Report on RCL-Cortez Workshop: Lithospheric Rupture in the Gulf of California – Salton Trough Region

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Introduction

From January 9 to 13, 2006, a group of about 70 professional and student researchers gathered at the Hotel Coral in Ensenada, Baja California, Mexico, to discuss the status of geophysical and geological research in the MARGINS Gulf of California – Salton Trough focus site (Fig. 1). The main goals of the workshop were to summarize emerging new data and results, identify existing gaps in knowledge, and suggest possible directions for future research. Theoretical models and studies of other rifted margins allowed participants to compare and contrast results from this region. A 2-day field trip, led by John Fletcher and Gary Axen, illustrated a well-studied example of low-angle normal faulting in the Laguna Salada area, and provided new insights into Late Cenozoic extension and transtensional tectonics in the Salton Trough (Fig. 2).

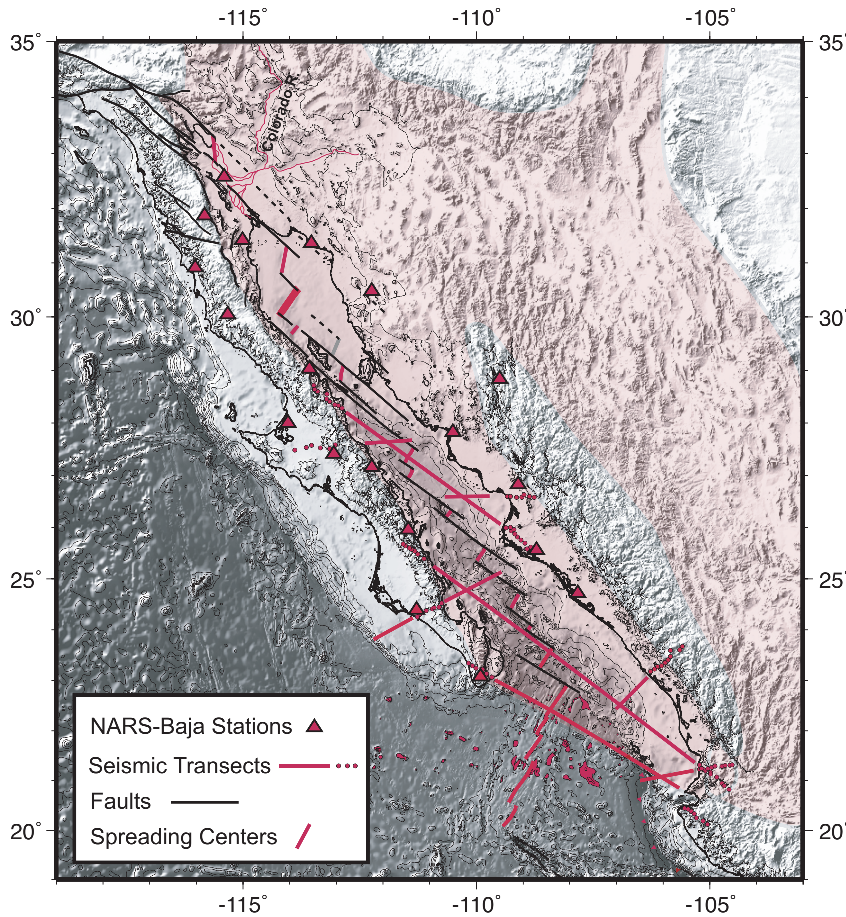

Figure 1. Shaded relief map of Gulf of California and Salton Trough. Pink shading denotes the area of Tertiary Basin-and-Range extension.

Financial support for U.S., Mexican, and other international participants came from the MARGINS and International programs of NSF. The workshop was sponsored by NSF and CICESE (Centro de Investigación Científica y de Educación Superior de Ensenada). Workshop conveners were Rebecca Dorsey, Raul Castro, John Fletcher, and Daniel Lizarralde. Julie Morris, Paul Wyer, and Meredith Berwick from the MARGINS Office provided invaluable support at all levels, from the mundane to the profound. Federico Graef, Director of CICESE, and Enrique Gómez, Director of the Earth Science Division at CICESE, welcomed the group with introductory remarks that highlighted the current atmosphere of international cooperation and collaborative research. Additional information about the workshop, including participants list, technical program, working groups, and downloadable oral and poster presentations, is available at http://www.rcl-cortez.wustl.edu/index.html.

