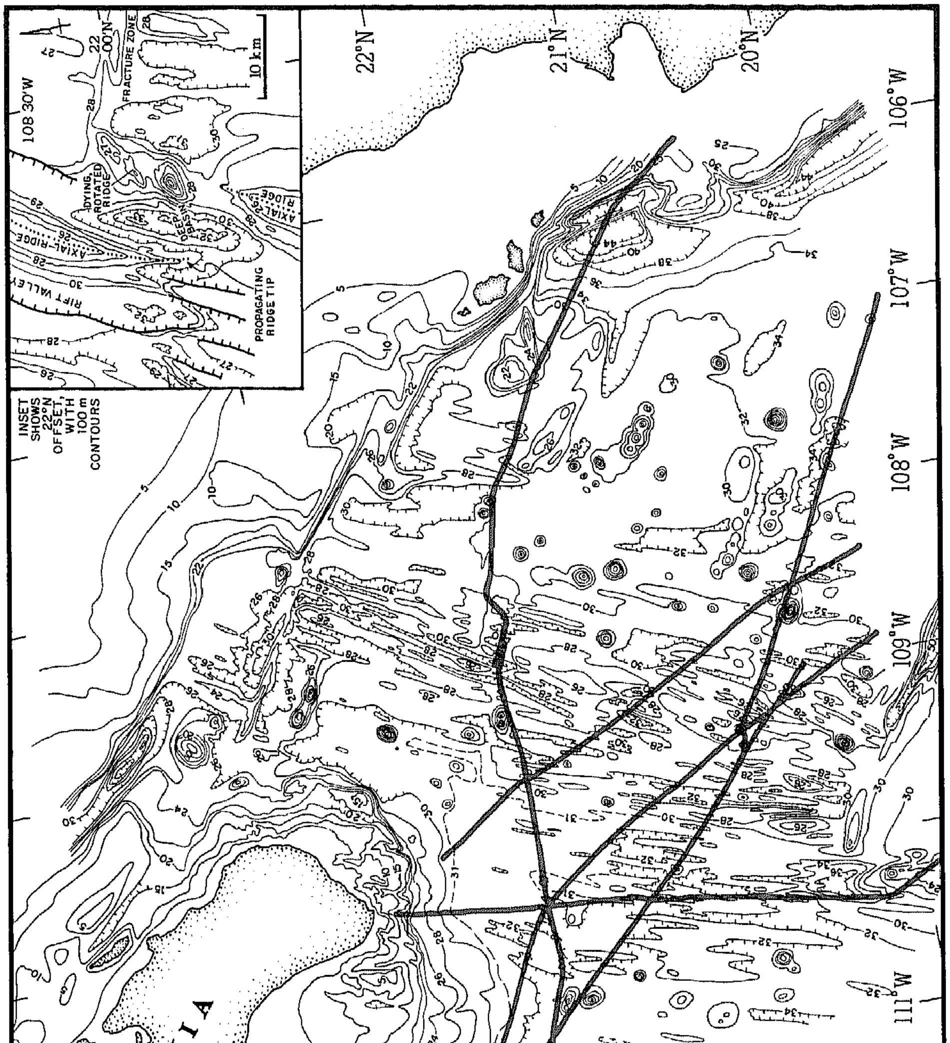


Figure 7. Bathymetry of the mouth of the gulf, revised to incorporate recent multibeam (Sea Beam) traverses. Inset at top right shows details of the 10 km left-offset of the East Pacific Rise at lat 22°N, which marks the southern limit of the gulf.

