Lithospheric Rupture in the Gulf of California – Salton Trough Region

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ABSTRACTS

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Seismic imaging of the transition from continental rifting to seafloor spreading, Woodlark Rift system, Papua New Guinea

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The Woodlark rift system of Papua New Guinea accommodates 25-40 mm/yr north-south extension in continental crust. Extension rates increase eastward so that full seafloor spreading occurs east of highly rifted crust, making this one of the few active examples of complete continental rifting. We report on the results from the first passive seismic survey in the region. The survey deployed 19 PASSCAL broadband seismographs and 14 ocean bottom instruments, covering a 360x280 km region surrounding the active spreading tip. From these data 1152 earthquakes are well-located within the network, and jointly inverted for hypocenters and 3D velocity structure. Also, teleseismic receiver functions provide crustal thickness estimates, and travel times give variations in mantle velocity. Crustal thickness varies from 30-35 km off the rift flanks to 20 km in the most extended crust just ahead of the rift tip. The crustal thinning approximately balances the stretching inferred from tectonic reconstructions, localized along an E-W axis extending westward from the rift tip. Beneath the continental seismic Moho lies a 10 to 15 km thick gradient zone with Vp increasing from 7.0 to 7.9 km/s, which may reflect an underplated mafic, granulite-facies lowermost crust, or perhaps magmatic intrusion into the lithospheric mantle. Otherwise, crustal velocities in continental crust show typical continental values (Vp = 5.6 - 6.9 km/s), indicating that basaltic magmatism prior to the onset of seafloor spreading does not form a significant crustal addition. By contrast, we observe Vp = 6.5 - 7.2 km/s close to the oceanic rift tip in a zone 60 km wide, indicating a narrow region of mafic crust. This sharp contrast suggests that the transition from distributed continental rifting to localized seafloor spreading likely occurs across a narrow zone and close to the onset of rifting in both time and space.

Most earthquakes lie along a narrow belt extending from the oceanic rift tip westward along strike, in continental crust. This belt lies just north of the chain of young metamorphic core complexes and follows a graben structure identified on high-resolution bathymetry; focal mechanisms confirm that it represents a normal fault system. The fault system also follows the axis of maximum crustal thinning, and lies above a swath of very low upper-mantle velocities inferred to represent shallow asthenosphere. Thus, both brittle faulting and lithosphere-scale thinning are localized in an along-strike extension of the ridge axis, and it seems possible that this belt denotes the site of future sea floor spreading. However, much of the continental crust shows minor seismicity along other trends, in some cases following apparent transfer fault systems acting to broaden the region of deformation. It appears that some process localizes lithospheric thinning and faulting in the upper crust within 100 km of the oceanic rift tip, as the continental crust fully extends before forming a new ocean basin.

Rift-to-rift Drift Transition in the Gulf of California

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Asymmetry is a conspicuous feature throughout the length of the Gulf of California rift. Based on the interpretation of ~3600 km of multichannel seismic reflection data collected by PEMEX, we show that the eastern side of the northern Gulf hosts a now-inactive, and well-developed system of rhombochasmic basins that includes the Altar, Adair-Tepoca and Tiburón basins, with depths ranging from ~4.5 to ~6.0 km. Subsidence was controlled by the Altar, Amado, De Mar, and Tiburón faults, which now show little activity, but may have accommodated large amounts of dip-slip and strike-slip motion during the early transtensional evolution of the Gulf of California in late Miocene?-Pliocene time. The western side of the northern Gulf holds a system of coalescing and laterally continuous basins that includes the Wagner, Consag, Upper Delfín and Lower Delfín basins, with depths grater than ~4-5? km. Subsidence appears to be controlled by broad deformation strips partially located in the hanging wall of the Wagner Fault Zone. The inactive and active basin systems in the northern Gulf are separated by a broad antiform structure cored by an inferred basement high. The stratigraphic relationships across this antiform indicate that the upper deposits in the inactive basins correlate with the mid and lower deposits in the active basins, evidencing that locus of maximum subsidence and sedimentation shifted from the eastern to the western Gulf. We propose that deformation shifted westwards during late Pliocene time towards zones of lower yield stress, which are likely related to the higher thermal conditions, and discrete volcanism tied to the Baja California margin since late Miocene time. We interpret that the antiform structure dividing the active and inactive basins developed as an accommodation zone linked to the westward re-localization of deformation. The coherent shift of strain left a strip of abandoned basins along the length of the eastern rift, which now forms an incipient drifting margin, while rifting is still ongoing along the western side of the rift.

Low-angle normal faults in the northern Gulf of California extensional province: summary and implications for fault mechanics and strain partitioning

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The role and mechanics of low-angle normal faults (LANFs or detachments) are a focus of MARGINS-RCL inquiry. The Gulf of California focus site was chosen in part due to their presence. Significant LANFs related to Gulf opening are known only along the western side of the rift, north of Puertecitos, BC.; from S to N, these are: the Santa Rosa, Las Cuevitas, Cañada David, and west Salton faults. They cut older intrusive and metamorphic rocks but display only brittle tectonites. Slip estimates are generally <20 km, and the Cañada David fault appears to be active. We explore their mechanical significance and role in Gulf strain partitioning.

LANF mechanics are controversial. The northern third of the active rift axis and its western flank trend about 20 degrees more northerly than the southern two-thirds, so LANFs formed where the angle between the rift axis and the relative plate vector is largest. Thus, LANF formation may be favored above some threshold reflected by this angle (e.g., a threshold extension rate, minimum work criterion, etc.) In several places these LANFs cut across older foliations or through relatively isotropic granitoids, so their orientations were not controlled by older fabrics. Much of the west Salton detachment is exposed within a few kilometers of its breakaway, where it intersected an older, low-relief erosion surface, demonstrating that the fault dipped gently to within ~1 km of earth's surface. If models are correct in which LANF dip is controlled by rotated stress-fields, then stress rotation occurred even at very shallow depths. Some such models invoke basal shear traction to rotate the stress field; such boundary conditions might fit the NW Gulf if it opened largely in response to shear between microplate fragments below continental lithosphere. These models predict uniform LANF dip directions, but three of the LANFs dip east whereas one (CaÃ±ada David) dips west, so it seems unlikely that this, or any other regionally consistent boundary condition, controlled LANF formation and dip direction. Other models invoke lateral gradients in basal vertical normal stress to rotate the stress field. These may operate on spatial scales compatible with observed along-strike dip reversals.

The nature, degree, and evolution of strain partitioning among dip- and strike-slip faults of the Gulf extensional province (GEP) are uncertain. Gulf transforms trend ~NW and have probably been well integrated since at least ~3-4 Ma; the southern San Andreas fault is probably ~6 Ma old. LANFs are the largest dip-slip faults but piercing points and net slip vectors are not well known for any of the four. The prevailing model of GEP evolution has ~ENE extension on NNW-striking normal faults from ~12 until ~6 Ma, when the plate-boundary localized in the GEP, NW-striking dextral faults became dominant, and ESE extension began. This is generally consistent with extension directions from published fault-slip inversions. In contrast, map-view homogeneous simple shear parallel to transforms predicts initially E-W extension and N-S shortening, rotating progressively toward the ESE and NNE, respectively. This is generally consistent with geodetically determined strain in the Salton trough. (However, the ~N-S shortening apparently dies out southward, so ~N-S shortening may be related to the Peninsular Ranges entering the big bend of the San Andreas instead, and may operate over a related dynamic length scale.) The post-6(?) Ma Las Cuevitas detachment has sparse striae trending E to SE, consistent with a wrench-strain model. However, dip- and strike-slip faults with parallel strikes are fairly common worldwide (e.g., flower structures), so NE- to ENE extension on dip-slip faults post-6 Ma may not exclude a wrench model. The Cañada David detachment displays W to WSW trending striae, consistent with slip partitioning between dextral and normal faults. West Salton detachment striae scatter mainly from WNW to ESE with most concentrated between NE and ESE trends. The best interpretation of this array is unclear at present--ongoing paleomag and low-T cooling studies may elucidate this.

Volcanism along the eastern margin of the Salton Trough: Constraints on the kinematics of initiation of the southern San Andreas transform fault system

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In coastal and near offshore southern California, the relationship of volcanism to Basin and Range extension and the evolving Pacific-North America transform margin remains enigmatic. Early and Middle Miocene basalts with geochemical affinities to MORB and primitive arc basalts are typically the mafic end members of compositionally expanded calc-alkaline volcanic suites, whereas Middle Miocene and younger basalts are alkalic and associated silicic rocks are rare. Inland, the Mojave Desert region was also characterized by Early Miocene calk-alkaline volcanism superseded by Late Miocene and younger alkali basalts. While the transition to alkali basalts is reminiscent of the volcanic transition associated with extension elsewhere in the western United States, small volume alkali basalts in coastal and inland southern California may be more closely related to strike slip faulting in the upper crust, and thus provide insights into mantle structure during transform tectonism.

Late Miocene to Pliocene alkali basalts in the eastern Transverse Ranges of southern California erupted along the eastern Salton trough margin, near to the southern San Andreas fault and adjacent sinistral faults. Previous paleomagnetic studies and new 40Ar/39Ar geochronology suggest that these volcanic centers were temporally and spatially associated with early Gulf rifting and transrotation on a series of sinistral faults connecting the evolving San Andreas transform to the eastern California shear zone. Although these basalts erupted on Proterozoic continental crust, compositional variations suggest mantle sources across the western edge of Proterozoic lithospheric mantle, where it abuts oceanic lithosphere accreted in early Cenozoic time. We hypothesize that early Gulf opening and initiation of slip on the southern San Andreas fault between about 5.3 and 4.5 Ma was associated with rapid block rotation along sinistral transform faults along this pre-existing mantle lithospheric boundary. This hypothesis can constrain the magnitude and timing of kinematic linkage between the Gulf of California, the evolving San Andreas fault, and the eastern California shear zone, and may reconcile widely divergent estimates of net slip on the southern San Andreas fault.

Numerical models of extending and rifting thickened continental crust

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Initial numerical simulations demonstrating different modes of extension, including core complex style extension, wide rifts, and narrow rifts, on a regional scale of thickened areas of continental lithosphere are presented. In these two-dimensional models, a layer of thickened continental crust and adjacent crust of normal thickness is underlain by a mantle layer, and the system is extended by pulling at the edges. The temperature-dependent viscous rheology is based on power-law creep flow law for diabase. Temperature profiles are calculated using conductive heat transport and radiogenic heat production that decreases exponentially with depth. Temperature profiles are altered by varying the bottom mantle heat flow and thermal conductivities within acceptable ranges. The style of extension is dependent on the initial temperature profile, vertical width of the plateau, and horizontal width of the plateau. Transitions from core complex to narrow rift extension and from wide rift to narrow rift extension have been observed. To date, we have not observed a transition from core complex to wide rift style extension.

Gravity Modeling and Crustal Structure of northern eastern Baja California and the western Salton Trough

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The Gulf of California has experienced obliquely divergent plate-boundary processes since the mid-Miocene, with complex and evolving kinematics. We model NOAA Mexico97 gravity data to examine the regional 3D crustal structure. 2D models are locally well constrained by seismic receiver-function and wide-angle reflection data, and gravity data will allow extrapolation to 3D. Using this 3D image, we intend to constrain the amount and style of extension in the Salton Trough and northern Gulf of California.

Significant extension was accommodated on low-angle normal faults in the Salton Trough and northern Baja California, but documented upper crustal extension is generally low: 5-11 km in the western Salton Trough and 7-11 km in northern Baja California. This minor upper crustal extension appears too small to account for thinning of the entire crust. Preliminary crustal cross sections through geologically constrained areas were reconstructed to minimum ranges of pre-extension thickness, yielding the permissible range of whole crust extension. However, the amount of extension required to restore the whole crust to a minimum thickness of 25-30 km still slightly exceeded the maximum upper crustal values documented in geologically constrained areas. Furthermore, this low original crustal thickness seems unlikely because (1) the present maximum Peninsular Range crustal thickness west of the rift is ~40 km, and (2) the gulf was occupied by a magmatic arc prior to late Cenozoic extension. Therefore, the complex kinematic history of the region requires a 3D assessment, which we undertake in this project in order to constrain the amount of crustal thinning, and confirm if a discrepancy between upper- and whole-crust extension exists.

In general, styles of brittle upper crustal extension are well known but the nature of lower crustal ductile deformation is controversial. Deficit of upper crustal extension relative to that of the whole crust combined with conservation of mass requires that the lower crust is able to flow laterally. If our crustal models require such flow, we hope to constrain its scale length(s), extent, distribution and importance, providing key input to models of how the “whole” crust responds to transtension.

Constraining Upper Mantle Flow Using Seismic Anisotropy & Geodynamic Modeling

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Geologic studies indicate that the tectonic history of the Gulf had two main episodes. Deformation associated with these plate motions may be 'recorded' as structural fabric within the lithosphere and asthenosphere. Such preferred alignment of anisotropic minerals can be detected by analysis of shear wave splitting and in azimuthal variation of P-wave travel time delays and polarizations. A proposed array of ocean bottom seismometers extending across the Gulf of Mexico and onshore to the east and west would provide constraints on the pattern of anisotropy and any dependence on back azimuth.

If we (collaborative group including SIO, CICESE, SDSU, and Indiana University) succeed in getting the OBS experiment funded, we aim to develop a geodynamic model that is consistent with the data obtained. The approach we'd employ is a finite element modeling of variable rheology mantle and crust that rifts at a specified rate. Current work on deformation modeling is being done in 2D. In working to match the OBS data we would emphasize 3D modeling with a current implementation of Tekton. Temperature and deformation fields are determined, melting can be included, and the calculated strain along particle paths serves as the starting point for computing the flow-induced texturing of polycrystalline (olivine and enstatite) mineral aggregates. The corresponding elastic structure is obtained directly from the orientation distributions. Wave propagation modeling through each heterogeneous, anisotropic model structure provides surface predictions that can be compared to the observed measurements. The nature of the misfit between model and data guides the development of refined forward models that optimally match all known geophysical and geological data.

Crustal Structure of the Southern Gulf of California, the East Pacific Rise to the Jalisco Block

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We present new seismic images and a velocity model that comprise the most detailed picture to date of the crustal structure of the southeastern Gulf of California. Multi-channel seismic data were recorded in 2002 using the R/V Maurice Ewing and a 480-channel, 6 km-long streamer. Wide-angle data were recorded for this section using 25 ocean bottom seismometers and 7 RefTeks. Initial migrated images of the southeastern Gulf show broad bathymetric highs of oceanic crust at the East Pacific Rise, the Maria Magdalena Rise, and a more lumpy high at the northern end of the Maria Magdalena Knoll. Very little sediment overlies the oceanic crust, only a few small basins are present. Pre-stack time migrated images of the continental shelf show large sedimentary basins that have filled in lows created by blocks of faulted continental crust. Different periods of faulting, and hence rifting, are distinguished by sedimentary structures and faulted layers of the basins. The seismic stratigraphy can be correlated with sub-aerial stratigraphy on the Tres Marias islands in the southern Gulf. Preliminary wide-angle modeling predicts an oceanic crust with a thickness of ~6 km and a continental crust with a thickness of ~30 km. A ~200 km transition zone, composed of half transitional and half extended continental crust, lies between the typical oceanic and continental crusts.

Why It Is Hard to Make a Core Complex

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A key feature of terrestrial and oceanic core complexes appears to be a normal fault that has offset by an amount that is large compared to the thickness of the brittle layer cut by the fault. The abandoned portion of such large-offset normal faults naturally rotate to a flat-lying position as the footwall of the fault is exhumed. Analytic and numerical models indicate that several conditions need to be met before a large-offset normal faults can form. Requirements include: (1) the fault has to be several tens of percent weaker than the unfaulted brittle layer, (2) if the fault weakens with strain it must do so at a moderate rate, (3) viscous flow resistance at the base of the brittle layer must be small compared to fault weakening, (4) lateral variations in the thermally controlled brittle layer thickness must be small, (5) faults cannot migrate far from the thinnest part of the brittle layer and, (6) buoyancy forces associated with crustal thinning must be small compared to fault weakening. Condition 1 and 3 are most easily met if the brittle layer is thin, for condition 3 that is comparable to the maximum depth efficient of hydrothermal cooling. Thus, regions of anomalously high heat flow have potential for core complex formation. For terrestrial core complexes condition 6 requires that the lower crust flow to fill in areas of crustal thinning caused by localized extension. For oceanic core complexes condition 5 required that magmatic dikes accommodate about 50 percent of the plate separation at a ridge. Recent compilations of data on the occurrence of core complexes at mid-ocean ridges (Tucholke, pers. Comm. 2005) are consistent with this prediction.

Exotic vs. Fringing Arc Models For the Growth Of Continents: Evidence From Mesozoic Arc-Related Basins of Baja California and Western Mexico

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The western margin of Mexico is ideally suited for testing two opposing models for the growth of continents along convergent margins:
(1) the exotic arc model, where western Mexico grew through accretion of exotic island arcs by the consumption of entire ocean basins at multiple subduction zones with varying polarities, and
(2) the fringing arc model, where extensional processes in the upper plate of an east-dipping subduction zone produced arc-related basins, some rifted off the continental margin and others formed of new oceanic lithosphere that largely lay within reach of North American turbidite fans. In the fringing arc model, later phases of east-dipping subduction juxtaposed these terranes through transtensional, transpressional or compressional tectonics.

These arc terranes are significant for composing about a third of Mexico, a country that was tectonically assembled in relatively recent geologic time (largely Late Paleozoic to Mesozoic). Busby's (2004) model takes the view that all of the Mesozoic elements that added to the growth of the Mexican margin were formed and accreted within the upper plate of the convergent margin onshore and offshore of North America (except for oceanic materials offscraped into accretionary wedges). In this model, also proposed for the Mesozoic of California (Saleeby and Busby-Spera, 1992), extension of transitional to oceanic crust in outboard parts of the convergent margin created arc-related basins that rapidly fill with volcaniclastic material. This thick fill transforms them into nonsubductible items that get accreted during later compressional stages of convergence. This model contrasts with the other end member model, a very widely-cited, widely-accepted model which proposes that many of the Mesozoic elements in California and Mexico are exotic to North America, and were accreted by closure of major (not marginal) ocean basins (Dickinson and Lawton, 2001).