Oral presentations were organized into thematic sessions, interspersed with poster sessions and group discussions. Each thematic session had a 4- to 5-member working group, which encouraged all participants to contribute directly to the talks and discussions. On the final day, 5-minute "pop-up" presentations distilled critical "knowns" and "unknowns." Group discussions then explored broader themes that unify the different topics and point to needs for future work. From this we conclude that: (1) recent work has produced a huge amount of new data and insights into processes of lithospheric rupture, and thus the first generation of MARGINS-funded research in this focus site has been very successful; (2) emerging results have generated new questions that a diverse community of scientists believes are important to address; and (3) this region provides an excellent natural laboratory for tackling such questions. Participants recognized many dynamic links among the topics that were discussed, and it was widely agreed that interdisciplinary research is needed to improve our understanding of the complex systems involved in rupturing lithosphere and creating a new ocean basin.

Summary of Workshop Outcomes

Below we synthesize the workshop proceedings in order to provide guidance to NSF and the community of researchers

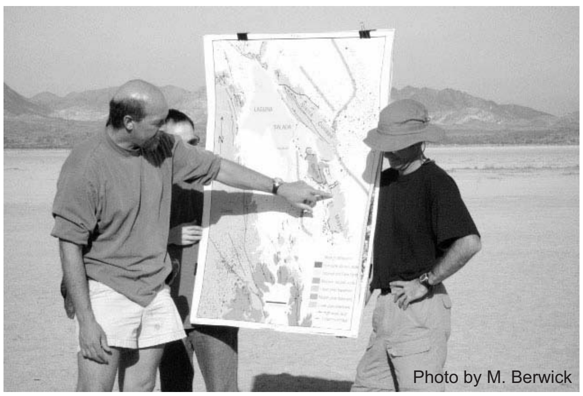

Figure 2. RCL-Cortez Salton Trough field trip photos (Laguna Salada area).

working in this and related areas, and to encourage new researchers to become active in the Gulf of California – Salton Trough focus site. Toward this end, we group the major scientific advances and unresolved problems that were discussed at the workshop into four broad themes: (1) Plate-Boundary Kinematics; (2) History of Strain Localization; (3) Domains of Deformation; and (4) Upper-Mantle Processes. We hope these unifying concepts will help stimulate thinking about underlying processes of lithospheric rupture and motivate future research in this region. Given the volume of material to be covered, we cannot individually recognize personal contributions here, but we thank all who participated and refer readers to the online workshop presentations for more detailed information.

1. Plate-Boundary Kinematics

The plate boundary in the Gulf of California/Salton Trough region formed in response to the southward migration of the Rivera triple junction and subsequent end of subduction along the western margin of the Baja California peninsula around 12-14 Ma. Through an incompletely understood sequence of events, this resulted in the transfer of the Baja California peninsula to the Pacific plate. Today the Gulf of California represents virtually all Pacific-North America (P-NA) relative motion (48 mm/yr). The Baja peninsula presently acts as a rigid microplate, moving slowly (~2-6 mm/yr) relative to the Pacific plate. The modern plate boundary in the Gulf of California and Salton Trough is an oblique rift system with a large component of dextral shear, in which the angle between the overall trend of the rift and the direction of relative plate motion varies from about 15-20° in the south to 30-40° in the north. The obliquity of the active rift is accommodated by short spreading centers linked by long transform faults (Fig. 1).

The global plate circuit requires up to 640 km of P-NA relative motion since ~12.5 Ma. Correlation of volcanic centers across the northern Gulf of California indicates that Baja California has been mostly coupled to the Pacific plate since ~6.1-6.3 Ma, and ~300 km of relative plate motion has been accommodated by opening in the northern Gulf since that time. New seismic data from the southern Gulf reveal ~350 km of opening by extension and seafloor spreading within the Gulf. Additional crustal thinning across the rifted margins in the south may increase the total amount of extension to 450-500 km, though the timing of this extension is uncertain. In the Guaymas basin, ~300 km of extension appears to have been accommodated by nascent seafloor spreading since ~6 Ma.