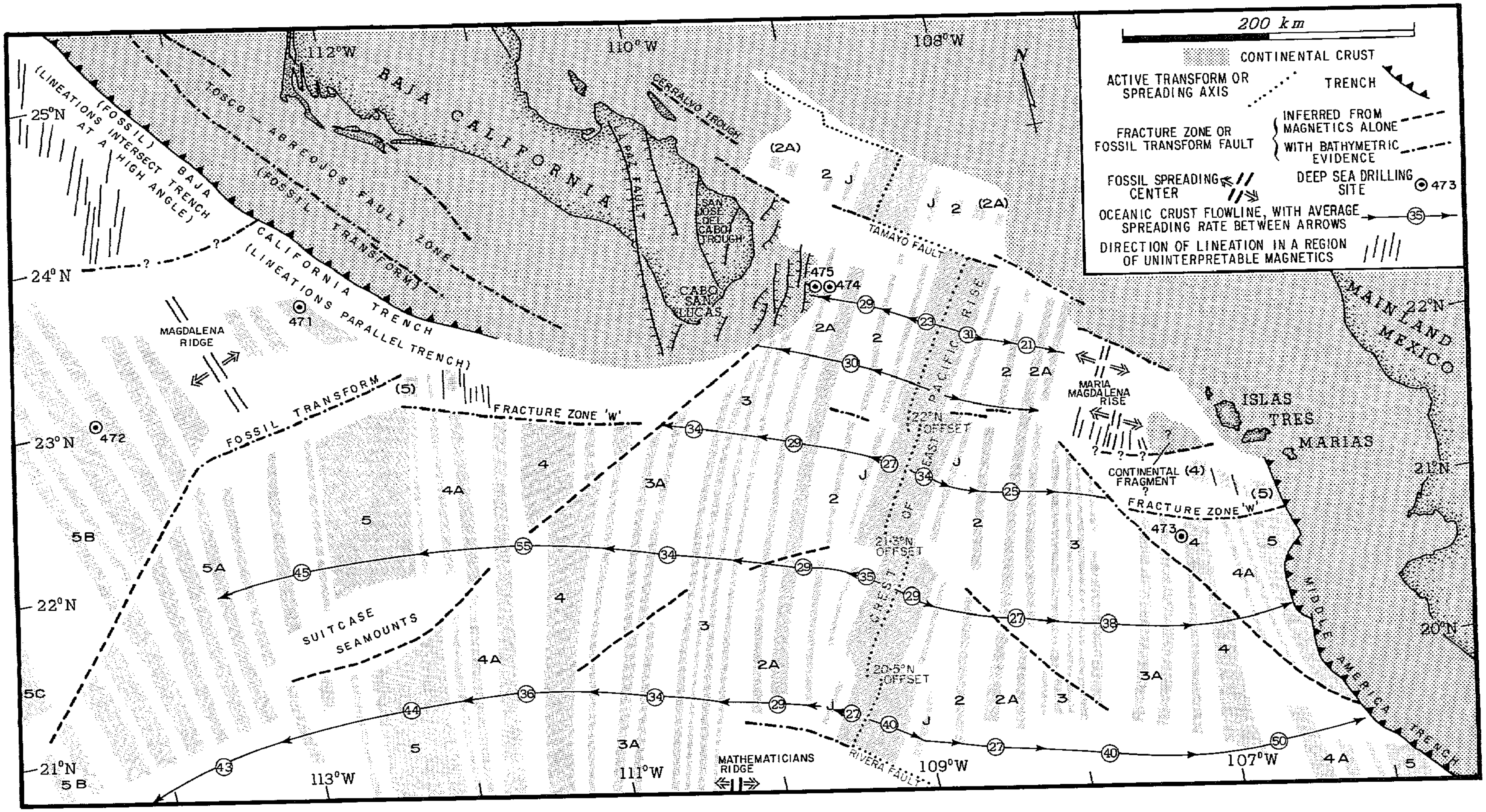


Figure 8. Magnetic anomalies at the mouth of the gulf (positively magnetized oceanic crust is shaded). This revision of the interpretations of Chase and others (1970) and Larson (1972) relies mainly on post-1970 satellite-navigated traverses which reveal large navigational errors in the older data. Recent Sea Beam swaths (see Fig. 7) are particularly valuable because the azimuth of (abyssal hill) lineations is measured concurrently with the magnetic anomaly.