In collaboration with Elena Centeno Garcia (UNAM), George Gehrels (University of Arizona) and Marty Grove (UCLA), I am currently carrying out provenance studies of zircons in sedimentary rocks, as well as the provenance of zircons that were entrained in magmas or pyroclastic flows, using ICP-MS single crystal analysis. This will allow us to establish the relative importance of accretion of exotic vs. semi-autochthonous arc terranes in the construction of western Mexico.

Additionally, preliminary results show that detrital zircon studies can be used to correlate Late Paleozoic to Mesozoic strata across the Gulf of California. These correlations can be used to constrain Tertiary tectonic reconstructions of the Gulf of California.

An overview of the petrology of oceanic basement in the southern Gulf of California

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The Gulf of California is a young ocean basin formed within the southwestern margin of North America by Miocene crustal extension followed by Plio-Pleistocene intercontinental spreading. Lava samples collected in 2004 from the axial rift valleys, rift mountains and transform valleys of Pescadero Basin are similar to previously studied basalts from Alarcon Rise at the mouth of the Gulf. Both sample suites are tholeiites that are compositionally fairly homogeneous, slightly light-REE-depleted and have low overall incompatible trace element contents. They are geochemically similar in many, but not all respects to typical normal-MORB from the EPR south of Tamayo Transform. Older tholeiitic diabases and gabbros in sediment/sill complexes that represent some of the earliest "oceanic crust" in the southern Gulf, sampled by drilling near the foot of the continental slope (DSDP Site 474) and in transform-valley outcrops in Alarcon Basin, have more variable trace element compositions. They resemble young tholeiitic sills sampled by drilling at the axes of Guaymas Basin in the central Gulf, which show a wider range of incompatible trace element ratios, 87Sr/86Sr and 143Nd/144Nd than the Alarcon and Pescadero axial lavas; axial tholeiitic intrusives in drill cores and xenoliths from the subaerial Salton Trough have still higher incompatible trace element contents. We have not yet found in oceanic crust of the southern Gulf any of the highly fractionated silicic lavas that are characteristic of eruptions in the thickly sedimented Salton Trough and northern Gulf. Despite the compositional variation, many investigators (e.g., Saunders et al., DSDP 64, 1982; Herzig & Jacobs, Geol. 22, 1994; Castillo et al., JGR 107, 2002) infer that the main source of axial lavas throughout the Gulf is a geochemically depleted Pacific-type mantle. The differences in the composition of lavas and shallow intrusives are attributable to variable degrees of fractional crystallization, assimilation of crustal materials and possible presence in their mantle source of varying amounts of a "subduction component" inherited from Miocene subduction beneath Baja California. The clearest evidence for a subduction-modified mantle beneath oceanic crust of the southern Gulf is a calc-alkaline andesite dredged from a seamount in Farallon Basin in 2004. This rock has not yet been dated, but the seamount may be an oceanic equivalent of the Plio-Pleistocene post-subduction calc-alkaline cones that are subaerially exposed on continental crust near the Gulf coast of Baja California Sur, and near the middle of the central Gulf at Isla San Esteban.

Seismotectonics and Upper Mantle Deformation at the Southern Basin and Range Province in Sonora, Mexico

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Because the tectonic and morphologic characteristics of northeastern Sonora, this region is considered part of the southern Basin and Range Province. This region is being extended in the East-West direction at approximately 6 mm/yr (Dixon et al., 2000). In the Mexican Basin and Range, North-South striking and west-dipping normal faults form the western edge of the Sierra Madre Occidental (Suter, 2000). These faults have generated important earthquakes in the past. For instance, in 1887 a magnitude 7.4 normal-fault earthquake generated a surface rupture more than 100 km long. In order to study the seismicity pattern along the western margin of the Sierra Madre Occidental, the seismic network RESNES was installed between 2001 and 2002 (Castro et al., 2002). This network consists of 9 short-period digital stations and one broadband station that extend for nearly 190 km south of the border between Arizona and Sonora. The stations of RESNES are distributed along the three fault segments that ruptured during the 1887 event and have recorded several local and regional events. We will present the distribution of the epicenters determined with the data set generated by this seismic network and we will discuss the tectonic implications of the seismicity observed.

Besides the stations of RESNES, there are also two broadband stations from the Nars-Baja array, one located at the northwest (NE80) and another at the southeast (NE81) of the Mexican Basin and Range Province. These stations have recorded several teleseismic earthquakes with clear SKS and SKKS wave arrivals. This data set has permit us studying the seismic anisotropy of the upper mantle and infer the deformation pattern under the region of Sonora. We obtained the splitting parameters of the events recorded using the method of Silver and Chan (1991). We found that the direction of fast polarization of the splitting SKS waves rotate from NE-SW to ENE-WSW, approximately perpendicular to the strike of the normal faults of the region. The direction of polarization at NE81 coincides with the absolute plate motion direction of the North American plate. On the other hand, the observed splitting direction (ENE-WSW) at this station, which is located near the edge of the Sierra Madre Occidental, is different from the present E-W extension of the Southern Basin and Range, suggesting that the upper mantle deformation under NE81 may be the result of a different tectonic process.

Velocity Model for the Gulf of California

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A lithosphere/upper-mantle velocity model is determined for the Gulf of California region from surface wave group velocities and receiver functions, determined from data recoded by the NARS-Baja and RESBAN seismic networks. The main features of the model are a mid-Gulf high-velocity zone, 50% thinning of the crust on the eastern side of the Baja Peninsula, and crust differences on either side of the Gulf. We have also used receiver functions to look at lateral variations in the 400 km seismic discontinuity and with less resolution the 670 km discontinuity.

The surface wave group velocities are determined both from a dozen events in the greater Gulf region, and from correlations of seismic noise. For the earthquake sources, reliable measures are generally determined for periods from 10 to 100 secs. These data provide sampling from the crust to about 200 km into the mantle. For the noise source both the ocean microseism band (5 to 20 sec) and the infrasonic band (30 to 100 sec) are used. The data are correlated for several times periods and for temporal lengths varying from 15 to 99 days. The correlations provide an estimate of the Green's function of the surface wave traveling between the two stations. We generally see that the microseism band correlates in the on-shore direction and shows some complexities that may be related to multi-pathing. The longer period wave correlate in both directions and are generally somewhat simpler in structure.

Our plan is to construct a model for the region that can be used as a framework for detailed studies. We plan to start with the basic seismic parameters such as velocity, density, and attenuation, and use these as the basis to include the derived properties of viscosity and temperature. We plan to make the model portable and easily modifiable.

The Lomonosov Ridge from End to End.

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Understanding the development of the Lomonosov Ridge is in many ways the critical problem to be solved to illuminate the history of the entire Arctic Ocean basin. This ridge was created by the major events that formed the two independent sub-basins of the Arctic Ocean. Each event has modified this piece of continental crust. Distinguishing these effects will lead to a better understanding of the mechanics of rifting, which created the Eurasian basin, and the probably more complicated processes that created the Amerasian Basin.The Eurasian Basin margin of the Lomonosov Ridge is marked by an obvious continent-ocean boundary. The COB is clear in both the magnetic and gravity anomalies. The sinuous form of the ridge mimics the form of the Gakkel Ridge axis, clearly indicating inheritance of the form of the initial break. While the formation of the Eurasian Basin is simply understood in terms of plate tectonics, albeit at very slow rates, the form and structure of the ridge are unusual, owing to the absence of transform faults and variable, low magma production.By comparison the Amerasian Basin is poorly understood. Much of the history of the basin hangs on the few facts that have been gleaned from the Alaskan and Canadian passive margins. The Amerasian edge of the Lomonosov Ridge is structurally complex and, lacking quantitative constraints on these structures, has been of little use for reconstructing the history of the basin.

From MCS data collected by the Alfred Wegner institute and gravity data from a variety of sources, it is clear that the Lomonosov Ridge can be subdivided into a series of linear blocks and basins. Some of these grabens are sediment filled below the Cenozoic pelagic sedimentary cap, others show up clearly in the ridge bathymetry. Towards the Greenland end of the ridge, the horsts and graben trend parallel to the ridge itself. Towards the Siberian margin, the basins trend oblique to the ridge itself, appearing to plunge beneath the sedimentary cover. Marvin Spur, a subdued ridge in the Makarov Basin, can be traced back to a large graben that defines the edge of the Lomonosov Ridge. Marvin Spur can be traced in gravity data beneath the sedimentary fill of the Makarov Basin, raising questions about whether or not it is oceanic and where the edge of continental crust might be found. Mapping the Amerasian edge of the Lomonosov Ridge and distinguishing between Mesozoic (Amerasian Basin) and Cenozoic (Eurasian Basin) extensional structures of different ages are the most important tasks to further understanding this transitional structure in the Arctic Ocean. It has been recognized for some time that the lesser strength of continental lithosphere compared to oceanic lithosphere localizes plate boundaries on the edges of continents. This explains the long, narrow form of the ridge. This may be what Baja California will look like in 60 million years.

An Ocean Bottom Seismograph Experiment to Measure Upper-Mantle Structure Beneath the Gulf of California

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2. *WHOI*

In October, 2005, we will initiate a passive seismic experiment to evaluate the degree to which mantle processes control lithospheric rupture and the initiation of seafloor spreading in the Gulf of California (GoC). We will deploy, for 15 months, 18 wide-band ocean bottom seismographs (OBS) in the GoC. The data from these stations, in conjunction with observations from the MARGINS-funded NARS-Baja experiment, will be used to image mantle structure beneath the Gulf and the surrounding region. We will specifically address two questions that are important for achieving the goals of the Rifting Continental Lithosphere science plan:

• Is the upper-mantle directly underlying GoC extension anomalously hot? This question is critical to understanding the magmatic budget of GoC extension, and the role of this magmatism on strain localization and partitioning. The GoC lies on a broad region of low seismic velocities, implying that temperatures in the upper mantle are elevated. Volcanism, however, is quite modest in the region compared to rifted-margins worldwide. The OBS deployment will allow us to image structure directly beneath the gulf and its margins, better constraining thermal processes in the region.

• To what extent do North-South variations in extensional style correlate with upper-mantle velocity variations? Addressing this question will allow us to evaluate the importance of mantle state in controlling or modulating rift extension. Despite nearly constant total extension all along the rift axis over the past 5 Ma, the style of extension changes dramatically from continental extension in the north, to sea-floor spreading in the south. Mantle thermal and rheological properties probably modulate this process. The OBS deployment will allow us to image along-axis variations in mantle structure, placing better constraints on the impact of this structure on rifting.

At the Ensenada workshop, we will present a report of the OBS deployment cruise and discuss our scientific objectives in detail.

Recovery of a 1.6-Myr Subsidence and Fault Interaction Record From the Stratigraphy in the Hanging-Wall of the Laguna Salada Fault, Northeastern Baja California, Mexico

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The Laguna Salada fault in northeastern Baja California, Mexico, is a ~40 km-long fault bounding the northeastern margin of the Laguna Salada basin, one of the northernmost active rift basins of the Gulf of California Extensional Province. Up-section changes in sedimentary facies deposited in the hanging-wall block of this fault reveal a history of activity pulses, which we relate to the initial breakage of the fault and to fault interaction with neighboring faults to the south. In this paper we obtain changes in sedimentation rates associated with these pulses. We derive rates by showing that most of the low frequency variability in a gamma-ray log from a deep geothermal borehole drilled in the hanging wall of the Laguna Salada fault can be attributed to periodic Milankovitch climatic forcing on sedimentation. We use this result to constrain the ages of 27 horizons (resolution of ~50 kyr) with an estimated uncertainty of ±3 kyr. Our analysis shows that the activity pulses of the Laguna Salada fault lasted on average 500 kyr. Subsidence rates during these pulses vary by a factor of 2 with respect to an average subsidence rate of 1.4 mm/yr. The first pulse, characterized by deposition of boulder conglomerate, started at 1.6 Ma and records initiation of the Laguna Salada fault and rapid uplift of the adjacent crystalline block of the Sierra Cucapá. This event isolated the basin from the delta plain of the Colorado River to the east. The second pulse started at about 1.2 Ma and culminated with the hard linking of the Laguna Salada fault with the Cañada David detachment by the Cañon Rojo fault. This event led to deposition of brackish lacustrine mudstone beds capped by breccia and boulder conglomerate. The last pulse is related to an increase in slip rate by the fault to catch up with the trend set in the early slip history. The onset of the Laguna Salada fault at 1.6 Ma appears to be synchronous with early Pleistocene fault reorganization among the San Jacinto, San Andreas and Elsinore fault systems of southern California, suggesting that fault reorganization may have affected a large area from San Gorgonio pass to the northern Gulf of California at around that time.

Chronology of Late Miocene to Early Pliocene Sedimentation at Split Mt. Gorge, Western Salton Trough: Implications for Development of the Pacific-North America Plate Boundary

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Two contrasting kinematic models have been proposed for Late Cenozoic opening of the Gulf of California: (1) 12- to 6-Ma margin-normal extension and continental sedimentation followed by rapid localization of the Pacific-North America plate boundary in the Gulf at ~ 6.0-6.5 Ma (Stock and Hodges, 1989; Oskin and Stock, 2003); or (2) long-lived accommodation of plate motion northeast of Baja California since ~12.5 Ma in one kinematic phase (Fletcher et al., 2003, 2004). Miocene-Pliocene sedimentary rocks at Split Mt. gorge and surrounding areas in the western Salton Trough, at the north end of the Gulf of California, contain a record of basin subsidence, sedimentation, and transtensional deformation that helps constrain regional models of plate boundary evolution. We measured a detailed section in the lower ~1000 m of basin-fill, dated it with magnetostratigraphy and micropaleontology, and integrated these data with new geologic mapping that permits major revision of the chronology of units in this area.

The base of the oldest alluvial sandstone at Split Mt is estimated from imagnetostratigraphy to be 8.0 +/- 0.3 Ma, much younger than inferred in previous studies. We remove this basal sandstone from the Red Rock Formation, which predates the 22-14 Ma Alverson Volcanics, and re-assign it to the lower Elephant Trees Formation (Me). Me sandstone and conglomerate accumulated in a fault-bounded nonmarine rift basin at Split Mt between ~ 8.0 and 6.3 Ma. A progressive unconformity in lower Me records SE-ward tilting about a NE-trending axis. The general paucity of similar-age deposits in the western Salton Trough suggests, but does not require, that faulting was only locally active in late Miocene time, and spanned at most 2 m.y. The Fish Creek Gypsum (FCG) and a few meters of underlying marine clastic rocks record earliest marine incursion at Split Mt. The age of the FCG is bracketed by magnetostratigraphy between 6.27 and 6.14 Ma, consistent with previous assignment to nannofossil zone NN10-15 (Dean, 1988, 1996). The age of oldest marine strata here (6.1-6.3 Ma) is nearly identical to ages documented at Isla Tiburon (Oskin and Stock, 2003), Sierra San Felipe (Boehm, 1984), and San Gorgonio Pass (McDougall et al., 1999). The synchronous change to marine conditions over this very large area likely records an abrupt increase in the rate of regional transtensional strain, as proposed by Oskin and Stock (2003). The base of Colorado River sand ~21 m above the base of the Wind Caves Mbr of Latrania Fm is dated at 5.36 ± 0.06 Ma, very close to the Mio-Pliocene boundary. Sediment accumulation rates (not decompacted) increased from ~0.2-0.4 mm/yr in upper Miocene strata to ~0.5-1.0 mm/yr in lower Pliocene deposits. This change coincides with the first appearance of Colorado River-derived sand.

Pliocene extension and basin formation in the western Salton Trough was accommodated mainly by slip on the west Salton detachment fault (WSDF), and the marine Imperial Group contains the oldest regionally extensive strata that accumulated in the supradetachment basin. We infer that the onset of strong regional transtensional strain, which seems required for marine incursion over this large area, also caused initiation or integration of the WSDF at about 6.5-6.3 Ma. The late Miocene Elephant Trees Formation corresponds to the end of the 12- to 6-Ma phase of relatively slow extension documented around the margins of the Gulf of California.

Our new results thus support the rapid-localization model for opening of the Gulf, but do not preclude significant PAC-NAM strain NE of the Gulf in mainland Mexico.

Distribution of bedrock outcrops and lithologies on the floor of the southern Gulf of California

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Geologic sampling of the subsided continental crust, syn-rift volcanics, and accreted oceanic crust beneath the Gulf of California has been hampered by ignorance of where bedrock crops out on the generally muddy seafloor. The distribution of outcrops at >500m water-depths in the southern Gulf was defined by acoustic reflectivity ("back-scatter") data acquired during an extensive multibeam sonar survey in 2004; analysis of rocks collected by subsequently dredging 44 sonar-imaged targets has allowed a start to be made on mapping lithologic patterns.

Fault scarps of the conjugate rifted margins at the mouth of the Gulf expose Cretaceous granitic rocks of the once-continuous Peninsular/Jalisco batholith. These rocks were also sampled from isolated "orphan knoll" outliers seaward of the margins. Within the Gulf, 1km-high boundary-fault scarps on the Nayarit margin and 1-2km-high scarps along transtensional transform valleys near the axis expose subaerially erupted andesitic/dacitic lavas and volcaniclastics, and Miocene granodiorite; they are interpreted as the ruptured remains and roots of the Comondu arc. These scarps, and localized volcanic relief on deeply submerged marginal plateaus, also have outcrops of Late Miocene-Pliocene subaqueously erupted syn-rift trachybasalt and rhyolite.