Substantial uncertainty exists regarding how and where strain was partitioned in the Gulf extensional province (GEP) between ~12.5 and 6.0 Ma. The above observations suggest that the Gulf region evolved in two stages, with a pronounced increase in strain rate in the modern Gulf at about 6 Ma. It seems that the 300 km of post-6.1 Ma P-NA motion inferred for the northern Gulf can be accounted for

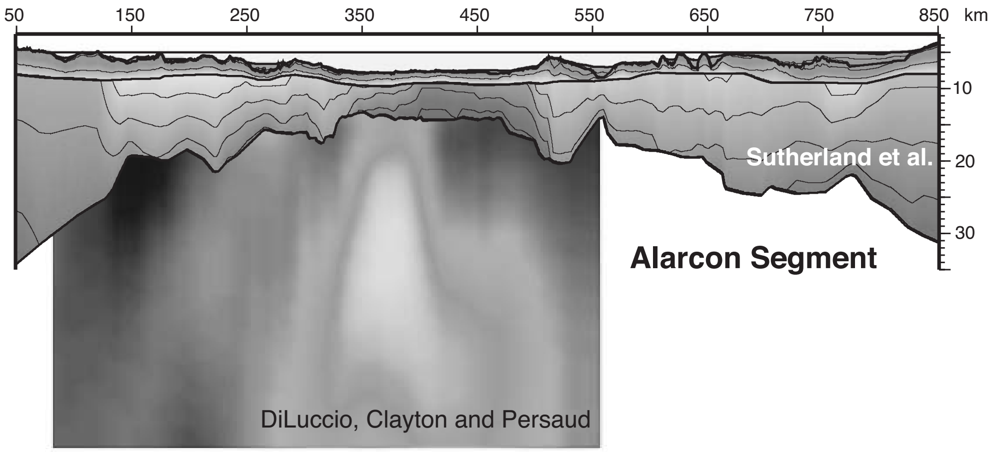

Figure 3. Integrated upper-mantle and crustal cross section from recent work presented at the RCL-Cortez workshop. See http://rcl-cortez.wustl.edu/Presentations.html

in the southern Gulf, though the timing of extension there is not well known. In the Alarcon segment (the most submerged segment of the Gulf), at least 150 km of the remaining 350 km of 12.5-6 Ma P-NA motion is accounted for by extension across the continental margins, as imaged by marine seismics (Fig. 3). Isostatic and gravity modeling suggest that similar amounts of extension may have occurred beneath the continental margins of the Gulf, perhaps accounting for up to ~500 km of post-12.5 Ma relative plate motion throughout the GEP. Recent studies of volcanic rocks in coastal and interior Sonora reveal zones of intense late Miocene dextral faulting and clockwise block rotation, strengthening this suggestion.

The location, magnitude and kinematics of faults that accommodated plate motion during late Miocene time are poorly understood. One hypothesis calls for regional strain partitioning in which much of the dextral motion was taken up by strike-slip offset on the Tosco-Abreojos fault, southwest of the Baja peninsula, while orthogonal NE-SW extension occurred in the GEP. An alternative hypothesis holds that relative plate motion since ~12.5 Ma has been accommodated by a single phase of strain that extends beyond the traditional bounds of the GEP. Resolution of these problems is critical for understanding the history of strain localization, plate boundary forces, and other fundamental controls on lithospheric rupture.

2. History of Rift Localization

Recent structural and geochronologic studies show that there was a long period (~15-20 m.y.) of Basin-and-Range style extension and magmatism in mainland Mexico during late Oligocene to middle Miocene time, prior to relocation of the P-NA plate boundary inboard of the Baja Peninsula. Discussion about the factors that may have caused protracted “unsuccessful” extension included the role of strain rate, slab geometry, thermal structure, and lithospheric strength. The point was made that, while the opening of the Gulf can be viewed as a plate-boundary “jump” related to the transfer of the Baja peninsula to the Pacific plate, it can also be viewed as a localization of strain following a long history of westward migrating extension and magmatism. This idea led to discussion of how the earlier period of extension may have conditioned the lithosphere and influenced the eventual evolution of rifting in the Gulf of California, generating a number of questions: How did pre-12.5 Ma extension and magmatism modify the strength of the lithosphere? What was the role of Pacific/North American coupling in acceleration and localization of strain? Were strain rate and localization related to external boundary conditions (e.g., remnant slab, plate coupling), intrinsic conditions (e.g., increasing temperature, decreasing strength), and/or other factors? What was the effect of the change to more northerly-directed extension and the resultant onset of transtensional deformation at ~12 Ma?

The view of Gulf of California rifting as related to Basin-and-Range extension motivates an assessment of analogies between GEP processes and processes in the Mexican and U.S. Basin-and-Range provinces. New data from Sonora show that volcanic episodes tended to immediately precede deformation episodes, suggesting that strain becomes localized in areas of magmatic heating and weakening of the lithosphere. Comparison of the late Miocene Gulf of California to the modern Walker Lane belt in western Nevada shows that transtensional deformation navigates around large batholiths (e.g., Peninsular Ranges and Sierra Nevada). Both regions reveal a narrow belt of deformation focused at the eastern margin of a large Cretaceous plutonic province. These similarities suggest that a common set of factors and processes may be involved in oblique rifting and ultimate rupture of continental lithosphere.