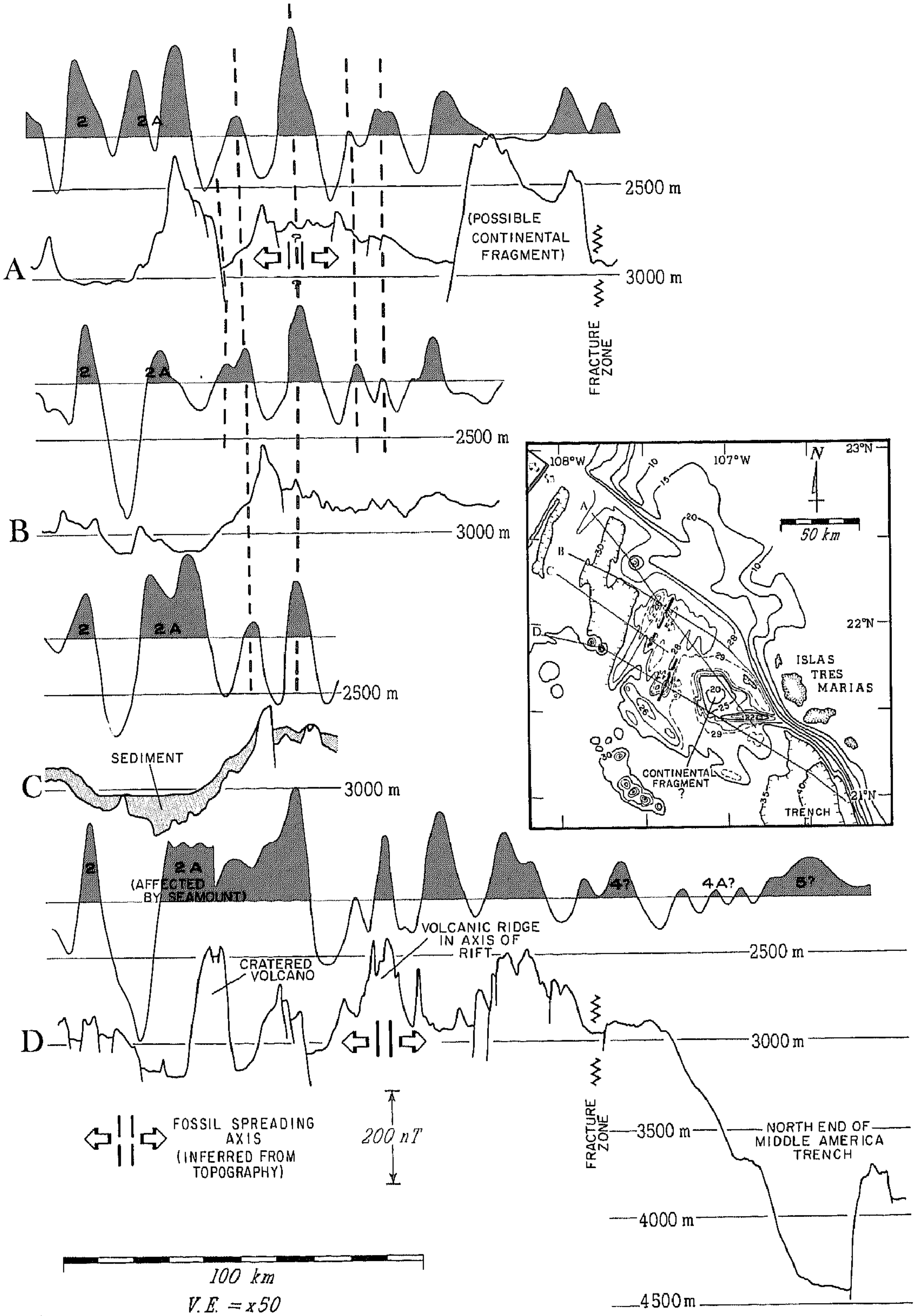


Figure 9. Bathymetric, magnetic, and (one) seismic profile across Maria Magdalena Rise. Profile A collected by Scripps R/V *Melville*; faults are inferred from the 3.5 kHz record. B: from Ness, 1982; C: from Moore, 1973; D: a Sea Beam narrowbeam profile; faults are inferred from slope steepness and linearity. All profiles are projected orthogonal to 026°, the dominant trend on the Sea Beam crossing.

gulf is outlined in the final section, which seeks to draw together information now available from the mouth, head, and center of the gulf into a consistent history of the entire province.