Young oceanic tholeiites are widely exposed on the risecrest and abyssal-hill scarps of the <2.5Ma Alarcon Rise, and more locally on Maria Magdalena Rise (a 6-3Ma predecessor of the East Pacific Rise in the mouth of the Gulf). The axial rift valleys at most other spreading centers in the southern Gulf (e.g., South Pescadero, Farallon, Carmen axes) are depocenters at the ends of turbidity current channels, where rapid accumulation of low-density sediment has prevented basaltic eruptions. Volcanic knolls at these sites appear to be domes raised over shallow intrusions, like those known from the Guaymas Basin axes in the central Gulf. Sediment/sill complexes with coarse-grained tholeiitic intrusions, like those drilled in Guaymas Basin, outcrop along transform valleys that cut the older part of Alarcon Basin and probably other (unsampled) basins. Most seamounts poking through the sediment cover of oceanic crust are made of MORB and OIB lava, but calc-alkaline andesites were sampled from one volcanic massif that may be an oceanic equivalent of the "post-subduction" arc volcanoes known from the onshore Gulf margins.

Seabed sampling to date has literally scratched the surface of just a tiny fraction of the widespread and informative submarine outcrops in the Gulf of California. Opportunities remain for many productive man-years of future fieldwork at this MARGINS focus site.

Geomorphology of the Southern Gulf of California Seafloor

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We present a series of detailed bathymetric maps of the southern Gulf of California derived from a Spring 2004 multibeam sonar survey and archival data. The sonar imagery of this part of the Pacificâ•„North America plate boundary zone illuminates the principal features of this MARGINS â•˘Rupturing Continental Lithosphereâ•˙ focus site: (i) active and inactive oceanic risecrests within young oceanic basins that are rich in evidence for off-axis magmatic eruption and intrusion; (ii) transforms with pull-apart basins and transpressive ridges along shearing continental margins and within oceanic crust; (iii) orphaned blocks of continental crust detached from sheared and rifted continental margins; and (iv) young, still-extending continental margins dissected by submarine canyons that in many cases are deeply drowned river valleys. Many of the canyons are conduits for turbidity currents that feed deep-sea fans on oceanic and subsided continental crust, and channel sediment to spreading axes, thereby modifying the crustal accretion process. The maps should prove useful to researchers investigating the structural and sedimentation patterns that have developed during opening of the Gulf, and for locating sampling and moored-instrument sites. The Spring 2004 survey also collected numerous rock dredge hauls, with lithologic results presented in a companion poster by Lonsdale et al.

Magmatism and Extension in the Sierra Madre Occidental: Genesis and Evolution of a Large Siliceous Igneous Province on the Eve of the Formation of the Gulf of California

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The Sierra Madre Occidental (SMO) is the result of Cretaceous-Cenozoic magmatic and tectonic episodes associated with the subduction of the Farallón plate beneath North America and to the opening of the Gulf of California. The stratigraphy of the SMO consists of five main igneous complexes: (1) Late Cretaceous to Paleocene plutonic and volcanic rocks and (2) Eocene andesites and lesser rhyolites, traditionally grouped into the so-called "Lower Volcanic Complex" (LVC); (3) silicic ignimbrites mainly emplaced during two pulses of Oligocene (~32-28 Ma) and Early Miocene (~24-20 Ma) ages and grouped into the "Upper Volcanic Supergroup"; 4) transitional basaltic-andesitic flows outpoured after each ignimbritic pulse, which have been correlated with the Southern Cordillera Basaltic-Andesite (SCORBA) of the southwestern U.S.; 5) post-subduction volcanism consisting of alkaline basalts and ignimbrites emplaced in Late Miocene, Pliocene and Pleistocene, and associated to the separation of Baja California from the Mexican mainland.

Tensional tectonics began as early as Oligocene in the whole eastern half of the SMO, forming grabens bounded by high angle normal faults, traditionally referred to as the Mexican Basin and Range. In the Early to Middle Miocene the extension migrated westward. In northern Sonora the deformation was sufficiently intense to exhume lower crustal rocks, whereas in the rest of SMO did not exceed 20%. In the Late Miocene time, extension focused in the westernmost belt of the SMO, adjacent to the Gulf of California, where NNW normal fault systems defining both ENE and WSW tilt domains with transverse accommodation zones. It is worth noting that most of the extension occurred when subduction of the Faralón plate was still active.

Geophysical data indicate that the crust in the un-extended core of the northern SMO reaches ~55 km, whereas it may be ~40 km-thick to the east. The anomalous thickness in the core of the SMO suggests that the lower crust was largely intruded by mafic magmas. In the westernmost SMO adjacent to the Gulf of California the crustal is ~25 km-thick, implying over 100% of extension. The upper mantle beneath the SMO is characterized by a low velocity anomaly, typical of the asthenosphere, which extends from the Basin and Range province of western U.S.

The review of the magmatic and tectonic history presented in this work suggests that the SMO is the result of the Cretaceous-Cenozoic evolution of the western North America subduction system. Particularly the SMO as a silicic large igneous province is linked to the final stages of subduction of the Farallón plate and can be seen as the precursor of the opening of the Gulf of California. The mechanism responsible for the generation of the ignimbrite pulses seems to be related to the removal of the Farallon plate from the base of the North America plate after the end of the Laramide orogeny. This process involves the rapid increase of the subduction angle and, possibly, the detachment of the deeper part of the subducted slab as a consequence of the arrival of younger and buoyant oceanic lithosphere at the paleotrench and, eventually, the direct interaction between the Pacific and North America plates.

Relative Magnitudes of Seafloor Spreading and Continental Rifting Across the Gulf of California: An Example of Orogen–Scale Strain Compatibility

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Palinspastic reconstructions of serial crustal profiles drawn parallel to transform faults yield consistent magnitudes (450-500 km) of total tectonic transport across the Gulf of California despite marked variations in magnitudes of seafloor spreading. Nine serial profiles drawn parallel to transform faults show that magmatically robust spreading ridges with well developed magnetic anomalies like the East Pacific Rise, Alarcon and Guaymas have accommodated 210-340 km of separation. In contrast, magmatically starved spreading centers that form deep rhombochasmic basins like the Pescadero, Carmen and Farallon have accommodated only 100-130 km of separation. Nonetheless, differences in the magnitude of seafloor spreading are systematically compensated by differences in the magnitude of continental extension, which was calculated by reconstructing thinned continental crust to its pre-rifting thickness. Continental crustal thickness was calculated from topographic profiles assuming local airy isostatic compensation, and model parameters like crust-mantle density contrast and thickness of a reference crust were calculated by fitting independent gravity and crustal thickness data throughout the Gulf extensional province. The remarkable similarity and large magnitude of total tectonic separation 450-500 km across the Gulf, indicates that since 12.5 Ma, it opened in one kinematic phase with transport subparallel to modern transforms.

Lithosphere Delamination and Small-Scale Convection Beneath Southern California Imaged with High Resolution Rayleigh Wave Tomography

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High-resolution imaging of the upper mantle beneath central and southern California reveals many features associated with delaminated lithosphere, lithospheric drips, and associated small-scale convection in the underlying asthenosphere. Using amplitude and phase of Rayleigh waves from teleseismic events recorded at stations of the USArray/Trinet network and finite-frequency sensitivity kernels, we resolve finer features in the shear wave structure than has been possible previously. The continous coverage provided by surface waves yields better resolution of the shape of known anomalies reported by others, as well as the detection of previously unknown features of apparent convective origin.

The images reveal very low velocities requiring the presence of melt beneath the volcanic fields of the southern Sierra Nevada and Walker Lane, centered at a depth of 50-70 km. The lithosphere beneath this region has been removed, with a corresponding high-seismic-velocity lithospheric drip existing now beneath the adjacent southern Great Valley, which we image at depths of 70 to 120 km. This Great Valley drip may still be connected to foundering lithosphere at depths of 110 to 160 km beneath the southern Sierra Nevada. We also image the dripping lithosphere beneath the Transverse Ranges at depths of roughly 50 to 130 km and anomalously low velocities near the Salton trough from near the surface to 100 km or more. Previously unknown features include: a high velocity anomaly dipping to the north, centered beneath the Channel Islands at depths of 60 to 120 km; a high velocity anomaly at depths greater than 120 km beneath the Peninsular Range at the California-Mexico border; and a low velocity anomaly beneath the eastern edge of the Mojave block, trending north into the Basin and Range Province at depths greater than 120 km. There is dynamic convection in the asthenosphere on a scale as fine as can be resolved by the surface wave data - scales of 100 km or less. We speculate that extension in the California borderlands or Gulf of California triggered lithosphere delamination beneath the Peninsular Range.

Structure of the crust and upper-mantle beneath the Gulf of California from a broadband seafloor seismic array

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In this experiment, which is part of the NSF Margins initiative on Rifting Continental Lithosphere (RCL), the investigators will deploy 15 wide-band ocean bottom seismographs (OBS) in the Gulf of California (GoC) for a period of 12-15 months. These seismographs will record naturally occurring seismicity (over 200 moderate and large earthquakes) from around the globe. Using these seismic recordings, the investigators will construct images of the mantle beneath the Gulf and the surrounding region, providing a means to evaluate the degree to which mantle processes control lithospheric rupture and the initiation of seafloor spreading in the GoC. The experiment is focused on two questions that are particularly important for achieving the goals of the RCL initiative: (1) Is the upper-mantle directly underlying GoC extension anomalously hot? (2) To what extent do North-South variations in extensional style correlate with upper-mantle velocity variations? The OBS deployment also provides the means to better characterize seismically active faults within the GoC, improving the assessment of the natural hazards environment of the region. The GoC OBS array builds on two ongoing Margins-funded experiments: the NARS-Baja onshore broadband seismic array (Clayton and others, co-PIs), and an active-source crustal survey (Lizarralde and others, co-PIs). The ocean-bottom seismic data collected in this experiment will be available to any interested investigator 2 years following instrument recovery through the IRIS Data Management Center.

Structural and Magmatic Evolution of the Sonoran Rifted Margin

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New geologic mapping and 40Ar/39Ar data from a transect across southern Sonora (Guaymas/San Carlos to the Sierra Madre Occidental provide constraints on the character and timing of Neogene deformation, magmatism, and sedimentation on this rifted margin. Neogene volcanic activity youngs westward toward the coast, but is episodic in detail. In eastern Sonora (e.g., Santa Rosa, Sahuaripa), voluminous 37-28 Ma rhyolitic volcanism of the SMO was followed by scattered eruptions of basalt and basaltic andesite at 29-25 Ma, ~ 20 Ma and 17-15 Ma. In central Sonora (Suaqui Grand to Rio Yaqui), voluminous 27-25.5 Ma mainly andesitic lavas and breccias represent the Late Oligocene arc, and were followed by basalt eruptions at 20 Ma and a distal 12.5 Ma rhyolite tuff. Coastal Sonoran volcanics (e.g., S. Libre, S. Santa Ursula, S. El Aguaje) include scattered remnants of 24-16 Ma "arc" basalt to andesite lavas and breccias overlain by voluminous 12.5 to 8 Ma mafic to silicic lavas and tuffs. These voluminous post-subduction volcanics are neither bimodal nor alkalic, but instead geochemically resemble the syn-subduction magmas with strong "arc" signatures.

Most of southern Sonora is highly extended and this deformation also youngs toward the coast. In the east, extension is locally as old as latest Cretaceous, but is mainly 25 to 20 Ma. In central areas (including S. Mazatan core complex) two episodes of extension are recorded an earlier ~25-23 Ma, and a younger 20-15 Ma episode. In contrast, deformation within the ~100-km-wide the coastal belt is distinctly younger - mainly 12 to 9 Ma. This late Miocene "Proto-Gulf" deformation of the coastal belt is distinctly transtensional in character, with kinematically coordinated NS-trending normal dip-slip faults, NE-trending sinistral-normal oblique slip fauults, and NW-trending dextral slip faults. Preliminary paleomagnetic data indicates clockwise block rotations of up to 90°.

Gently tilted Neogene coarse basin fill deposits (loosely termed Baucarit Fm) post-date most local extension and are controlled by younger widely-spaced high-angle faults. These late-tectonic basins young westward, from 20-15 Ma in the east to post 12 Ma in the west. NW-trending high-angle faults in the interior part of the transect commonly display evidence for right-slip, though the magnitude and timing of this transcurrent deformation is not yet clear.

These observations suggest a model for the Gulf of California region, where most of extension on the Sonoran margin occurred prior to cessation of subduction at ~12 Ma, and was controlled in space and time by the westward retreat of the arc. Baja was captured by the Pacific Plate as soon as subduction ceased and subsequent transtensional deformation was distributed across the previously extended Basin and Range but mainly concentrated in a 100 km-wide strip adjacent to the Gulf.

How close is the link between plate tectonics and magmatism in western North America?

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Since the widespread acceptance of plate tectonics, magmatism in western North America has been explained by subduction along the west coast of North America and destruction of the subduction system by development of the San Andreas transform fault system. However, re-analysis of space-time patterns of magmatism in western North America calls many of these inferred patterns of magmatism into question. Animation of space-time patterns found in the developing NAVDAT dataset (which currently hosts over 30,000 Cenozoic age and/or geochemical analyses; navdat.geongrid.org), demonstrates that: (1) subduction-type (e.g., intermediate) volcanism is poorly linked to the subduction system; (2) there is little evidence that slab windows controlled magmatism; (3) magmatism was clearly migratory in ways that cannot be explained by plate-tectonic processes; and (4) magmatism was migratory at length scales ranging from 1000s of km to 10s of km.

Several space-time patterns are evident in the NAVDAT animations, including: (1) a sweep from Montana into Nevada from 50 to about 20 Ma; (2) a clockwise sweep around the Colorado Plateau from New Mexico to southern Nevada, from about 30 to 15 Ma; (3) a burst of magmatism at about 16 Ma in northern Nevada, followed by outward sweeps to Yellowstone, central Oregon, and the Sierra Nevada; (4) a burst of magmatism in the Sierra Nevada at 3.5 Ma; and (5) several local migrations, including from Phoenix north onto the Colorado Plateau and from the San Francisco Bay area north to the Geysers geothermal field. Several of these patterns (e.g., the sweep around the Colorado Plateau, activity in southern New Mexico and Arizona, and activity around the Gulf of California) must continue into Mexico, but data there are currently too sparse to follow. The Coney-Reynolds pattern of magmatism sweeping first inland and then toward the coast may be present in Mexico, but again data density is too sparse to define it.

Some of these patterns have been tied to specific events (e.g., impingement of the Yellowstone plume and Pliocene delamination), but the others are difficult to relate to plate-tectonic events. They may be caused by local tectonic events, minor convective rolls in the asthenosphere, lithospheric delamination, or delamination of a flat Laramide slab. Whatever their origin, database animation provides a powerful tool for examining these space-time patterns.

Acquisition, processing and interpretation of seismic, gravity, magnetic and bathymetric data for the Gulf of California and other areas of western Mexico. Tectonics of continental margins.

Antonio Gonzalez-Fernandez

CICESE

From September to November 2002, a marine geophysics experiment was carried out, using 2 ships and onshore personnel, recording deep MCS (Multichannel Seismics), wide angle, gravity, magnetic and bathymetric data. The main objective of this experiment is to better understand the continental breakup processes and the rifting of the Baja California Peninsula from Mexico mainland.

An array of airguns with a total air volume of 8000 cu.in. was the seismic source and a 6000 km-long, 480-channel streamer was used to record the deep MCS data. This equipment was towed by the R/V Maurice Ewing. The airgun energy was also recorded as wide-angle seismics by OBS's offshore and by portable seismic stations onshore.

A series of seismic sections have been obtained for 5 transects, one crossing the southern part of Baja California Peninsula, from the Magdalena Fan to the Farallon basin in the Gulf of California. 4 more seismic lines suround the Peninsula, showing a number of noticeable structures. The fossil trench is covered by recent sediments, that are part of the Magdalena Fan. The Tosco-Abreojos fault zone is clearly imaged, showing some extensional component. Near the coast, a recent half-graben structure can be observed. Under this structure, a reflective zone can be interpreted. Normal faults in the sediments of the basin are synthetic and antithetic with it. The master fault probably is the continuation to the S of the Santa Margarita-San Lazaro fault, reported previously as a detachment in Santa Margarita and Magdalena islands.

In the Gulf of California margin there is a conspicuous slope at the mouth of the La Paz Bay, that corresponds to the same strike-slip fault observed in Partida and Espiritu Santo islands. The rest of the line is characterized by numerous strike-slip and normal faults, producing strong bathymetric variations.

Wide-angle interpretations show an image of the general crustal structure across the southern part of the Baja California Peninsula, reaching the oceanic slab under the Peninsula and providing crustal thicknesses.

Neogene Tectonic Evoltuion of the Magdalena Shelf

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The Magdalena fan is an apparently beheaded submarine depocenter that has figured prominently in Middle to late Miocene reconstructions of Pacific-North American plate interactions. The deposit accumulated rapidly at the base of the continental slope atop newly formed oceanic crust of the Farallon plate from 14.5-13 Ma. Subduction of this crust ceased as the Pacific-Farallon spreading center encountered the trench. The widely accepted two-phase kinematic model for the formation of the Gulf of California holds that ~300 km of dextral shear between the Pacific and North America plates occurred along faults west of Baja California prior to the onset of dextral-transtensional shearing in the Gulf at ~6 Ma. However, detrital zircon U-Pb ages strongly indicate a western Baja source region for the fan and imply that cumulative dextral slip along faults west of Baja was < 150 km. Previous models held that the fan was fed by a major extraregional river system that traversed the mouth of the protogulf. We alternatively regard fan formation as reflecting enhanced activity of the same depositional processes that infilled the formerly active trench along the entire strike length of the Magdalena microplate. Specifically, we envision that the ridge-trench collision and underplating of buoyant nascent oceanic crust triggered erosional denudation of the Magdalena shelf along western Baja and caused sediment to spill over the continental shelf. Previously recognized geologic relationships and new low-temperature thermochronology (K-feldspar MDD, and apatite and zircon fission track and (U-Th)-He analysis) indicate that the Early Middle Miocene topography in the region was controlled by a NNE-trending buttress unconformity established east of the Magdalena shelf that followed the western margin of the present Los Cabos block and extended northwards into the present Gulf. Detrital zircon age distributions within the fan are easily accounted for by reworking of Magdalena shelf Tertiary strata (Eocene Tepetate Fm., Miocene Comundu Group) with (or without) additional input of basement-derived detritus from exposed basement further east. The fan's source shut off when normal faults west of Baja California began to accommodate transtensional shearing and form rift basins that captured detritus that previously reached the trench.