The record of marine deposition provides useful information about the history of rift localization. Studies of marine micropaleontology enable us to map and date ancient marine incursions in the Gulf-Trough region, which indicate where and when the Earth’s surface was lowered below sea level in response to crustal thinning. It is now known that a narrow marine seaway inundated the entire Gulf of California and Salton Trough by latest Miocene time (~6.0-6.5 Ma), with marine deposits as old as ~8 Ma documented in the southern Gulf. Late Miocene marine incursion appears to record an abrupt increase in strain rate in the Gulf-Trough region at about 6.0-6.5 Ma, but this is a matter of ongoing discussion and debate. At least some of the plate-boundary strain became focused in the Gulf region starting ~12.5 Ma. Reworked microfossils provide indirect evidence for an earlier, middle Miocene marine incursion in the northern Gulf and Salton Trough, but the data for this period are very sparse and incomplete. A complete record of middle Miocene marine deposition is central to our understanding of the early stages of basin evoltuion.

3. Domains of Deformation

New results from active-source seismology provide the first crustal-scale images of continent-to-continent conjugate rifted margins. These images and related onland studies reveal substantial along-axis variations in the geometry and style of extension that can be broadly grouped into 3 to 4 structural domains based on mapped upper crustal features and crustal thinning profiles. Onland, Late Cenozoic to modern low-angle normal faults are found only in the northern Gulf and Salton Trough, where the overall trend of the plate margin is moderately oblique (30°-40°) to the relative plate motion. Within the northern Gulf, deformation occurs in a diffuse system of oblique-normal faults with no evidence for transform faults. This contrasts with the southern two-thirds of the Gulf where faulting occurs on discreet large transform faults linked by short spreading centers (Fig. 1). This first-order difference may be related to the change in obliquity from north to south and/or to the large input of sediment from the Colorado River. It's clear that a significant portion of crust in the northern Gulf and Salton Trough consists of young, voluminous, Colorado River derived, sedimentary and metasedimentary rock. This young crust is strongly affected by rapid burial, high heat flow, and associated mafic to rhyolitic magmatism. Consequently, crust in the Gulf of California is thickest in the north (up to ~20 km) and decreases to as little as 7 km in sediment-starved southern basins.

The Guaymas basin and perhaps the northern Gulf seem to have ruptured in a narrow-rift mode, with spreading and new igneous crust formation beginning ~6 Ma. There is controversy, however, concerning the origin of igneous crust at depth in the northern Gulf. Some workers infer that this crust consists of Cretaceous plutons that have experienced lower-crustal flow during large-magnitude stretching. Others suggest that the crust is entirely new (post-6-Ma) igneous crust overlain by sediment and metasedimentary rock. This problem is central to our understanding of lithospheric rupture in this area and to our understanding of "transitional" crust at other rifted margins as well as the efficacy of lower-crustal flow in general. In the southern Gulf, seismic results reveal that the Alarcon basin segment deformed in a wider rift mode (Fig. 3), with rupture and formation of new igneous crust beginning at ~3.5 Ma. Based on seafloor morphology, it appears that the Farallon, Pescadero, and Carmen segments between Alarcon and Guaymas rifted in a mode similar to Alarcon. This morphology and other similar characteristics suggest a north-central domain that shares characteristics of both the northern and the south-central segments. The southernmost segment at the mouth of the Gulf represents a distinct domain characterized by narrow, amagmatic rifting.

The along-axis variability in crustal-scale deformation is unexpected, since the commonly assumed primary forcing functions of extensional style – strain rate, rheology, and mantle temperature – ought to be more or less constant throughout the Gulf of California. The underlying controls on this variability thus remain unknown and require further study. Relevant factors likely include rift obliquity, strain rate, lithospheric strength and composition, disposition of the remnant slab, mantle-wedge metasomatism, and history of arc magmatism. Voluminous sediment in the Salton Trough, northern Gulf, and Guaymas basin plays a major role in the production of post-6 Ma crust, but the nature of its control on crustal rheology, styles of faulting, and spatial variations in rift architecture remains poorly known. Numerical models predict that heating and weakening should localize strain, so we might expect that thick sediments would trap heat, reduce the strength of the lithosphere, and form discrete localized lithosphere-scale faults. However, the observation of diffuse, distributed upper-crustal deformation in the thickly sedimented northern Gulf suggest the opposite. Thus the Gulf of California – Salton Trough focus site provides a unique opportunity to explore the role of large sediment input in controlling crustal composition, thickness, rheology, and architecture of rifted continental margins and nascent ocean basins.