AN INTERPRETATION OF THE STRUCTURAL EVOLUTION OF THE GULF PROVINCE

The necessary preconditions for initiating the gulf as an intracontinental part of the Pacific–North American boundary were (1) contact between these two plates, which first occurred along the entire (western) continental margin of Baja California about 12.5 Ma, and (2) the changing motions of a third plate, which during the next 6 to 7 m.y. caused rotation of the East Pacific Rise until its spreading axis was almost orthogonal to this shearing margin. Most of the record of these middle and late Miocene events is to be found on the ocean floor southwest of Baja California.

At 15 Ma, the age of Anomaly 5B, the East Pacific Rise, striking about 340°, was obliquely converging with a trench aligned at 325° along the continental margin (Fig. 10A). As the rise neared the trench, the narrowing north end of the intervening plate fragmented into independently moving slabs. In response, the spreading axis broke into short segments of differing orientation; some of the segments rotated until they intersected the trench at a high angle (Fig. 7, northwest corner), as had occurred off central California some 10 m.y. before (Atwater, this volume). Just before the time of Anomaly 5A (12 Ma), spreading ceased at the Guadelupe and Magdalena segments of the rise (which had not rotated), and probably at every intervening segment, so that the boundary of the newly enlarged Pacific Plate jumped to the North American continental margin, and the Tosco-Abreojos transform fault was initiated (Spencer and Normark, 1979). The limit of cessation of spreading on the East Pacific Rise was a northward-migrating right offset that has left a pseudofault trace in the magnetic anomalies and a zone of rotated fault blocks mapped by Sea Beam, from about lat 21 °N, long 115 °W to lat 22.6 °N, long 113.3 °W (Figs. 7 and 8). The latter point, the northern tip of the East Pacific Rise at 12 Ma, was connected to a Pacific–North American–Rivera triple junction on the continental margin near the junction of the Baja California and Middle America trenches by an obliquely shearing boundary along the volcanic ridge near lat 23 °N (Fig. 10B).

The reduced Rivera Plate changed direction from northeast to southeast once it was no longer being pulled down the Baja California trench, as shown by the changing strike of abyssal hills and magnetic anomalies that are inferred to stay orthogonal to the spreading direction. On the west flank near lat 22°N there is a 30° clockwise rotation between Anomaly 5A (12 Ma) and the beginning of Anomaly 3A (6 Ma). This change in plate motion was accompanied by a change in the triple-junction geometry. By 9 Ma (end of Anomaly 5) at the latest, a new segment of East Pacific Rise, offset right from the main axis, connected to the southern end of the Tosco-Abreojos fault zone, and the continental slope southeast of the triple junction was becoming more of a transform than a convergent margin (Fig. 10C).

In Figure 10 (panels B–E) it is suggested that left-lateral strike-slip faulting, antithetical to the right-lateral slip in the Tosco-Abreojos system, fragmented the continental crest on the landward side of the triple junction. The best documented left-lateral slip is on the La Paz fault, where about 50 km of post-middle Miocene motion has been proposed (Hausback, 1984). Northward motion of the tip of Baja California, relative to the rest of the peninsula, is held responsible for the major embayment in the continental margin that developed at the future site of the mouth of the gulf.

Rotation of the long, formerly unbroken segment of East Pacific Rise was effected by highly asymmetric spreading, with much faster accretion to the west flank at its north end and was accompanied by the formation of new left-stepping offsets. These are common responses of the rise crest to a change in spreading direction, as exemplified by the previously discussed abrupt change at the East Pacific Rise 1.7 to 1.0 Ma. One short offset whose early west-flank trace is marked (or obscured) by the linear volcanic ridges known as Suitcase Seamounts was temporarily eliminated by a minor ridge "jump" at Anomaly 4A (Fig. 8), but was reestablished as a northward-migrating offset that displaces Anomaly 4 by 10 to 20 km; it may have resembled the modern (southward-migrating) lat 22°N offset (Fig. 7, inset). By 5.5 Ma the Suitcase Seamounts offset had migrated, by propagation of the southern ridge segment, up to the right-offset fracture zone called Fracture Zone W by Mammerickx (1980). It continued to propagate past the fracture and through the older (but poorly dated) oceanic crust on its north side until, by 4.5 Ma, the tip of the propagating ridge was in contact with subsided continental crust off the southern tip of Baja California (Fig. 10F). The ridge continued to extend north, along the foot of the continental slope, and a burst of rapid extension at 3.5 Ma extended it all the way to the Tamayo transform.