Tertiary sedimentary basin offshore central Israel and its tectonic significance for the early stages of Arabia-Africa breakup

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We focus on a thick sedimentary basin formed offshore central Israel at a time which the Suez Rift was active, but prior to the formation of the Dead Sea Transform. Initially the rims of that basin were uplifted and eroded while its center accumulated sediments, but then, approximately along with the jumping of the plate motion inland to the Dead Sea Transform, the basin started decaying and the entire region including its truncated rims, tilted westward and completely buried by younger sediments. Our goal is to establish the existence of that basin in time and space; model its subsidence history; and explain its formation within a general tectonic framework In light of the common knowledge that the northern expression of continental breakup between Africa and Arabia had started in the Suez Rift and then jumped eastward to the Dead Sea Transform, our research may fill an important gap in the knowledge about the early stage of breakup and shed new light on several opened questions. Is the formation of a Tertiary basin at the southeast corner of the Mediterranean Sea related to the opening at the Suez Rift; is its abandoning related to jumping of the plate motion eastward; where is the continuation of the Suez Rift towards the Mediterranean lithosphere; what was the cause for the renewed subsidence of the Levant continental margins in the Tertiary; and how did the continental margin subside in the Tertiary without significant E-W extension or oceanic rifting in the Mediterranean?

The Walker Lane and Gulf of California: Related Expressions of Pacific-North American Plate Boundary Development

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The Walker Lane (WL) and Gulf of California (GC) have undergone similar and, according to us, related evolution but are currently in different stages of development of the Pacific-North American plate boundary. Nevertheless, the GC illustrates the future of the WL. In both areas, a major episode of extension began ~12-13 Ma (proto-Gulf extension, GC) in what had been a continental volcanic arc. ENE proto-Gulf extension, which represented the orthogonal component of oblique Pacific-North American plate motion along the transform boundary west of Baja California (Stock and Hodges, 1989, Tectonics), was mostly sandwiched between the Cretaceous Peninsular Ranges batholith and the mostly 32-20 Ma Sierra Madre Occidental caldera province (SMO). In the WL, extension may have accommodated minor clockwise rotation of the Sierra Nevada block relative to the central Great Basin as western North America expanded toward the transform boundary. This interpretation implies that the amount of extension pre-dating strike-slip faulting should decrease northward along the WL. Extension in the WL was mostly sandwiched between the Sierra Nevada batholith and ~35-10 Ma calderas of the ignimbrite flare-up in central Nevada.

In both areas, extension avoided the mid-Cenozoic caldera belt. Calderas are underlain by large, crustal magma chambers, so a nearly continuous batholith probably underlies both belts. The core SMO remains unextended, but the central Nevada caldera belt has undergone ±10% WNW extension, probably related to WL dextral shear. Also in both areas, extension, and subsequently strike-slip faulting, cut through the Cretaceous batholiths because arc magmatism had heated and weakened the crust.

Strike-slip faulting and the plate boundary either totally (GC) or partly (WL) stepped into the area that had undergone arc magmatism followed by extension. Development of the ridge-transform system in the GC ~6 Ma placed the WL in a favorable position to accommodate part of the transform motion. We predict that WL strike-slip faulting will propagate northwestward, following the migrating Mendocino triple junction and arc, and that the WL — GC will eventually accommodate all plate boundary motion. Whether the WL part will be a single, major strike-slip system (e.g., San Andreas) or a “leaky transform” (e.g., GC) is unknown.

Seismic structure of the Southern Gulf of California from Los Cabos Block to the East Pacific Rise.

P. Paramo, W.S. Holbrook, H.E. Brown, D. Lizarralde,J. Fletcher, P. Umhoefer, G. Kent, A. Harding, A. Gonzalez, and G. Axen

Multichannel reflection and coincident wide-angle seismic data collected during the 2002 PESCADOR experiment provides the most detailed seismic structure to date of the southern Gulf of California. Multichannel Seismic (MCS) data were recorded with a 6-km-long streamer, 480-channel, aboard the R/V Maurice Ewing, and wide-angle data was recorded by 19 instruments located every ~12 km along the transect. The MCS and wide-angle data revealed the seismic structure across the continent-ocean transition of the rifted margin. The boundary between typical continental and oceanic crust is formed by a ~75 km wide zone of extended continental crust dominated by block-faulted basement with seismic velocities and crustal thicknesses characteristic of non-volcanic margins. Little variation in crustal thicknesses and seismic velocities is observed in the entire oceanic crust, suggesting a constant rate of magmatic productivity since ocean floor spreading began. Oceanic crustal thickness and mean crustal velocities suggest normal mantle temperature (1300 C) and passive mantle upwelling at the early stages of seafloor spreading. The crustal thickness, width of extended continental crust and predicted temperature conditions all indicate a narrow rift mode of extension. However, based on upper and lower crust stretching factors, an excess of lower crust thickness of ~5km is found in the transitional crust. The predominate brittle or semi-brittle deformation of narrow rift mode might have driven small-scale flow of the deepest crust to accommodate block fault offsets to produce the excess of lower crust. This interpretation suggests that the structural evolution of rifting could have been controlled by a major fault.

The Newfoundland-Iberia rift system: Seismic evidence from the Flemish Cap margin.

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The Newfoundland-Iberia conjugate margin pair is considered a type example of an amagmatic rift system that ruptured to form seafloor spreading. Recently acquired seismic reflection and refraction data acquired off Flemish Cap provide new information on the structure of this important rift system. The data presented here are from a transect that is conjugate to profiles across the Galicia Bank margin where the "S" reflection has been observed. This reflection is proposed to represent a major detachment surface that forms at the crust-mantle boundary during the final stages of continental rupture. There is no evidence beneath Flemish Cap for a final phase of extension that resulted in thin continental crust underlain by a strong "S"-like reflection, which indicates that this mode of extension occurred only on the Galicia Bank margin. Compelling evidence for a broad zone of exhumed mantle or for peridotite ridges is also lacking along the Flemish Cap margin. Instead, anomalously thin, 3-4 km thick oceanic crust is observed. This crust is highly tectonized and broken up by high-angle normal faulting. The thin crust and rift structures that resemble the abandoned spreading center in the Labrador sea suggest that initial seafloor spreading was affected by processes observed in present-day ultra-slow spreading environments. Landward, Flemish Cap is underlain by a highly reflective lower crust. It is unlikely that this fabric originates from lower crustal flow. Instead, the reflectivity most likely originates from older Paleozoic orogenic structures that are unrelated to extension and breakup tectonics.

Magnetostratigraphy and Rotation of Pleistocene-Miocene Sedimentary Rocks in the Western Salton Trough, CA.

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The kinematics of block rotation, and the history of basin subsidence and evidence for changes in the nature of sedimentary inputs can be well constrained with paleomagnetic and magnetostratigraphic studies. Ongoing work in the SW Salton Trough, concentrated in the Pleistocene sedimentary rocks in the SE San Felipe Hills (SFH) and western Borrego Badlands (BB), and the Pleistocene-Miocene section in the Fish Creek-Vallecito Basin and Split Mtn Gorge, reveals many interesting relationships. In this abstract, discussion of paleomagnetic results will focus on determinations of vertical axis block rotations. Other important contributions obtained from magnetostratigraphic analyses of these data are presented in abstracts by Dorsey and others, and Janecke and others.

Paleomagnetic results from 31 sites in the Plio-Pleistocene lacustrine Borrego Fm and the overlying alluvial Ocotillo Fm in the southwest (BB and Ocotillo Badlands) and its finer-grained equivalent (Brawley Fm) in the northeast (SFH), sampled in the Oil Well Wash and Beckman Wash sections, have well-defined components of magnetization in most samples. A persistent magnetic overprint, and some mineralogical alteration during thermal demagnetization, hampers analysis of magnetization vectors in some sites. The results indicate that the age of the Ocotillo and Brawley Fms ranges from ~ 0.5-0.6 Ma to 1.0-1.1 Ma, based on the presence of the Brunhes / Matuyama boundary and Jaramillo sub-chron in both sections, and Bishop ash in the BB. The Borrego-Ocotillo contact coincides with the base of the Jaramillo in both sections and in the nearby Ocotillo Badlands section (Brown et al., 1991). Sites with well-defined directions and k > 16 can be used to determine vertical-axis rotations. In Oil Well Wash the tilt-corrected mean is D = 8.5, I = 61.1, k = 51.0, _$_{95}$ = 9.5°, N = 6, indicating a clockwise rotation of 8.8° ± 5.7°. In Beckman Wash the tilt-corrected mean direction is D = 360, I = 38.2, k = 48, _$_{95}$ = 8.1°, N = 8, indicating little or no rotation. Combined, these data lead us to conclude that only minor (9°or less) rotation has occurred in the two areas since 1.0 Ma, despite structural and stratigraphic evidence for significant fault reorganization of both dextral and sinistral faults during this time. The difference between the larger CW rotation observed in the OWW section, and the smaller rotation in the BB section may be due to more pronounced transrotation within the OWW area.

Prior study of the Fish Creek-Vallecito Basin (Opdyke et al., 1977, Johnson et al, 1983) documented larger (35°) clockwise rotations, which have been interpreted to represent block rotation since ca. 1.0 Ma. Examination of the stratigraphic section from which the majority of their data comes reveals that a median age of about 2.5 Ma is more appropriate for these results, and would indicate relatively rapid (14°/m.y.) rates of rotation. This rotation estimate, and the 9°/m.y. estimate derived from the Plio-Pleistocene rocks mentioned above, are both markedly higher than those estimated using modern GPS data and fault-block models (McCaffrey, 2005), suggesting that higher rates of rotation prevailed in the geologic past or that higher rates of rotation are restricted spatially. Current efforts to document the temporal history and spatial scale of block rotation in the Western Salton Trough are ongoing, and will yield interesting comparisons with other regional paleomagnetic datasets.

Strain evolution and the relative role of lithospheric heterogeneities during continental rupture

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The evolution of strain patterns during continental rupture can be quite complex, and may be due to either changes in far-field stresses, and/or lithospheric heterogeneities. The West Antarctic Rift system (WARS) is an example of a rupture system that experienced a distinct switch in deformation style. During the first stage (Late Cretaceous through middle Paleogene Periods) extension was broadly distributed throughout most of the Ross Sea region. Later (Late Paleogene and younger) the style of extension changed and was focused primarily in the Terror Rift, near the boundary with the East Antarctic craton. Although absolute timing is difficult to determine, this switch in strain style may be coeval with volcanism and/or oblique faults in the area. These possible temporal and spatial associations may indicate that a change in the stress field is responsible for the change in strain.

To explore the relative role of far-field stresses and lithospheric heterogeneities on the evolution of the WARS we have developed a 2-d finite element model to discern the processes and conditions responsible for the observed evolution of rifting. Model results indicate that the transition from broadly distributed extension to focused rifting can evolve naturally without requiring external changes in either the regional stress regime or thermal state.

The initial stage of modeled diffuse extension throughout West Antarctica results from a prescribed uniformly weak West Antarctic lithosphere (thinner, hotter) versus a prescribed stronger East Antarctic lithosphere (thicker, colder). However, the strength of the West Antarctic lithosphere increases during thinning, and eventually is no longer the weakest region. At this time, strain moves to a weaker narrow region near the boundary with the East Antarctic Craton. Thinning focuses in this region, and runaway necking leads to rupture. Thus, no change in plate motion directions or rates nor impingement of a plume is required to explain the evolution of strain patterns.

Roles of Strain Softening and Heterogeneity in Determining the Geometry of Rifts and Continental Margins

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Despite the large number of studies of continental rifts and rifted continental margins, many of which have produced high quality data, we still lack a unified understanding of the mechanical and thermal processes that control their extensional geometry. This problem is compounded by the wide range of styles that include both, non-volcanic and volcanic rifting. In addition, the relative importance of active versus passive rifting, that is whether rifting is driven by active mantle upwelling or whether mantle upwelling is a passive response to lithospheric extension remains to be determined

Previous work defined end-member styles of lithospheric extension and their associated geometries, pure shear, simple shear and combinations of these styles. These kinematic models served as templates for the interpretation of observations with the primary focus whether rifting is symmetric, or asymmetric as predicted by the simple shear template.

We use numerical modeling to investigate factors that are potentially important controls on the mode of lithospheric extension during non-volcanic passive rifting. We focus on processes that create shear zones and lead to mode selection, and the effects of noise in the context of 2D plane strain models of lithospheric rifting.

We assume that the lithosphere can be represented by a prototype uniform layered model comprising frictional-plastic and viscous layers and consider the effects of different factors or processes on the style of extension of this model lithosphere designed to answer the following particular questions.
1) What is the effect of strain-softening of the frictional-plastic parts of the system on the geometry during extension and does this feedback into mode selection?
2) Can mode selection be explained by a general governing principle, in this case the minimum rate of dissipation of energy?
3) What is the effect of inherited inhomogeneity, “noise”, in the model crustal properties on the style of extension? Does mode selection still occur in the presence of noise, or does noise lead to incoherent extension that is merely an expression of the noise?

Deeply-Concealed, Mid-Pleistocene Rhyolite Domes in the Salton Sea Geothermal Field, California — Implications for the Tectonic-Magmatic-Hydrothermal History and Subsidence Rate of the U.S. Salton Trough

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Thick intercepts of potassically-altered, aphyric to sparsely porphyritic extrusive rhyolite have been penetrated in a number of deep geothermal production and injection wells in the Salton Sea geothermal field (SSGF). The distribution, texture, and isotopically determined ages of these domes and associated subvolcanic intrusives provide fresh insight into evolution of the sediment-smothered, so-called "spreading centers" of the U.S. Salton Trough. The geometric configuration of the rhyolite intercepts, up to more than 200 m in thickness, suggests that these felsic volcanics were emplaced as flow/dome complexes. They are unmistakably extrusive, as the rhyolite preserves well-defined flow foliation and glass devitrification texture from the base to the top of each intercept. Moreover, some of these thick rhyolites are overlain by several tens of meters of blocky-shard- and sediment-rich phreatomagmatic tuff, much like the deposit discontinuously blanketing Red Island, one of the field's four surficially-exposed felsic domes (and one of only five volcanoes on land in the entire Salton Trough).

The buried SSGF rhyolites, U-Pb [zircon] age-dated by one of us (Schmitt) at ~0.4 Ma), are too rich in K2O and, locally, SiO2 to represent original emplacement compositions—not surprising in view of their obvious alteration to adularia, quartz, sericite, epidote, actinolite, allanite or chevkinite, and traces of base-metal sulfide in various combinations. Assuming that the rhyolites' rare-earth-element compositions have been more or less unaffected by the alteration, these REE signatures look neither like those of the exposed SSGF rhyolites nor the unit previously identified in the Salton Sea Scientific corehole as the 0.74 Ma Bishop Tuff. The buried rhyolites' geochemistry, however, does appear permissively to call for a parental magma with a major crustal-melt component rather than being simply a differentiate of a gabbroic-magma precursor. This finding suggests strongly that local magmatic heat sources for the Salton Sea geothermal system and affiliated systems like Brawley could in part be high-level granitic magma chambers (or cooling granitic stocks) rather than or in addition to the basaltic heat sources heretofore exclusively envisioned for the Trough.

Nonetheless, one of the rhyolite domes occurs at about the same depth (top = 1676 m below ground level) -- though several km south of -- the Bishop tuff horizon in the Salton Sea scientific corehole. Based on the Bishop occurrence, the sedimentation rate for this part of the trough was calculated to be ~2.4 mm/yr. The 0.4 Ma rhyolite at the same depth would correspond to a sedimentation rate of ~4 mm per year; a still-deeper neaby 0.4 Ma rhyolite (1890 m) would correspond to a rate approaching 5 mm/yr. We suspect that the discrepancy is due to position of the Bishop intercept outside, and the younger rhyolite inside, the very rapidly sinking principal SSGF pull-apart.

Local Seismicity Recorded by the Network RESNES at the Southern Basin and Range Province in Sonora, Mexico

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We present results of a local seismicity study made in the southern Basin and Range Province within the region of Sonora, Mexico. In this region, North-South striking normal faults have the potential to generate important events. For instance, on May 3, 1887 a Mw 7.4 earthquake occurred at the western edge of the Sierra Madre Occidental, breaking three fault segments of a system of normal faults that extend to the south between the San Bernardino basin and the Sahuaripa basin for nearly 300 km (Suter, 2000).

With the purpose of monitoring the seismic activity of this fault system a regional seismic network (RESNES) was recently deployed. RESNES consists of 9 digital K2 seismic stations with four recording channels, two horizontal that record ground acceleration and two vertical, one for ground acceleration and one for velocity. In the central part of the network there is also one broadband station with a Guralp CMG-DM recorder connected to a CMG-40T sensor. The stations of RESNES are distributed around the segments Pitaycachi, Teras and Otates which ruptured during the 1887 event. The network extends from Agua Prieta, at the border between Arizona and Sonora, to the south for nearly 190km.

During the time of operation we have recorded and located local events within the network and along other neighboring faults. The distribution of the hypocenters and their relation with the active faults of the regions will be discussed.