The modern expression of faulting and related basin formation in the Gulf of California is in many respects asymmetric. Active strain is presently focused along the steep southwestern margin of the Gulf, whereas the relatively inactive northeast side has a broad shelf and low topographic gradients. Spreading rates at the spreading centers indicate that the margins have moved into the "passive" stage of development. Asymmetry exists in part because the center of extension shifted to the northwest in most rift segments at about 3.5 Ma, resulting in an overall westward shift throughout the Gulf. The causes, timing, and synchronous versus diachronous nature of this westward shift are not well known.

4. Upper Mantle Processes

Upper mantle processes clearly play an important role in the history and mechanics of faulting and basin evolution in the Gulf-Trough region. For example, the prolonged period of Basin-and-Range extension, and its westward sweep toward the margin, was probably influenced by the depth and condition of the Farallon slab. It is likely that the slab continued to control rifting after it stopped actively subducting. Possible slab windows may explain some of the observed NW-SE variation in rift architecture.

Studies of upper mantle structure, fabric and state will provide an important next step in understanding the dynamics of this rift system, and exciting new results are already emerging. Recent shear-wave splitting studies using data from the NARS-Baja and other broadband seismic arrays reveal NE-SW to ENE-WSW anisotropy beneath mainland Mexico. These directions may reflect present-day absolute motion of North America, or could be inherited from now-inactive Miocene extension. E-W directions beneath the Baja peninsula are similar to patterns seen in southern California and appear to record asthenospheric flow related to removal of the subducted Farallon slab. Preliminary tomographic analyses reveal the first images of lithospheric-asthenospheric structure beneath the active rift. A low-velocity anomaly beneath the Peninsular Ranges may be related to delamination and sinking of dense lower lithosphere and associated upwelling of asthenosphere. Regional uplift related to dramatic thinning and/or heating of lithosphere beneath the Peninsular Ranges may have begun as recently as 1.0 to 1.5 Ma, but the timing and cause of this recent uplift event are not well known.

The NARS-Baja array has considerable potential, but the existing array is too widely spaced to accurately locate earthquakes within the Gulf of California. In contrast, results from the Salton Trough reveal the evolution of an earthquake swarm on a single fault system that was precursory to a major slip event. Denser deployments of passive seismic stations can address questions ranging from mantle dynamics and state to upper-crustal stress relief and deformation. Small dense OBS arrays are currently deployed in the Gulf in Guaymas and Alarcon basins, but a Gulf-scale passive OBS deployment would enable detailed imaging of lithosphere-asthenosphere geometry, disposition

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of the relic slab and slab windows, and many other targets that would shed considerable light on the fundamental processes controlling lithospheric rupture in this focus site.

Concluding Remarks

The above summary is our attempt to synthesize some of the main topics and ideas that were discussed at the workshop. Any summary of this nature cannot include everything, and we recognize that we may have missed topics of interest to some participants. It is clear that emerging data from this focus site are providing remarkable new insights into processes of oblique rift formation, continental rupture, and plate-boundary deformation. There was a strong consensus that future research is needed to continue the success achieved to date and address new questions of broad global significance. This document does not attempt to prescribe specific direction for future research, but hopefully provides a useful overview of workshop outcomes that can be used in future planning and steering of the MARGINS-RCL initiative.

Some examples of research and data needs:

- Passive seismics in the Gulf of California
- Hi-resolution fault and basin imaging in the southern Gulf of California
- Mapping, dating, and kinematic analysis of onland faults and basins
- Geodetic studies of modern strain partitioning and elevation change
- Paleo-elevation studies
- Geophysical studies onshore in the northern Gulf, Salton Trough, and Sonora
- Ocean drilling
- Reconstruction of large volcanic units across regions of uncertain fault offset
- Micropaleontology to track and date marine incursions
- Isotope and trace-element geochemistry of volcanic rocks
- Tectonic geomorphology and paleoseismology to document Quaternary faults and slip rates
- Acquisition/compilation of regional potential field datasets

Examples of modeling efforts needed:

- Community models for paleogeography through time
- Numerical models of lithospheric extension
- Integration of strain recorded over three time scales along multiple transects