In the scenario outlined in the previous paragraph, propagation of a segment of the East Pacific Rise into the continent to precipitate opening of the Gulf of California is seen as merely the continuation of a long history of northward propagation by this same spreading segment. However, this appealingly simple picture is complicated by the existence of Maria Magdalena Rise on the eastern margin of the crust accreted at this propagating rift. If this rise is indeed pre–3.5 Ma oceanic crust, then the northward propagation of the East Pacific Rise along the foot of the Baja California slope was not between two blocks of fractured continent, but along the boundary between continental crust and oceanic crust. Perhaps this unusual situation accounts for the unusual clarity of its near-continent magnetic anomalies. As a slight variation on one of Larson's (1972) models for the initiation of the gulf, I suggest (Fig. 10F) that Maria Magdalena Rise was occupied during the time of Anomaly 3 by a dying rift that was being progressively overlapped by the northward-migrating

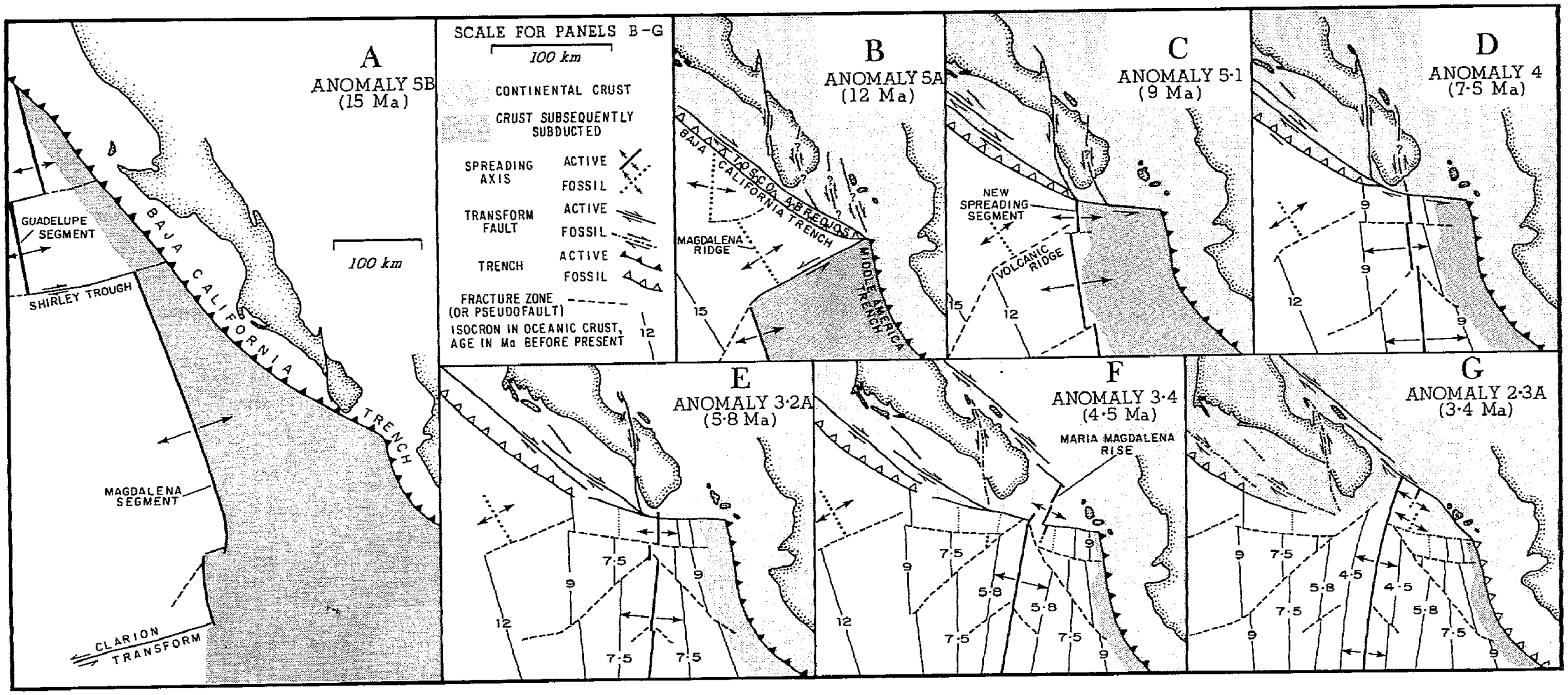


Figure 10. An interpretation of the sequence of adjustments of plate boundaries and plate motions that led up to the birth of the gulf. The complex deformation within continental crust has been grossly oversimplified. This evolution, discussed in the text, is based on the magnetic interpretation of Figure 8.

East Pacific Rise. Direct evidence for an offset at this time includes the eastward curvature of anomaly 3 on the west flank of the East Pacific Rise, where it extends farther north than on the east flank (Fig. 8), and a set of oblique lineations mapped by Seabeam at the western margin of the East Pacific Rise (Fig. 9); these are typical features of migrating nontransform offsets. The dying spreading center became extinct 3.5 Ma, when it was completely overlapped by the East Pacific Rise.