Early Pleistocene emergence of new dextral faults SW of the southern San Andreas fault, Salton Trough

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Results from several years of field studies and magnetostratigraphy at 6 study sites in the SW Salton trough suggest a major plate reorganization in early Pleistocene time slightly before, during and after the 1.07 to 0.99 Ma Jaramillo subchron (Brown et al, 1991; Kirby, 2005; Lutz, 2005; Steely, 2005; Janecke et al 2004, 2005). From late Miocene to late Pliocene time the top-to-the-east West Salton detachment fault controlled sedimentation in subbasins of the SW Salton Trough. The 4 km thick syndetachment section is conformable above local unconformities at the base. Starting as early as 1.4 Ma and as late as 0.8 Ma, a new set of cross-cutting dextral and dextral oblique-slip faults offset, folded, and deactivated most of the West Salton detachment. The first sign of the new structural regime is seen in growth of the basement-cored San Felipe anticline before (?) and during deposition of the 1.1 to 0.5 Ma Ocotillo Formation. An angular unconformity across the crest of this >15 km long, E-W trending anticline changes north, south and east into a subregional disconformity. North and south of the anticline the contact between the Borrego and Ocotillo formations is conformable. Magnetostratigraphic dating of this progressive unconformity at a disconformable, conformable, and nearly conformable contact shows that its age is identical (~1.1 Ma) across the entire San Felipe-Borrego subbasin.

Shortly after emergence of the transpressive San Felipe anticline, the dextral-normal Fish Creek Mountains fault uplifted older basin-fill deposits and basement in the Fish Creek and Vallecitos Mountains and provided source material for the Ocotillo and Brawley formations. The Fish Creek Mountains fault is part of the San Felipe fault zone, which currently stretches from the Elsinore fault in the NW to the San Jacinto fault in the SE. Southwestward coarsening and thickening of the Ocotillo and Brawley formations toward boulder-bearing fault-scarp breccias along the Fish Creek Mountains fault zone, NE-directed paleocurrents, and the presence of recycled sandstone clasts from newly uplifted older basin-fill deposits show that this fault uplifted the Fish Creek and Vallecito mountains for the first time in early Pleistocene time (~1.1 Ma). This uplift separated the formerly contiguous Fish Creek-Vallecitos subbasin from the San Felipe-Borrego subbasin, and drove progradation of a 600 m thick sheet of Ocotillo-Brawley gravel and sand 25 km NE into the former perennial lake basin of the Borrego Formation. By ~1.0 Ma the Clark lake and Santa Rosa segments of the Clark strand of the San Jacinto fault zone were shedding pebble to cobble gravel SW into the northern San Felipe-Borrego subbasin. By 0.9 to 0.8 Ma, the NW end of the Coyote Creek strand along Coyote Canyon had developed NW-flowing streams that deposited sandstone and conglomerate within the fault zone. At about 0.9 Ma the Fish Creek-Vallecito subbasin ended a 7 m.y.

period of steady subsidence and began to be exhumed. Uplift SW of the Fish Creek Mtns fault is more likely to explain this fundamental change in the Fish Creek-Vallecito basin than initiation of the SE Elsinore fault (e.g. Johnson et al., 1983) because the NE strand of the Elsinore in the Tierra Blanca Mountains has a significant NE-down slip component.Structural and basin analysis in the San Felipe Hills, Borrego Badlands, and Yaqui Ridge area show that the fully modern San Jacinto fault zone appeared after 0.6 to 0.5 Ma.

On the NE side of the Salton Trough an angular unconformity across the crest of a large NW-trending anticline in the Mecca Hills, parallel to the San Andreas fault, may date from the same time but probably records more missing time because the entire Jaramillo event was omitted (Boley et al 1994). Angular unconformities in the Indio Hills also appear to date from the Jaramillo subchron (Boley et al., 1994). If future work confirms the regional nature and synchroneity of this major unconformity we predict that it reflects a region-wide and abrupt inception of dextral strike-slip faults SW of the southern San Andreas fault. This major change may have been incited by changes and barriers to slip along the Big Bend of the San Andreas fault zone and coincides with the end of slip on most of the West Salton detachment fault.

Microseismicity Studies in Northern Baja California: General Results.

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Since 1997, we have installed local seismological networks in northern Baja California with digital, three-component, Reftek instruments. Each local network had from 15 to 40 stations. Surveys have been carried out for the Mexicali seismic zone and the Ojos Negros region (1997), the San Miguel fault system (1998), the Pacific coast between Tijuana and Ensenada (1999), the Agua Blanca and Vallecito fault systems (2001), the Sierra Juárez fault system (2002), and other smaller areas (2001 and 2003). These detailed microseismicity surveys are complemented with data from regional networks (RESNOM and SCSN). Selected locations presented here have errors (formal errors from HYPO71) less than 1 km. Phase reading errors are estimated at less than or about 0.03 s.

Although 90% of the hypocenters may be considered to belong to one of the main fault systems, most of the activity is located between fault traces, along alignments which do not follow mapped faults, and where tectonic alignments intersect. The results show an orthogonal pattern at various scales. Depth distributions generally have two maxima, one at about 5 km; the other, located at 12-17 km. The Agua Blanca fault is essentially inactive for earthquakes with ML > 1.7.

Most focal mechanisms are strike-slip with a minor normal component; the others are dominantly normal; the resulting pattern indicates a regional extensional regime for all the regions with an average NS and ENE-WSW azimuths for P- and T- axes.

Fracture directions of 15 events, obtained from directivity measurements, show orthogonal directions, one of which approximately coincides with the azimuth of mapped fault traces. These results are quite interesting because they indicate that the Pacific-North American interplate motion is not being entirely accommodated by the NW trending faults, but rather is creating a complex system of conjugate faults.

Structural and depositional style of the syn-rift systems of the West African and Brazilian continental margins: Conditions for continental break-up

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Many passive continental margins are characterized by a regional distribution and thickness of syn-rift and post-rift sediment packages that are not consistent with the minor amounts of brittle deformation observed in either seismic sections across the margin (e.g., Exmouth Plateau, northwest Australia; Marion Plateau, northeast Australia; Grand Banks; Brazilian and West African margins; and West of Shetlands basins) or from field mapping of syn-rift systems (e.g., Brazilian and West African margins). While the geo-logical details and sedimentary facies differ between the various margins, the style of deformation and the regional distribution of accommodation are remarkably similar. The development of significant post-rift accommodation in the same region characterized earlier by minor syn-rift faulting and shallow depositional environments has been ex-plained in terms of depth-dependent extension that is partitioned vertically across a zone of decoupling that results in the development of a relatively non-deforming upper crust (i.e., the upper plate) from a ductile-deforming lower crust and lithospheric mantle (i.e., the lower plate), the boundary between them having a ramp-flat-ramp geometry.

The West African and Brazilian passive continental margins are characterized by the stacking of regional syn-rift sag basins, the amplitude and distribution of which are inconsistent with the minor amounts of brittle deformation interpreted from seismic sections across the margin or mapped from field studies of the exposed rift stratigraphy. Despite being syn-rift deposits (by virtue of their age), the sag basins exhibit none of the diagnostic features expected of extensional systems, such as the existence of normal faults, the rotation of crustal blocks, the existence of prominent rift onset unconformities and the generation of sediment wedges. For West Africa, this observation is appropriate either side of the Atlantic hinge zone, which separates regions of relatively low extension from regions of large extension. Much of the information that defines the geological development of the West African margin comes from exploration to the east of the Atlantic hinge zone and !a small number of deep exploration wells immediately to the west of the hinge zone. The break-up of West Africa and Brazil consists of multiple phases of accommodation space generation that produced multiple phases of stacked sag basins. Ostracod data from the West African margin indicate that the syn-rift sag basins either side of the hinge zone is Neocomian to Aptian in age. Seismic sections across the Camamu-Almada and Sergipe-Alagoas margins of Brazil indicate that the regional generation of space is essentially independent of faulting, as indicated by an absence of stratigraphic growth across normal faults and a regional seaward dip of the entire syn-rift stratigraphic package (i.e., equivalent to West Africa).

60 k.y. Record of Extension Across the Western Boundary of the Northern Walker Lane: Estimate of slip rates from offset shoreline terraces and a catastrophic slide beneath Lake Tahoe

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Deformation across three major fault strands within the Lake Tahoe basin has been mapped using a novel combination of high resolution seismic CHIRP, airborne laser and acoustic bathymetric imagery, deep-water 14C-dated sediment piston-cores, and shallow-water 14C- and optically stimulated luminescence (OSL)-dated vibra-cores. Submerged erosional terraces of late Pleistocene age (19.2 +/- 1.8 ka) show vertical deformation that ranges between 10 to 15 m, with 10 m observed across the central portion of the West Tahoe fault. Debris from the catastrophic McKinney Bay slide (~60 ka) is offset across the Stateline fault by at least 21-25 m. The submerged paleo-shorelines and debris avalanche provide a baseline from which to understand extension during the past 60 ka and to evaluate future seismic hazard of the region. Deformation across these two important tectonic markers, combined with chronological control from 14C and OSL measurements, yield an estimate of extension across the Lake Tahoe basin that is on the order of 0.4 to 0.6 mm/yr (assuming 60° dipping faults), with the potential for a large, seiche wave generating M7 earthquake about every 3,500 years. These new underwater, geomorphic constraints beneath Lake Tahoe, in combination with trenching across the nearby Genoa fault [Ramelli et al., 1999] and basin-wide geodetic measurements [e.g., Thatcher et al., 1999], provide a complementary view to recent work done on the conjugate Wasatch fault system.

Gulf of California Electrical Hot-Spot Hypothesis: Climate and Wildfire Teleconnections

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The prevailing view that radioactive decay is the major thermal source for the interior of the planet may create limitations in geophysical modeling efforts. New theoretical insights (Gregori 2002) provide for an electrical source driven by solar induction processes from the core-mantle-boundary (CMB). Joule heating at density boundaries within the upper mantle and base of the lithosphere from CMB electrical emanations may provide some of the hotspot energy for upper mantle melts and associated magmatism driving seafloor spreading and lithospheric rupture. Two recent lines of observational evidence within the Salton Trough (Fig. 1 – Area 2) support this hypothesis.

I.) Sea Surface Temperature (SST) anomalies over the Gulf of California/Baja (Fig. 2 - Area 2) are teleconnected to the peak El Nino SST anomaly patterns. Also note the spurious SST anomaly over the Cocos Ridge (Fig. 2 – Area 3). This pattern repeats itself over multiple El Nino's. Seismic precursors to El Nino by 6-7 months have also been documented (Walker 1988, 1995, 1999) during multiple recent events. Electrical stimulus of earthquakes is highly suspect, especially below the lithosphere, and provides a geophysical mechanism for explaining the SST anomaly teleconnections. Earthquakes beginning in November 1996 at the beginning of a solar sunspot cycle (Hale Cycle) may have provided the heat inputs for the 1997/98 El Nino. The larger implication is that El Nino may be solar-tectonically modulated (Leybourne 1997, 1997; Leybourne and Adams 2001).

II.) In late October 2003, a powerful Coronal Mass Ejection (CME) directed straight at Earth erupted on the Sun's surface, when wildfires simultaneously broke out along an arc shaped pattern of geomagnetic anomaly trends extending from Mexico to north of Los Angeles. The wildfire ignitions slowed dramatically when the CME period ended. The geomagnetic anomalies are inter-splayed by fault systems connected to the Gulf of California hotspot through the San Andreas Fault complex and to the Hawaii hotspot through the Murray Fracture Zone. These orthogonal fault systems intersect in the San Gabriel Mountains where a huge wildfire out break occurred near strong geomagnetic signatures (Fig. 3). Strong electrical impulses emitted from the CMB during CME may not only joule heat local geologic hotspots, but unconverted superfluous electrical energy and ionic plasmas could be transmitted further along conductive igneous complexes and fault systems through the lithospheric fractions of the earth, arcing to power lines and igniting tree lighter or underbrush. In 1859 during the strongest CME on record, telegraph wires in western United States and Europe caught fire and were destroyed. Potential voltage differences between hotspot locations may create electrical ground shorts at geomagnetic intersection areas, starting fires near power line circuits or from discharges directly to the ionosphere (Leybourne et. al. 2004).

An electrical hot-spot hypothesis based on Gregori's theoretical construct is understood in terms of deep earth electromagnetic induction coupled to solar perturbations. The induction process creates anomalous electric currents from the internal-geodynamo. Ocean basin heating and electrical wildfire propagation may be linked. Atmospheric pressure teleconnections are also suspected (Namias 1989).

Rift structure and magmatism of the Guaymas basin and comparison with basins to the south

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We present a detailed seismic velocity model of the crust from margin to margin across the Guaymas Basin and compare this model to transects across other basins of the Gulf of California. These results are based on data from a crustal-scale, active-source seismic experiment conducted in 2002, where multi-channel and wide-angle seismic data were acquired along three flow-line transects across Guaymas Basin, Alarcon Basin, and between Puerto Vallarta and Cabo San Lucas, and a fourth, two-part, "coast-perpendicular" transect extending from the Pacific margin across the Baja Peninsula through Bahia de La Paz and, on the Mexican mainland, across the margin south of Mazatlan and up into the Sierras. Each of these transects was instrumented with OBSs spaced 10-15 km apart and similarly spaced seismometers on land recording the offshore shots to ~100 km inland.

The Guaymas basin is a narrow rift. Lithospheric necking occurred after ~150 km of extension, and a subsequent ~300 km of extension has been accommodated by the formation of new lithosphere. The spreading center has been robustly magmatic, forming new igneous crust 7 to 10 km thick. In contrast, the Alarcon basin is a wide rift, experiencing ~290 km of extension, including rift relocations, prior to the onset of seafloor spreading (~160 km of extension), which produces crust ~6 km thick. Thus, total extension for these two basins is similar (~450 km), but the mode of extension and manifestation of magmatism are very different. Differences in sedimentation may provide an explanation for the variation in magmatism between these basins, with the thicker sediments in the north providing a thermal blanket that enables more complete melt extraction from the mantle. Magmatism does not provide a sufficient explanation for the difference in rift width, however, since rifting between Cabo San Lucas and Puerto Vallarta, just one segment south of Alarcon, was particularly narrow and amagmatic. This observation also indicates that a continuous, along-axis transition from wide to narrow rifting does not to exist in the Gulf of California. Rather, the mode of extension seems best correlated with geologic provinces on the Baja peninsula.

Temporal evolution of strain across the Superstition Hills fault, CA

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The Mw 6.5, 1987 Superstition Hills, CA earthquake occurred on the Superstition Hills fault in the Salton Trough. Postseismic creep was observed along the fault in the year following the earthquake, as well as GPS and InSAR observations of episodic slip events over the following decade and a half. The depth range, magnitude and temporal evolution of these slip events are interesting in their own right, as the modes by which the shallow crust (upper 1-2 km) accumulates and releases stress are poorly understood. Within the Salton trough, it is not even clear how much of the observed deformation signal is related to long-term tectonic forcings, since anthropogenic groundwater withdrawal may induce stress changes that would result in shallow creep. The high heat flow associated with the Salton trough may result in a higher proportion of smaller earthquakes swarms than are found along most continental strike-slip faults.

We invert the observations of deformation for the best-fit slip distributions in space and time, accounting for the spatial correlation of noise calculated from the data in the far field as well as any correlation of the signal with topography. We also examine the sensitivity of the inversions to horizontally layered and 3-D varying elastic spaces, as well as within an elastic half space.

In addition to our fault slip inversions, we examine interferograms over time intervals spanning several of the small earthquake swarms within the Salton trough in order to determine to first order whether we can resolve the deformation associated with these swarms. Since many of the swarms occur within the regions of the trough that are mostly decorrelated due to agriculture, we will utilize the persistent scatterer method.

Magmatic and structural history of the Sierra Libre and Sierra Santa Ursula and implications for early opening of the Gulf of California

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Geologic mapping, remote sensing, geochemistry, and Ar/Ar geochronology have provided new insights into the early history of the Gulf of California in western to central Sonora. The semi-continuous Sierra Libre (SL) and Sierra Santa Ursula (SSU) mountain ranges contain evidence for at least three distinct periods of magmatism. First, latest Cretaceous to earliest Tertiary plutons have intruded and metamorphosed Cretaceous (?) Tarahumara volcanic rocks and earlier Mesozoic sedimentary rocks. Second, after 40 m.y. andesite arc volcanism resumed from 23 to 19 Ma. Voluminous hornblende to bearing domes and flows were extruded early in this period and were followed by abundant olivine-cpx bearing basaltic andesite flows. After this time, the arc most likely swept westward to Baja California. For the next 6 m.y. the region was magmatically quiescent. Lastly, at 13 Ma, low volume basalt flows portended the later copious silicic volcanism that characterizes the SL and SSU. This unique magmatism was jump started by the 12.34 Ma Tuff of Sierra Libre. This large, vapor phase altered, qtz-san-cpx bearing ignimbrite (locally remobilized as a rheomorphic flow) has only been observed in SL to date. Following this explosive eruption, the character of volcanism significantly changed as scores of effusive, trachydacite and rhyolite lava flows blanketed the landscape until 11.5 Ma. Magmatism finally ceased in the SL and SSU after several mafic lava flows were erupted along the flanks of the ranges from 11 to 10 Ma.

This prolonged volcanic history has proven quite useful for reconstructing the deformational history of this region. The youngest mafic flows are ubiquitously flat-lying and have experienced only very minor extension. The 12.5 to 11.5 Ma silicic flows have been tilted moderately (15 to 30 degrees) in both ranges by normal faults. In SL, this unit also shows a fanning of dips, indicating syn-depositional extension. In addition, several strike-slip faults (with consistent right lateral kinematic indicators) were observed cutting these silicic volcanic rocks in SL. It is unclear at this time if this transform faulting is caused by regional tectonics, or by a complex stress field induced by an accommodation zone located in northern SL. Evidence for earlier Miocene (20 to 12.5 Ma) extension is also present in SL in the form of more steeply dipping volcaniclastic conglomerates (40 to 50 degrees). Curiously, no obvious evidence for extension of this age is recorded in SSU. No basin formed there during this time, and the 7 m.y. unconformity here is remarkably flat. The oldest deformational event in this region may have been the most significant. The earliest Tertiary plutons emplaced at mid-crustal levels, and their greenschist grade country rocks were uplifted and exposed by mid-Miocene time, however the style and exact timing of this event remains poorly constrained.