If Maria Magdalena Rise had spread as fast as the East Pacific Rise, its 50 km width of oceanic crust (Fig. 9) could have accreted in just 1 m.y. However, its spreading rate was probably lower, accounting for its rougher topography, because it marked the spreading boundary between North America and an accelerating Baja California microplate, rather than between the Rivera and Pacific Plates. The Rivera–North America boundary probably extended north of Islas Tres Marias (causing the Pliocene uplift of the islands) only after Maria Magdalena Rise became extinct. While it was active, and the first phase of plate motion was occurring in the gulf (Fig. 10F), the Tosco-Abreojos fault zone probably continued to act as a major plate boundary until Baja California was effectively joined to the Pacific plate Until better age estimates are available for Maria Magdalena Rise, the best evidence for the time of initiation of the gulf comes from the other end of the system, in southern California. The 50 km of accreted crust on the rise correlates with the 50 km of pre-4 Ma offset on the San Gabriel fault, which probably originated 6 to 5 Ma. There is also a sedimentary record of rapid subsidence and the onset of marine conditions in Salton Trough at this time (Lucchita, 1979; Boehm, 1984).

Where are the (inactive) faults that once linked the now-extinct San Gabriel fault zone and Maria Magdalena Rise? Good candidates include major inactive strike-slip faults identified by onshore field mapping in coastal Sonora and near the gulf coast of central Baja California (e.g., Gastil and Krummenacher, 1977). Offshore traces of the same fault systems (Fig. 2) have been tentatively identified by geophysical surveys, using gravity and magnetics in the sediment-choked northern gulf and bathymetry and seismic profiling in the south; examples include San Pedro Nolasco Trough (Fig. 2), a fault scarp off the northeast side of the Concepcion peninsula, and Cerralvo Trough (Fig. 7). A distinctive feature of these fault traces is that they strike 320–325°, parallel to the preexisting fault zones along the western margin of the peninsula, as might be expected if they shared the Pacific–North American motion during the 6 to 4 Ma interval. This orientation determined the overall trend of the present gulf. The breadth of the belt of inland faulting (Fig. 11) suggests that intracontinental shearing was initially widely distributed, as at the comparable plate boundary in the Gulf of Aqaba, where early

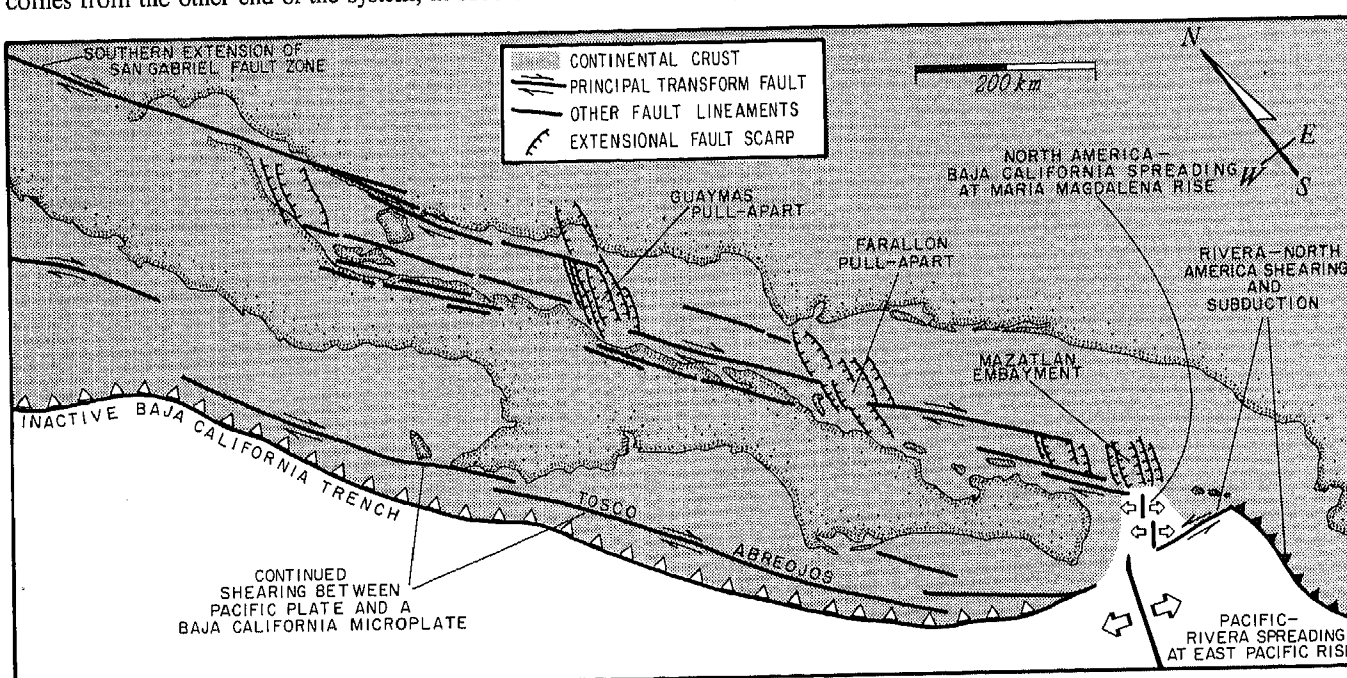


Figure 11. The Gulf of California province at an early stage in its opening (about 4 Ma), after Baja California had separated about 100 km from North America, mostly by slipping along northwest-trending faults parallel to those of the older offshore fault zones (e.g., the Tosco-Abreojas fault zone). Crustal accretion was not yet occurring within the gulf, but pull-apart basins with attenuated continental crust had formed at steps between the principal right-lateral fault zones. Concurrent faulting on both the offshore and gulf fault zones isolated Baja California as a microplate, gradually transferred from the North American to the Pacific Plate. Soon after the stage sketched here the Pacific-Rivera spreading center propagated rapidly past Maria Magdalena Rise, significant motion ceased on the offshore fault zones, and strike-slip faulting within the gulf (responsible for 200 km of subsequent plate motion) changed direction to parallel the long axis of this sketch map (see Fig. 2).

motion responsible for almost half the total displacement to date was dispersed over a belt of subparallel faults 30 km wide on the Sinai margin, before consolidation into well-defined submarine fault zones (Eyal and others, 1981). Subsidence of continental crust in fault wedge and pull-apart basins between the strike-slip faults probably initiated the submergence of the central Gulf of California, and caused rapid subsidence of basins at the head of the gulf (e.g., the pre–4 Ma subsidence of Salton Trough; Johnson and others, 1983) that may have been inherited from earlier basin-and-range faulting. Near the gulf coast of central and southern Baja California, onset of strike-slip faulting was associated with intense late Miocene–early Pliocene faulting on north-south normal faults, attributed to extension inducted by the right-lateral shearing (Angelier and others, 1981). Offshore, east-west extension is marked by fault scarps on the continental margin near Isla Carmen. The Yaqui embayment (Fig. 2) is probably the abandoned part of a major north-south pull-apart between the fault zones of northwestern Sonora and southeastern Baja California; the rest of the pull-apart matured into Guaymas Basin.