23 to 19 Ma andesite volcanism corresponds well in space, time, and geochemistry with the expected position of the early Miocene Sonoran arc. 13 to 10 Ma bimodal volcanism

is also expected during times of rifting, as has been predicted for Sonora at this time. However, the amount of strain recorded by faulting is well short of that required by most tectonics models for the period 12 to 6 Ma. As they are possibly located at the same latitude as the northern jump off point of the 12.5 Ma Pacific-North America-Rivera triple point, the SL and SSU seem ideally located to assess the effect that major plate boundary changes have on the interior of plates. Indeed, the magmatic history in these regions seems to correspond well to previous tectonic models, however, these newly revealed structural relationships indicate that our understanding of the development of this rift system is still a work in progress.

Implication of the Baja California (Mexico)/ Pacific coupling on the Western hemisphere plate kinematics

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Is Baja California part of the Pacific plate? Coupling GPS observations with numerical modeling we can answer this important question and evaluate the effect of a non-complete coupling on the kinematics of the Western hemisphere. Until 12 Ma the western coast of Baja California (BC) was the location of the subduction of the Pacific plate (PA) underneath the North American plate (NA). It is a common assumption that the eastward migration of the plate boundary was complete ~3.6Ma and that since that time the Gulf of California has accommodate the full relative motion between North America and Pacific. One of the main consequences of this assumption is that the magnetic anomalies in the Gulf of California allow estimating the average relative motion between NA and PA.
On the other hand, published geodetic measurement (e.g. Sella et al, 2000) indicate that NA is moving respect to PA at an higher rate then estimated by the spreading rate (DeMets et al 1994) and the few published GPS measurements in the Baja California Peninsula (Dixon and DeMets 1999, Dixon et al 2000, Dixon et al. 2001, Beaven et al. 2002, Gonzalez-Garcia et al. 2003) indicate that the velocity of the sites with respect to a rigid Pacific plate have significant residuals. These observations suggest that the Peninsula is not completely coupled with the Pacific plate and the Gulf of California spreading does not fully represent the NA/PA motion. Here we suggest using the extensive network of campaign GPS of CICESE/University of Miami combined with the Southern California Earthquake Center (SCEC) for the Mexico/US border region, to quantify the missing motion and how it is accommodate. In particular, we will use the GPS and numerical models to verify if BC behaves as a rigid block as the absence of intra-peninsular faults seems to indicate (in this case the missing motion must be searched west of BC). The computation of a rigid block motion of BC respect to NA will allow evaluating the effect of this loose coupling on the NA/PA plate kinematics. In particular, in combination with numerical methods, we can answer to questions as: can we correct the geological rate of NA/PA estimated by the spreading in the Gulf of California to fit the observed geodetic motion? How stable has been the spreading of the Gulf of California in the past 3 Myr? How fast is the Gulf of California opening?

Mathematical Modeling of Geodynamic Processes in Continental Margins

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A number of tectonophysical models of marginal structures have been developed in order to study geodynamic processes in continental margins. These models are represented by: distribution of density of the matter, the outer and inner boundaries topography, and variation of rheological properties of the material. These models have been solved either by analytic or numerical methods. Such models have been used to study "continent-ocean transition" structures and "trough-like" structures. A special consideration has been given to the "Gulf of California - Salton Trough Region" structure. As a result, distributions of stress and strain tensor components are obtained and analyzed. The ultimate strain and strain rate criterions are applied to study the processes of rupture and formation of deep faults in these structures.

The work done demonstrated how close the relationship can be between a deep section structure and geodynamic processes taking place in it.

Late Neogene marine incursions and the ancestral Gulf of California

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Microfossil evidence in the Salton Trough, lower Colorado River, southwestern Arizona, and Gulf of California region suggest that there were three marine incursions from the middle Miocene to the Pliocene to Pleistocene. The middle Miocene incursion (~11-14 Ma) extended at least as far north as the Hermasillo/Guaymas area on the Mexican mainland side of the Gulf. Further north microfossil evidence is based on reworked microfossils (planktic foraminifers and calcareous nannoplankton); no in situ microfaunas have been found yet. Thus, the northern limit of this incursion has not been determined. Middle Miocene microfaunas suggest deposition occurred during warm climatic conditions and high sea level.

The late Miocene incursion (~6-7 Ma), extends as far north as San Gorgonio Pass, California, and as far east as Yuma, Arizona. Benthic foraminifers are not particularly diagnostic of age; however most species present first appear in the Miocene or late Miocene to early Pliocene. Planktic foraminifers and calcareous nannoplankton suggest a late Miocene to early Pliocene age (planktic foraminiferal zones N14?-N17, and calcareous nannoplankton zones CN9-CN11). This incursion appears to be the most extensive, and microfossils suggest a wide variety of environments in a warm climatic interva.

During the Pliocene to Pleistocene incursion (post 5.2 Ma), marine waters covered most of the Salton Trough, lower Colorado River area and parts of southwestern Arizona. The section is composed of a marine unit bracketed by non-marine units. The marine section, which is generally referred to as the Imperial Formation in California and the Bouse Formation in Arizona occurs in discontinuous outcrops throughout the area. Fossiliferous coeval strata also occur around the Gulf of California in Mexico; however, the stratigraphic sequence is not as simple as in the US. Microfossils are diagnostic of planktic foraminiferal zone N19 and younger. Paleogeographic reconstructions show the extent of the region covered by marine waters as well as the timing and influx of Colorado River water which rapidly filled the area with fresh water and sediment, reducing the marine influence.

The opening of the Gulf of California therefore appears to be two sequential events: 1) a middle to late Miocene proto-Gulf extension and 2) the Pliocene development of the North American Plate. The middle and late Miocene sediments lie within the extensional province and support the belief that the extension was sufficient to result in a reasonably broad seaway.

Examining changes in earthquake triggering behavior across the ocean-continent transition, Gulf of California.

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Woods Hole Oceanographic Institution

The transition from a transform to a spreading plate boundary in southernmost California, northern Mexico, and the Gulf of California also corresponds to a distinct transition in earthquake clustering behavior that has implications for seismic hazard and fault-zone rheology. In this area, the earth's crust changes from about 25 km thick continental material to 6 km thick oceanic crust, and the heat flow is extremely high throughout. The seismicity shows two distinct features that are characteristic of oceanic regions but here occur within the continental crust. First, the aftershock sequences following large earthquakes are relatively subdued. Secondly, there are often swarms of earthquakes, on both normal and strike-slip faults, that last from a few hours to a few days. Both types of clustering behavior can be quantified as deviations from seismic scaling laws. Moreover these deviations can be utilized as test of rheological models which are based on the interplay between brittle and ductile rheological laws. We are documenting the spatial variations in the anomalies relative to seismic scaling laws to help clarify the spatial variations in rheology and the interactions between the thermo-mechanical state of the lithosphere and brittle behavior. Both topics are primary goals of the Rupturing Continental Lithosphere portion of the MARGINS program.

Unfortunately, the quality of earthquake catalogs in this region, particularly offshore, is relatively poor. Many magnitude 4.5 and larger earthquakes in the Gulf of California routinely go uncataloged. Recently, seismic waveform data has become available for this region from the NARS and RESBAN arrays that is sufficient for developing earthquake catalogs complete down to about magnitude 3. We utilize this waveform data to construct the catalogs necessary for documenting the spatial transition from continental to oceanic earthquake clustering behavior. The anomaly in aftershock productivity that is characterized by Bath's law clearly extends from the Gulf of California onshore into the transform faults of Northern Mexico. Additionally the earthquake swarms in this region show considerable deviations from standard seismic scaling laws indicating the influence of an underlying, aseismic processes such as hydrothermal flow.

A Study of Seismic Anisotropy in Northern Baja California, Mexico Using SKS Waves

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The recent installation of broadband stations from the NARS-Baja, RESBAN and RESNOM networks in 2002, permit us study for the first time the seismic anisotropy of the upper mantle beneath the northern part of the Gulf of California region. This study provides insights into the past and recent style of deformation and tectonics. We selected events with well-recorded SKS and SKKS waves with magnitudes greater than 6.0 recorded by broadband stations located in northern Baja California Peninsula and the Gulf of California. We characterized the seismic anisotropy using the shear-wave splitting phenomenon. The splitting parameters, namely the fast polarization direction and the lag time between fast and slow shear waves, were measured using the method proposed by Silver and Chan (1991). We use a second-order Butterworth band-pass filter between 0.04 and1Hz. All the records were rotated to detect eventual transverse component of the SKS wave. In order to select the SKS window efficiently, we observed the particle motion in the polarization diagram, which allowed us to delimitate precisely the ellipse produced by the splitting of the SKS wave. Because the anisotropy parameters may depend on the chosen SKS window, we apply the cluster analysis developed by Teanby et al. (2004). Since most events arrive with similar back azimuth, no dependence on it is expected, and the misfit surfaces from individual event-station pairs can be stacked, as proposed by Vinnik et al (1992), to produce statistically more robust estimates.

We found evidence of upper mantle seismic anisotropy at nearly all the stations, with the exception of PPXB. The trends of shear wave splitting parameters obtained from individual events are consistent at each station and the results are well constrained, except at NE70 and NE74. We assume that the cause of upper mantle seismic anisotropy is the strain induced lattice preferred orientation of olivine crystal controlled by tectonic induced lithosphere deformation. The anisotropy observed at stations NE80, NE81, Guaymas and Hermosillo, all located in the South Basin and Range Province, appears to be highly dominated by ancient style of extension rather than for the most recent deformation pattern. Seismic anisotropy beneath NE70 seems to be produced by the main transform faults characteristic of the Gulf of California. Surprisingly, the anisotropic pattern of both, NE71 and CBX, does not reflect the modern shallow tectonic setting that comprises the highly active strike-slip features of the San Miguel fault. We rather invoke a larger process that seems to produce the roughly WSW-ENE to E-W fast axis observed along the west coast of the peninsular range at NE72, NE73, SPX and NE74. This pattern may be due to frozen anisotropy left by the ancient subduction of the now extinct Farallon plate.

Transition from distributed extension to continental rupture, northern Gulf of California

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The Gulf of California is a premier example of a young, transitional ocean basin where high-resolution records of seafloor spreading, faulting, volcanism, and marine deposition may be tied to its plate tectonic development. Matching distributions of pyroclastic flow deposits on conjugate rifted margins of the Upper Delfín basin of the northern Gulf of California support 255 +/- 10 km of opening and a close fit between present-day coastlines. Plate-circuit constraints together with isotopic ages of offset deposits indicate rapid localization of the Pacific - North America plate boundary into the Gulf of California ca. 6 to 6.5 Ma. The timing of volcanism at the nascent ocean basin axis, together with marine incursion over 600 km into the northern Gulf of California, further support that crustal rupture was a tectonically sudden event. Geologic structure and fault activity on the margins of the Upper Delfín basin indicate that crustal rupture was superposed on a setting of slow, distributed continental extension, similar to Basin and Range extension elsewhere in western North America. A narrow zone of transtension preserved on the Sonora margin may have accommodated some dextral shear prior to 6.5 Ma in a setting much like the Eastern California Shear Zone / Walker Lane today. The magnitude of this "proto-Gulf" shear is not yet well-constrained but is probably less than 100 km, based on geologic constraints from Alta California. Localization of continental rifting, rupture of the continent, and opening of the Gulf of California coincided with an increase in extensional strain rate by two orders of magnitude. Extensional strain rates also increased on adjacent continental normal faults, contrary to the expected response to a necking instability. Rather, the tectonic history of the Upper Delfín basin supports that a change in tectonic boundary conditions led to increased strain rates and continental rupture in the northern Gulf of California.

Recent vertical uplift in Baja, California

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Campaign GPS data over the last 7 years show vertical motion in Northern Baja California with the high rates correlating with high topography. Simple Elastic Half Space models showing the kinematic effects of normal faulting and the resulting isostatic rebound due to crustal thinning do not match the data. When the model out put is compared to the GPS data available, the fit is insufficient. An additional source of uplift is appears to be required. For example, recent unloading of the batholith by delamination of a dense root, analogous to delamination of the Sierran batholith to the north, may be occurring.

Estimates of Crustal Thickness of Baja California, Sonora and Sinaloa, Mexico, Using Disperse Surface Waves

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Dispersed surface waves of regional events recorded at NARS-Baja and RESBAN networks located over the Baja California Peninsula, Sonora and Sinaloa, Mexico, were used to estimate shear wave elastic models and crustal thickness. We analyzed fundamental modes of surface waves with period between 10 and 40 seconds. Multiple filter analysis and the inversion described by Herrmann and Ammon (2002) was used. Crustal thickness estimated in the Peninsular Ranges of Northern Baja California agree with those obtained by previous studies. We analyzed dispersion of surface waves with northwest-southeast travel paths along the east and west of the Baja California Peninsula as well as a northwest-southeast travel path west of Sonora-Sinaloa Mexican states.

It was found that the crustal structure east of the Baja California Peninsula is similar to the structure of Sonora and Sinaloa. The correlation between those two structures suggested that a distance of the order of 275Â±25 km separated them, if we consider Baja California Peninsula as a rigid body moving toward the northwest relative to the North America plate. This displacement between the structures agree with the displacement calculated with dating of Miocene deposits located in San Felipe Baja California Peninsula (Pacific Plate), and Isla Tiburon located west of Sonora (North America plate).

Investigation of segment controls on the rupture history of the southern San Jacinto fault

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Paleoseismic studies were performed at 7 sites along the southern San Jacinto fault zone to study the relationship between past ruptures across the segment boundary between the Coyote Creek (CCF) and Superstition Mountain (SMF) faults, and to understand their relationship to the timing of large ruptures along the Clark fault (CF). The CCF has ruptured repeatedly during the past 300 yrs (1.4m in 4-5 events) whereas the SMF has not failed at all in this timeframe. The large events on the southern CCF appear to correlate with large events (>2m of slip) on the SMF (3 in the past 1.1 ka). Our observations suggest that when the SMF ruptures, the >2m of slip punches through the ~2-3 km step-over between the SMF and the CCF. In contrast, when the CCF ruptures with 0.5m, only rarely does slip propagate onto the SMF. Thus, it appears that the southern end of the CCF is a fairly robust segment boundary in moderate 1968-type events but may be transparent in larger SMF ruptures. We interpret this to reflect the role that the amount of dynamic slip plays in the persistence of segment boundaries, which in turn affects our perception of fault segmentation and the forecasting of future events.

At Hog Lake near Anza on the CF, we identify evidence for 15 surface ruptures in the past ~3500 years, with the most recent event about AD 1760. The past seven events have accumulated a minimum of 28 m of slip in the past 1700 years, suggesting a late Holocene slip rate of at least 17 mm/yr. The timing of earthquakes at Hog Lake along the central SJF compared to those along the SMF-CCF suggests that these two major segments behave independently. This suggests that major step-overs, such as the one defining the step between the CF and CCF, are of sufficient size as to act as permanent rupture barriers.

A Magnetotelluric profile across central Baja California

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CICESE

A magnetotelluric profile across central Baja California reveals several electrical conductivity anomalies associated to major tectonic episodes that occurred during the evolution of Baja California's lithosphere. The resulting conductivity image helps to delineate the boundaries between distinct Mesozoic terranes juxtaposed in the peninsular crust, Based on our model the thickness of the crust is estimated in ~35 km beneath the western Peninsular Ranges batholith (PRB) and ~20 km beneath the eastern PRB, in agreement with other geophysical estimations. We also found an anomaly probably associated with fluids trapped at the base of the crust, presumably released by a subducted slab during the last stages of the Miocene convergence. Accordingly, the presence of a fluidized weakness zone supports the hypothesis that the current Baja lithosphere has not been entirely coupled to the Pacific plate.

Crust and Mantle Velocity Stucture of the Gulf of California

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Little is known of the large scale crustal structure of the Gulf of California. Using broadband seismic stations situated in southern California (CSN) and Baja California (NARS) along with large earthquakes within the Gulf an average velocity model for the northern Gulf of California is determined. This study utilizes the entire broadband seismic wavefield, which in this region shows great variability and the longest recorded surface wave trains on earth. In addition, constraints were placed upon the boundary between the Gulf and it's bounding land masses. The northern Gulf has a crustal thickness of 20 km at 26.5 degrees north and increases in thickness proceeding northwards towards the US/Mexico border, in agreement with recevier function studies. A crustal sediment layer within the Gulf is 7 km thick on average and shows incredibly high attenuation (1/Q = 0.1). Further, the boundary between the Gulf and Baja California is also very sharp, possibly due to the differences in sediment and crustal thickness. The same type of boundary is also present to the north in the Salton Trough. In constrast to the Gulf's eastern boundary which is less pronounced.

Expansion of the Baja California, Mexico GPS Network, June 2004

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The Gulf of California is an embryonic ocean ridge characterized by multiple sets of extensional and strike-slip faults. It is difficult to observe tectonic processes that span across the Gulf of California with Global Positioning Systems (GPS) because of the lack of land close to the active faults (GPS cannot be used under water). Also, dense arrays of GPS networks exist in northern and southern Baja, while central Baja had no GPS monuments. Arrays on the mainland side of Mexico are also sparse. Central Baja, however, may be an important area in understanding the processes that occur across the Gulf of California because of the locations of Islas de la Guarda, San Lorenzo and Tiburon.