After 3.5 Ma, when the East Pacific Rise had propagated to the shearing continental margin north of Maria Magdalena Rise, the coastal fault zones of western Baja California no longer carried a significant share of the interplate motion. This is determined by the high spreading rate (54 mm/yr) recorded by magnetics in the mouth of the gulf. Shearing within the gulf was correspondingly accelerated, and it rotated counter-clockwise, initiating a pattern of new en echelon transform faults oblique to the overall trend of the gulf. Some of the pull-aparts that linked the new fault zones had been sites of crustal extension during the first phase of gulf opening, but with acceleration of crustal separation they were converted to real spreading centers that accreted new crust. Judging from the approximately 130-km-wide strips of crust estimated to have accreted in Guaymas and Farallon Basins, this transition occurred at about 2.5 Ma in the southern gulf. There, it was accompanied by rotation of the extensional axes from north to south in the continental pull-aparts to a direction at right angles to plate separation, as on mid-ocean ridges. In Guaymas and Farallon Basins, reorientation of the axes was accompanied by their break up into a pair of spreading centers linked by short central transform faults. (The southern axis of Farallon Basin subsequently became extinct, as shown in Fig. 2.) Spreading centers in the northern gulf, which structurally have little in common with mid-ocean ridges, have maintained their oblique orientation.

Since 3.5 Ma, counter-clockwise rotation of the relative plate motion has continued, causing a component of extension across some transforms with such diverse effects as opening a graben (in continental crust) at the north end of the Guaymas fault system, and building a transverse ridge (in oceanic crust) at the Tamayo fault zone. The transform faults along the oceanic-continental boundaries in the central gulf appear to hae adjusted to the same change in the shear axis by changing their azimuths and creating small new pull-aparts, as in the Guaymas fault zone (Lonsdale, 1985) and at Carmen Basin. In Salton Trough the shifting of part of the plate motion away from the San Andreas fault zone to the less northerly trending San Jacinto and Elsinore faults may result from the same change in spreading direction, but it may be as sensible to consider the shift as the cause of the change in motion of a Baja California Microplate, which still does not move at exactly Pacific velocity.

Other lateral shifts of the plate boundary from one fault zone to a subparallel, overlapping zone have occurred within the gulf, causing transfer of a crustal block from one plate to another. For example, the shift that caused abandonment of the South Farallon spreading center (Fig. 2) transferred a 2,000 km^2 continental block, named the Mendoza Block by Ness (1982), from the North American plate to Baja California. In the central gulf the main event of this type was the shift that detached Isla Angel de la Guarda from Baja California. The limited right-lateral separation of the island, revealed by the small width of Lower Delphin Basin (Fig. 3), suggests that this could have occurred within the past 2 m.y., though it was probably a gradual transfer of strike-slip activity rather than a sudden jump. Transfer of the principal plate motion from northeast to southwest of Islas San Lorenzo, detaching those islands and opening new pull-aparts in Sal si Puedes Basin, was even more recent (judging from the small width of the pull-aparts) and is far from complete.

Many uncertainties remain about the brief but eventful history of the Gulf of California. The manner of its initial opening is particularly controversial, and an alternative interpretation is provided by Spencer and Normark (this volume). Several of the problems could be solved readily with additional fieldwork targeted to answer such specific questions as the age of Maria Magdalena Rise or the amount of offset on Ballenas fault zone. In the future, the results of more systematic regional surveys with modern geophysical equipment will no doubt raise new problems, the resolution of which will further enhance our understanding of the complex interaction of oceanic and continental crustal processes.

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