In June of 2004, we expanded the Baja GPS network by installing two transects of GPS monuments in central Baja perpendicular to plate motion. The more northern portion of the expansion is composed of four sites that are situated on the northern end of Isla de la Guarda and on mainland Baja. The southern transect consists of 12 sites and spans from El Arco through San Francisquito, Isla San Lorenzo, Isla Tiburon and into mainland Mexico, north of Bahia Kino. Only one observation for most of these sites exists, therefore this project is in its preliminary stages. In the future we hope to be able to apply the GPS data to further understand the tectonic processes spanning the Gulf of California.

New constraints on the origin of rhyolitic magmatism within the Salton Trough: evidence for episodic mobilization of hydrothermally altered intrusives

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The Salton Sea rift zone occurs at the transition from the continental transpressive San Andreas fault system to embryonic oceanic spreading within the Gulf of California. While metamorphism, hydrothermal activity and elevated surface heat flow within the Salton Sea area can be related to formation of young basaltic crust, the surface expression of magmatism is dominantly rhyolitic. In order to better constrain the thermal and compositional evolution of Salton Buttes volcanism and their precursors and the relation to basaltic magmatism, we examined recently discovered rhyolitic lavas and pyroclastic deposits that are now buried to depths of ~1.7 to 2.6 km as well as surface rhyolites. High spatial resolution ion microprobe measurements of zircon reveal that all rhyolitic magmas in the Salton trough have low primary d18O compositions (average d18OSMOW values between 3.2 and 4.9 permil), similar to low d18O rhyolites that occur in long-lived basaltic magma systems in oceanic rift settings (e.g., Iceland). These values are significantly lower than expected for rhyolite fractionation of mantle-derived basalt, and instead indicate that the rhyolite source experienced substantial exchange of oxygen with meteoric waters. New U-Th-Pb dating of zircon for these rhyolites and granitic xenoliths reveal episodic zircon growth at 600 ka, 400 ka, 21 ka, and 9 ka. This youngest age is consistent with a Holocene eruption age for the Salton Buttes as previously suggested by K-Ar and obsidian hydration dating. Hydrothermal zircons within granitic xenoliths unequivocally demonstrate the presence of shallow plutonic rocks in the subsurface which predate their host rhyolites by approximately 12 ka. The mobilization of altered plutonic materials and generation of low d18O rhyolites is consistent with the intrusion of high temperature basaltic magmas at shallow levels.

Paleoseismic Assessment of Fault Interactions in the Salton Trough Using Correlations of Lake Cahuilla Sediments

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At the south end of the Salton Sea the Salton Trough is bounded by the San Andreas (SAF) on the east and the San Jacinto fault (SJF) on the west. At this latitude, most of the the tectonic strain in the region is accommodated by large magnitude earthquakes that occur on these faults and the Imperial fault (IF). Because of the limited time period of historical earthquakes in this region, we can only use paleoseismology to address fault interactions using relatively short term fault slip rates, or the occurrence of individual earthquakes. Conducting paleoseismic investigations within the Salton trough has posed a special challenge to achieving long high-resolution paleoseismic records, because few sites exist where datable Holocene sediments overly the faults.

Fortunately, the longest paleoseismic records in the Salton Trough include faulted lacustrine sediments from the former Lake Cahuilla. Following are the key sites: Indio (SAF 4 events, 12m above sea level (sl); Sieh, 1986), Salt Creek South (SAF 8 events, 20mm/yr, 60m below sl; Williams and Seitz, 2005), Harris road (IF 3 events, 33.5 m below sl; Meltzer and Rockwell, 2005), Harris road (Brawley fault, 36.5m below sl; Meltzer and Rockwell, 2003), and the SJF northern shoreline site (SJF 4 events, 5mm/yr, 12m above sl; Gurrola and Rockwell, 1996). Ancient Lake Cahuilla sediments present a unique opportunity, because they can be correlated for long distances within the Salton trough and are generally C-14 datable. In the past 1000 years the closed depression filled to its spill point in at least five highstands at elevations near 13 m (Waters, 1983; Sieh and Williams, 1990; Rockwell and Sieh, 1994; Williams and Seitz, 2005). Three of the longest record sites, Indio, Salt Creek South and the northen shoreline site, include 5 distinct lake deposits that we have correlated. If accurate, these correlations provide the first robust relative age relationships of earthquakes among these sites. Also, these stratigraphic correlations provide a basis to build a regional chronologic model, which allows the combining of dates from all sites, potentially improving event date estimates at all sites. The SAF events that correlate can be considered to be the same earthquakes based on empirical surface displacement and rupture length relationships. Additional temporal and slip rate constraints are provided by two long event records at the 1000 Palm Oasis site (SAF 5 events, 2mm/yr, Fumal, Rymer and Seitz, 1999) located on the Mission Creek strand of the SAF, and at the Hog Lake site (SJF 15 events 20 mm/yr, Rockwell et al. 2005) on the SJF, both above the depositional reach of Lake Cahuilla sediments.

Constraints on Evolution of the West Salton Detachment System (WSDS), Salton Trough, From (U-Th)/He thermochronology

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The WSDS is a low-angle normal fault that bounds the eastern Peninsular Ranges and roots E beneath sedimentary and basement rocks of the Salton Trough. Slip on the WSDS controlled deposition of latest Miocene to Pleistocene syndetachment marine and fluvial strata in the western Salton trough. The WSDS contains several ESE-plunging arches, and detachment striae trend from N to ESE.

Twenty-five (U-Th)/He apparent ages of apatites from the footwall of the WSDS record rapid cooling through ~70°C between 10.3±0.5 and 2.2±0.1 Ma. We interpret samples with Late Miocene (~10-6 Ma) apparent ages as residing in the He PRZ. However, the exact timing of the onset of rapid cooling is not clear from the data. Footwall and hanging wall apatite ages record a significant thermal break across the detachment. Hanging wall apatite apparent ages are much older, ~25 to 44 Ma. Six zircon samples also record this thermal break: footwall ages range from ~51 to 35 Ma but one hanging wall sample is 72.7±3.6 Ma.

Hanging wall apatite apparent ages are similar to unpublished footwall apatite fission track ages (~30-50 Ma) (Stockli and Axen, unpublished data), and footwall (U-Th)/He ages on zircons (this study). These ages presumably record slow cooling during development of the regional Eocene-Oligocene erosion surface. In addition, the zircon apparent age from the hanging wall is consistent with regional rapid cooling following pluton emplacement determined from Ar/Ar cooling ages on biotite and K-feldspar (Grove et al., 2003).

Preliminary estimates from comparison of similar apatite hanging wall and zircon footwall ages suggest a minimum of ~3 km of exhumation since ~6 Ma and exhumation rates on the order of 0.4-1 mm/yr (assuming a geothermal gradient of 30°C/km). This estimate of overall exhumation is approximately half of the total exhumation estimated by low-temperature thermochronometers for large normal fault systems father south in Baja California. Additional samples from 2 vertical transects comprising ~1300 m and ~600 m of vertical relief will hopefully further constrain the timing of the initiation of slip on the WSDS and provide a point of comparison for stratigraphic estimates of the age of initial slip.

Correlation of the Tuff of San Felipe from Baja California into the Interior of Sonora; A Widespread Marker Horizon for Gulf of California Extension

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The Tuff of San Felipe (Stock et al., 1999 JVGR) is a regionally extensive pyroclastic flow deposit that erupted ca. 12.5 Ma in the region that later became the northern Gulf of California. It is an alkali rhyolite, with the predominant phenocrysts of alkali feldspar, and augite or ferroaugite. Accessory phases include plagioclase, diopside, hypersthene, quartz, magnetite, and fayalite (which is more common in the near-vent facies). The near-vent facies contains black inclusions with fayalite and feldspar. A key characteristic of this tuff is its unusual direction of paleomagnetic remanence: southwest and nearly horizontal (slightly down) in distal,unfaulted regions. This direction is far outside of the expected direction for Miocene North America and indicates that the tuff cooled during a magnetic field excursion or a field reversal.

The Tuff of San Felipe crops out extensively in northeastern Baja California, and was also identified on Tiburon Island and in coastal Sonora (Oskin et al., 2001 Geology) providing a key tie point for the amount of opening of the Upper Delfin Basin segment of the Gulf of California. The Tuff of Hermosillo (Paz-Moreno et al., in press 2005) was correlated to the Tuff of San Felipe by Oskin (2002 PhD thesis) on the basis of similarity in composition, age, and paleomagnetic remanence direction. The source vent is thought to lie on the Sonoran Coast between Punta Chueca and Bahia de Kino, with near-vent facies cropping out in Sonora and also in Baja California on the coast between San Felipe and Puertecitos (near Delicias). However, the inferred source region is entirely dismembered by large-scale normal faulting accompanied by steep stratal tilting.

Additional outcrops of what appear to be the same ignimbrite have been sampled from the Sierra Lopez, NW of Hermosillo; from regions west, NW, and south of Hermosillo; and from localities east of Hermosillo. Results thus far are consistent with this all being a single pyroclastic flow deposit. Where exposed in the interior of Sonora, the ignimbrite generally overlies river gravels and may have filled the channel of a major paleo-drainage system. It is found to distances now up to 150 km inland of the coastal vent, due to subsequent extension and strike-slip faulting. Ongoing work is attempting to define the pyroclastic flow directions from anisotropy of magnetic susceptibility (AMS), to better constrain the original depositional geometry, and to use this tuff as a marker horizon for a regional constraint on the post-12.5 Ma evolution of this sector of Sonora.

Crustal Structure and Basin Analysis Across the Southern Gulf of California

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An 880-km long transect across the Alarcon Basin, spanning the conjugate margins on mainland Mexico and the Baja Peninsular, forms part of the dataset from the Fall 2002 Margins experiment in the Gulf of California. The wide-angle dataset consists of data from 11 land-based Ref-Tek seismometers and 53 Ocean-Bottom Seismometers, with 600 km of co-incident MCS reflection data. A velocity model constructed from the wide-angle data shows the thinning of the crust from approximately 30 km in the Baja Peninsula and 28 km in mainland Mexico down to 6.5 km where seafloor spreading has created new oceanic crust for the last 3.6 Ma. The stretching factor calculated for the upper crust from the MCS is around 1.3, whereas an average for the whole crust calculated from crustal thickness in the velocity model is about 1.9. The velocity structure shows slower crust under the extended continental margin with no evidence of underplating. A major feature of the model is the presence of a crustal keel beneath a continental block near the southern continent-ocean transition, which separates the Alarcon Basin from a deep basin thinned to almost oceanic crustal thickness. This keel is interpreted to be the center of extension and the overall margin structure appears symmetric, suggesting pure shear as the overall extensional process. The upper crust shows brittle deformation with normal faulted basins, many of which appear to have a volcanic layer at the top of basement which is likely to be related to the volcanic arc that was active until the end of subduction 12 Ma. Many of the basins contain some syn-rift sediments, but the majority of sedimentation is post-rift, suggesting that most extensional faulting took place during the earlier stages of rifting.

Rifting and Breakup Between Newfoundland and Iberia

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The Newfoundland-Iberia rift is considered to be a type example of non-volcanic rifted margins. A key feature of the conjugate margins is a transition zone that lies between clearly continental crust and assumed "normal oceanic crust" that appears up to ~200 km farther seaward in the vicinity of magnetic anomaly M5-M3 (Hauterivian-Barremian). Basement ridges drilled in this zone on the Iberia margin appear to consist of serpentinized peridotite with continental affinity, and seismic refraction studies show velocity structure that is consistent with this interpretation. Although the boundaries between continental crust and the transition zone can be defined with relative confidence on the basis of basement morphology and velocity structure, major questions remain about the nature and position of the seaward limit of the transition zone. Notably, drilling at Site 1070 recovered serpentinized peridotite from supposedly oceanic crust near anomaly M2r on the Iberia margin, and drilling at Site 1277 in the Newfoundland Basin also recovered serpentinized peridotite from presumed oceanic crust near anomaly M1. In addition, existing interpretations place the breakup unconformity, classically associated with the end of continental rifting and the first formation of oceanic crust, near the Aptian-Albian boundary (~112 Ma). This age is some 15 m.y. younger than the oldest magnetic anomaly (M5) that has been proposed to have oceanic crustal affinity off Iberia, and it is 9 m.y. younger than anomaly M0, which most investigators argue is certain oceanic crust. There are three possible ways to explain this paradox: 1) the breakup unconformity has been misidentified, 2) the breakup-unconformity paradigm is invalid, or 3) actual "breakup" occurred within the crustal domain currently considered to be oceanic crust.

We have analyzed the basal (pre-Cenomanian) stratigraphy of the rift, focusing on synrift events, development of the proposed breakup unconformity, and formation of the first oceanic crust. From this analysis, we suggest that the first true oceanic crust was not formed until the earliest Albian, ca. 112-111 Ma, coincident with the formation of the historically proposed breakup unconformity. It appears that up to that time, the entire rift was under in-plane tensile stress that led to local extensional deformation throughout the rift, even though the last principal extensional episode probably ended in the Hauterivian-Barremian (>121 Ma). At the time of breakup, relative compression of the plates led to plate deformation, enhanced mass wasting of serpentinite ridges in the deep basins, shallow-water shelf erosion, and basin flooding by turbidites. Coarse debris that accumulated in the deep basins created a strong reflection that characterizes the breakup unconformity. Subsequent rift history reflects subsiding shallow-water platforms and reduced transport of coarse terrigenous debris into the deepening ocean basins.

A review of the patterns of upper crustal faulting in the SW Gulf of California in space and time

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The geology of the coastal belt and islands of the Gulf Extensional Province from Loreto to Los Cabos, Baja California Sur is moderately well known, and local areas are known in detail. The offshore region was largely incognito until the last few years. In the past few years, the offshore southern Gulf is being analyzed in a systematic way. Recent and planned offshore work includes a bathymetric survey of all areas deeper than the shelves, two seismic refraction and reflection transects across the Alarcon ridge and East Pacific Rise, CHIRP surveys of active faults in the greater La Paz bay region linked to work on the same faults onshore, a GPS network that includes many islands east and west of the Baja California peninsula, and many studies of shallow-water sediments and stratigraphy and the Guaymas and Alarcon spreading centers.

A transform-spreading ridge system is well defined in the southern Gulf and recent transform earthquakes confirm the relative motion at ~305°. Currently, virtually all strain is on the main plate boundary or west of it (there are a few active faults N of the Tres Marias islands); the main plate boundary has ~85-90% of the plate motion, about 10% is on faults west of Baja California, and a few percent in the wide SW Gulf zone of active faults from the eastern coastal belt of Baja California Sur to the central Gulf. West of the Baja California peninsula are two oblique-slip faults, while the SW Gulf, including the coastal belt, is a complex zone of tens of potentially active faults, 6-8 of which are exposed on the peninsula. Onshore fault scarps, uplifted marine terraces on islands, earthquakes, and seismic reflection data confirm active faulting, and suggest rates of faulting on individual faults is tenths of mm/year.

The coastal belt has three rift segments along the Gulf escarpment, which ends near La Paz, with complex accommodation zones between the segments. The San Jose del Cabo fault forms a final segment that cuts across the SE corner of the peninsula. These four segments were active since ~12 Ma. In all segments, the rate of has decreased and moved offshore since 2-3 Ma. The SW Gulf becomes narrower to the north because the Gulf escarpment trends more northerly than the rift axis in the central Gulf. Based on interpretations from bathymetry and known faults onshore, the orientations of faults in the SW Gulf are arranged in domains between the fracture zones and their northwesterly projections. The Los Cabos domain is largely normal faults with N to NNW strikes onshore and NE strikes offshore that suggest major strain partitioning between the peninsula and the main plate boundary. The major San Jose del Cabo normal fault was active since ~12 Ma, but slowed at ~3 Ma. The Tamayo fracture zone projects to a ~20 km wide zone of normal and oblique faults with more NW strikes that runs from the Cerralvo trough to San Jose island. The belt looks like a transtensional fault system, but earthquakes in 1995 were dip-slip and suggest partitioning. The Alarcon domain (NW of Alaracon ridge) is longer than the other domains and has N striking faults near the peninsula and NNE to NE striking faults closer to the Alarcon basin, which suggests little or no partitioning. The Pescadero fracture zone is only moderately defined and projects to NW-striking faults in the borderland and toward the Loreto fault. The Pescadero domain has mainly N-striking active faults. The Loreto fault and basin at the end of the domain had rapid faulting in Pliocene time that largely ended at 2 Ma, when faulting moved east offshore (and focused on the Pescadero basin?). Both the Pliocene and active kinematics and patterns of faulting suggest no partitioning. The Farallon domain has NNE to NE striking faults and a shorter and simpler (?) offshore area. The three domains emanating from the Alarcon, Pescadero, and Farallon spreading ridges roughly project to the three coastal rift segments suggesting that the rift segments were the fundamental framework for the geometry of the developing plate boundary.

Basin analysis across the southern Gulf of California based on geologic study of onshore basins and seismic reflection of selected offshore basins

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(i) Early syn-rift basins include the onshore Cabo basin and fragment of a basin on Maria Madre Island. These basins begin with a terrestrial alluvial section and change to marine facies; the Maria Madre appears to deepen much more rapidly than the Cabo basin. The oldest marine section of both of these basins are ~8 Ma, and initiation of the Cabo basin may be much older. The Maria Madre basin has at least two Pliocene unconformities. Greater tilts in bedding of the older units of the Cabo basin (15° – 30°) compared to gentle dips in the younger units suggests unconformities. Seismic lines show early rift basins on both sides of the northern East Pacific Rise and Alarcon ridge, but more basins across a wider belt on the east side. The westernmost basin is due north of the Cabo basin and east of Cerralvo Island; a major strike-slip fault cuts this basin, though normal faults are more common. There may well be early basins NW of these basins because there is sparse seismic data. In the SE Gulf, there is a line of basins from the north side of Maria Madre island to just offshore NW of Puerto Vallarta. There is another line of basins SE of the Alarcon ridge and south of Mazatlan. Seismic lines reveal that initially there were numerous half graben a few km wide. Normal faults commonly die or faulting jumps to new faults such that the basins are complex and grew wider and simpler through the early syn rift stage. Major sequence boundaries separate multiple lower syn rift sequences in many locations.

(ii) A simple upper sequence lies above the lower syn-rift sequences. These upper basins are commonly simple half graben that are wider than the lower basins. The upper basins offshore the Baja peninsula and south of Mazatlan are partially starved, while the basins on the shelf from Mazatlan to Puerto Vallarta are filled; the shelf is largely prograding clinoforms. Many of the faults related to the upper basins are active or recently inactive. The faults under the Mazatlan shelf are inactive. The upper sequence NE of Tres Marias ridge is a broad, unfaulted, basin that is growing wider; this may be a nascent forearc basin as there is a subduction zone S of the ridge.

(iii) Four latest Miocene(?) to Pliocene transtensional basins (Loreto, and on Carmen and San Jose islands) formed along or near the projections of the Tamayo and Pescadero fracture zones likely when they were major strike-slip faults. Unlike the other types of basins, these basins have been studied in detail. These basins have much in common with the early syn-rift basins in terms of complex faulting in narrow (few km) subbasins, common syn-sedimentation faulting and growth strata, and internal unconformities. But the detailed studies reveal complex systems of dip-slip and oblique-slip faults that control basin subsidence. We speculate that many early offshore basins are also transtensional. The timing of initiation of the transtensional basins is not known, but in all cases there are hundreds of meters of undated lower strata below the well-dated (3.5 – 2 Ma) upper strata implying that they began in late Miocene time. These basins had marine deposition between ~4 and 2 Ma and had major fault reorganizations and decrease in faulting at 2.4 – 2.0 Ma. This is part of a pattern of faulting decreasing substantially across the entire SW Gulf in the late Pliocene. Because the basins are on projections of the fracture zones, the death of the basins at 2.4 – 2 Ma is likely recording the initiation of the transform faults, or an increase of transform faulting as the modern plate boundary evolves.

Upper Mantle Shear Wave Anisotropy Under Stations Around the Southern Gulf of California

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We have calculated the splitting parameters that describe upper mantle shear wave anisotropy under stations around the southern Gulf of California, Mexico. SKS and SKKS arrivals recorded on both the radial and transverse horizontal components were used. The splitting parameters which quantify anisotropy are the delay time (delta-t) and the fast polarization direction (phi).

The anisotropy is calculated using the approach by Silver and Chan [1991]. A time segment containing the SKS arrival is selected from both horizontal components. The space of possible solutions is then searched in one-degree intervals with phi ranging between 0 and 180 degrees. Specifically, the coordinate axes are rotated every 1 degree increment and the autocorrelation and crosscorrelation between the components is calculated. For each value of phi, the delay time solution space is also searched in 0.05 s increments. Next the eigenvalues corresponding to each delta-t and phi combination are calculated. In the presence of noise, the desired solution will be given by the matrix which is most nearly singular. In order to check our results, we apply a correction in the amount of the measured delta-t and phi to the original records and then rotate them to make sure that the anisotropy disappears. The shapes and the difference in the arrival times of the fast and slow waves were compared to make sure that the result is robust. As a further check, the polarization of the particle motion for the radial and transverse components before and after correction was plotted.

The records used were taken from Mexico's Servicio Sismologico Nacional broadband network and from the NARS-Baja California deployment [Trampert et al., 2003]. For the data available, null measurements were obtained at stations NE76, NE77, NE78 and LPIG (La Paz) and may perhaps indicate that anisotropy is below the detection threshold. Stations NE76, NE77 and LPIG belong within the "La Giganta volcanic belt" geological province [Ortega-Gutierrez et al., 1992], whereas NE78 is located near this province. The volcanic belt is Cenozoic in age and formed in a continental arc environment. Farther south, the fast direction at station NE79 is oriented nearly E-W. This station belongs to the "La Paz plutonic complex", which is an entirely different province [Ortega-Gutierrez et al., 1992]. In this case the orientation of phi cannot be explained by the absolute plate motion (APM) of the Pacific plate. On mainland Mexico, across the Gulf, stations NE81, NE82 and MAIG (Mazatlan) show a fast polarization direction approximately ENE-WSW, consistent with the APM for North America. Due to the few records available, it was not possible to obtain reliable measurements at NE83. New data should make it possible to constrain the anisotropy at this station.

Recent/active tectonics in the Gulf of California extensional province
Multiscale/multimethod approach, from remote sensing to field

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Continental extension and induced-rift geometry are controlled by the interaction of various parameters (inherited discontinuities, magmatism, duration/intensity of extension and/or the variations of stress-field) that interplay at different spatial and temporal scales. Consequently, understanding any rift system and its neotectonic first implies to identify the different involved factors at various scales (mantle to crustal level) and next to define their respective role in strain processes. Most of those questions can be fruitfully investigated and further discussed about the complex/polyphased Miocene-Present tectono-magmatic evolution of the Gulf of California Extensional Province (GEP hereafter), and more particularly the Sonoran fault network, by performing a multiscale and multimethod approach combining various dataset such as remote sensing (Landsat ETM+ and Radar imagery), digital topography (Shuttle Radar Topography Mission), seismic reflection imagery and field data. Such an approach has ever been efficiently applied to a segment of the East African Rift System (Turkana, Northern Kenya; Vétel, Ph.D) and should further provide some new constraints for elucidating a number of questions dealing with the opening GEP and its neotectonic evolution. For that purpose, our study focuses on five specific research objectives dealing with:
1) the 3D morphostructural pattern of the GEP on the basis of recently available SRTM digital topographic data coupled with the overall available coverage of Landsat ETM+ high-resolution optical images.
2) the structural evolution and segmentation of major uplifted/downthrown blocks of normal fault system by taking into account the nucleation, propagation and longitudinal segmentation mechanism of the uplifted block, fault plane and downthown block in close relation with (inherited?) transverse structures and magmatic domains.
3) onshore/offshore structural correlations. Regarding the high-angle (~40°) intersection between oceanic transforms and onshore fault network, offshore seismic profiles or data through onshore syn-rift basins (Guyamas basin, â•œ) help to study the 3D-structure of the GEP crustal-oceanic domains and their kinematic relations (e.g. strain partitioning, inversion in basins in relation with stress-field rotation).
4) qualitative/quantitative analysis and scaling properties of normal fault networks. Geometrical and statistical analysis permit to determine their scaling law behaviour (self-similar, exponential) and precise their nucleation/growth mode in relation with pre-existing structures and/or magmatism whereas topographic data allow us to estimate minimum extension rate.
5) localisation/quantification of recent/active movements by using SAR imagery (Synthetic Aperture Radar). Such high-resolution remote sensing data are used to enhance localisation of active faults and quantify movements as low as few millimetres. In conclusion, our approach would give some new results about the Miocene-Present fault/fracture network of the Sonora fault network of the GEP. More generally, this

multidisciplinary study, which combines structural geology and remote sensing, should be of considerable practical value to structural geologists working on polyphased and oblique rift systems such as the GEP.

Middle Miocene peralkaline rhyolitic magmatism in Sonora. A peculiar volcanic episode associated to the continental break-up that preceded the opening of the Gulf of California.

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Peralkaline silicic magmatism is known to be a common feature during continental break-up and rift opening. In northwestern Mexico, Middle Miocene comenditic rocks related with bimodal volcanism represent an important piece for the magmatic evolution history of the proto-Gulf of California. Peralkaline volcanism outcrop in two distinct zones: the first one is located at the northwestern end of the Sonora State, east of the large Quaternary shield volcano of El Pinacate; the others are located along a 100 km wide E-W belt centered on the town of Hermosillo, in the central part of Sonora. Field studies, 40Ar/39Ar geochronology, mineral chemistry, geochemistry (major and trace elements) and finally isotope geochemistry (Sr, Nd, Pb) contribute to establishing the stratigraphy of the Tertiary volcanic successions and the petrogenesis of the peralkaline rhyolites.
In the Pinacate area two bimodal volcanic episodes (basalts and rhyolites) have been dated at 15 and 12 Ma, meanwhile in central Sonora only the 12 Ma episode is represented. Chemical analyses confirm the peralkaline character of the rhyolites. Rare earth and other trace elements support the existence of a genetic link between basalts and peralkaline rhyolites. Isotopic data show huge variations in the Sr isotopic ratios that vary from 0,705—a similar value than that of the associated basalts in the sequence—to extremely high values of 0,720. Nd and Pb isotopic compositions are on the contrary fairly homogeneous. These variations in Sr isotopes are evidence of contamination by the Precambrian crust. Modeling of the isotopic data support an origin for the peralkaline rhyolite by fractional crystallization of transitional basalts in a shallow reservoir, with about 10% contamination by the Precambrian crust. Evidences of mixing also observed in some places indicate that these liquids evolved in a periodically opened system.
The distribution of the Middle Miocene peralkaline volcanism in Sonora is not fortuitous. The Pinacate area constitutes the southernmost outcrops of a N-S belt of Miocene peralkaline rhyolites emplaced on the western margin of the North American craton from Nevada to California. Outcrops of central Sonora are the counter part of the 12.6 Ma Tuff of San Felipe (Stock et al., 1999) present in NE Baja California. These two groups are also located on a major lithospheric discontinuity represented by the limit between the North American craton and the accreted exotic fragments of the Guerrero Terranes. Peralkaline volcanism does not seem to be related to subduction processes but rather to asthenospheric upwelling (slab window?) that induces lithospheric thinning and partial melting producing basaltic magmas with a transitional character. This volcanic episode constitutes therefore a clear geological marker in the northern Gulf of California area and represents the first magmatic expression of the lithospheric extension as a consequence of new Pacific-North America plate boundary motions.

Current crustal movements across the southern San Andreas Fault and the southern Dead Sea Fault systems: A comparative study

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The southern San Andreas Fault (SAF) and the southern Dead Sea Fault (DSF) systems exhibit similar transperssional tectonic environments. Both fault systems are dominated by horizontal crustal movements, elongated and narrow extensional morphology, en-echelon fault segmentation, and active seismicity. Interestingly, the lowest topographies in both systems, the Salton Trough and the Dead Sea, are one of the few continental localities lying below sea level. The main differences between the two fault systems are their rates of horizontal movements and of seismic activities. The slip rate across the southern SAF is about 30-40 mm/yr, whereas only 3-4 mm/yr across the DSF, an order of magnitude lower. As a result, the seismic activity along the SAF is significantly higher with respect to the observed seismicity along the DSF.

In this study we present recent GPS measurements of current crustal movements across both faults systems and compare their similarities and differences. We also compare the observed geodetic rates to the geologic- seismic-determined slip-rates across both systems. Our results indicate larger differences between the various estimates (geodetic, geologic and seismic) along the DSF than those estimated for the SAF.

Southernmost San Andreas fault rupture history: Does this tail wag the dog?

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The earthquake history of the southernmost San Andreas fault (SSAF) has implications for the timing and magnitude of future ruptures of the southern portion of the fault, and for fundamental properties of the transform boundary. The SSAF terminates against the "weak" transtensional Brawley seismic zone, and conjunction of the fault against this ~35-km-wide extensional step isolates the SSAF from transform faults to the south. SSAF ruptures are therefore likely to be relatively independent indicators of elastic loading rate and local fault properties. Knowledge of whether SSAF ruptures are independent of, respond to, or initiate ruptures of the bordering San Bernardino Mountain segment of the San Andreas is essential for realistic modeling of the southern San Andreas fault.

To recover long-term slip parameters and rupture history for the SSAF, geological evidence of its past motion has been investigated at Salt Creek California, about 15 km from the SSAF's transition to the Brawley seismic zone. Radiocarbon ages were determined for 46 organic samples. Sediments dated at AD1540±100 are offset 6.75±0.7m across the SSAF at Salt Creek. Beds with an age of AD1675±35 are offset 3.15±0.1m. Williams (1989), and Sieh and Williams (1990) showed that near Salt Creek, ~1.15m of dextral slip accumulated aseismically over the 315-year 1703-1987 period, yielding a creep rate of 4±0.7 mm/yr. If similar creep behavior held through the shorter 1540-1675 interval (135±105yr), net seismic surface displacement at Salt Creek was ~2m in the latest event, and ~3m in the prior event.

The hiatus between ultimate and penultimate ruptures appears to have been at least 100 years shorter than the modern quiescent period of 335±35 years. This indicates a very high contemporary rupture hazard, and given the long waiting time, suggests that the fault's next rupture will produce a significantly larger displacement than the two prior events.

Paleoseismic and neotectonic studies of the Salton Trough benefit from repeated flooding of the Trough's closed topographic basin by the Colorado River. Ancient "Lake Cahuilla" reached an elevation of 13m, the spillpoint of the basin, at least five times during the past ~1200 years (Waters, 1983; Sieh, 1986; Williams, 1989). Flood heights were controlled by stability of the Colorado River delta during this interval.

Ongoing studies show excellent promise for recovery of the relationship between lake chronology and the San Andreas earthquake record. We have recovered sediment evidence at a new Salt Creek site, "Salt Creek South," of five flood cycles in the modern 1200-year period. Six earthquakes are tentatively described within this interval.

Continuing and planned work includes (i) high resolution age dating of the lake and interlake record, (ii) establishment of more robust field evidence for all the interpreted paleoseismic events, (iii) recovery of a slip-per-event history for the latest 3-4 events, (iv) development of fault interaction scenarios, (v) investigation of possible influences of lake filling on the timing of fault ruptures.

Geologic, structural, and thermochronologic constraints on the tectonic evolution of the Sierra Mazatan core complex, Sonora, Mexico

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Although rupture of the lithosphere in the Gulf of California did not occur until the late Miocene-Pliocene, extension was taking place in a broad region around the Gulf well before this final rifting. The pre-rifting crustal extension that took place in and around the Gulf is a critical component for understanding how the lithosphere ruptured because it provides insight into the forces that drove crustal extension/thinning and how such extension may have influenced the timing, location, and geometry of the final rift. Any discussion of rifting in the Gulf of California region is therefore incomplete without an understanding of the Neogene extensional history of its rifted margins.

The Sierra Mazatan core complex is a site of large-magnitude extension in central Sonora, Mexico that has exhumed mid-crustal rocks in the footwall of a >50 km long low-angle normal fault. As a site of large-magnitude extension in the Sonoran part of the rifted margin, the Sierra Mazatan holds key information on the timing, magnitude, rate, and style of crustal extension in the region. New geologic, geochronologic, and thermochronologic studies at Sierra Mazatan shed new light on the Neogene evolution of this core complex. Rapid footwall cooling inferred from 40Ar/39Ar thermochronology indicates that tectonic unroofing along this fault occurred in at least two distinct stages with an early pulse of slip occurring from ca. 25-23 Ma followed a major slip event from 21-15 Ma. Rapid basin formation in the hanging wall of the core complex largely occurred during the later slip event. The unconformable deposition of an ignimbrite directly on the footwall at 12.4 Ma demonstrates that the footwall had been exhumed by that time. Geologic and thermochronologic data indicate that the total slip on the fault system was likely 15-20 km, indicating that extension at Sierra Mazatan exceeds 100%. Slip rates on the main detachment fault are inferred to have been 3-4 mm/yr. Numerous lines of evidence, included footwall thermochronologic data, a tilted Tertiary footwall unconformity, and tilted footwall dikes demonstrate that the presently low-angle normal fault initiated at a steep dip (45-60°) and was rotated to a shallower angle as slip proceeded.

These results from the Sierra Mazatan core complex show that significant extension took place in central Sonora as early as the late Oligocene-early Miocene. Preliminary thermochronologic data from other Sonoran core complexes suggest that these areas were also tectonically unroofed during a similar period. Extension in much of at least central Sonora therefore appears to have largely predated the change from subduction to transtension at this latitude, suggesting that this extension was not directly linked to plate boundary forces. Middle-late Miocene appears to be largely restricted to present-day coastal Sonora. Future geologic investigations should focus on understanding what processes controlled the space-time patterns of extension in the rifted margins and how this extension influenced the timing and location of the final rift.

The Upper mantle beneath Gulf of California from surface wave data

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The recordings from the NARS-Baja stations provide a new dataset and a unique opportunity to determine some basic lithospheric properties on a regional scale around the entire Gulf of California (GofC). The aim of my work is to obtain a more detailed image of the upper mantle shear velocity structure beneath the GofC region by studying the data recorded by the NARS-Baja array. Surface waves are used to constrain crust and upper mantle velocities in an effort to create a 3D map of velocities in the GofC.
We have been carrying out a surface waveform inversion study of regional earthquake data recorded by the NARS-Baja array in or near the GofC. The method which we used is the Automated Multimode Inversion (Lebedev, 2000; Nolet, 1990). Inversion of the surface waves, S and multiple-S wave forms is an effective mean of constraining the structure of upper mantle. From the Nars-Baja data set, we have chosen 165 events, 1854 vertical component seismograms, which have appropriate event-station paths and sufficiently high magnitudes, to start with our inversion. We chose a two step procedure to constrain our starting models: first we calculated the average structure of Crust2.0 between every event and receiver pair; and then we use this crustal average plus AK135 as mantle model to constrain our 1-D starting models. Therefore we constrained 55 1-D starting models. For all these models we calculated the first 30 Rayleigh modes for our initial synthetics. The Automated Multimode Inversion (AMI) uses a nonlinear optimization to find the perturbations to the initial models. We successfully inverted 512 seismograms. The initial results show a noticeable lower shear velocity zone beneath the Gulf which varies for the different paths indicating structural mantle variations in the region.

The inversion results provide a dense distribution of models along the event-station paths. Before starting on constraining a 3-D S velocity image, we plan to use the two-station method to include more paths, especially in east-west direction across the Gulf.

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