PS Gravity and Geodynamic Modeling of the Gulf of California*

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Abstract

The Gulf of California is a young sheared margin that began rifting about 12 million years ago. It is characterized by substantial differences in extensional style and sediment thickness between the northern and southern part, and details of margin structure, the northward extent of oceanic crust, and sediment thickness are debated. We have constructed two-dimensional cross-sections from gravity data to understand the continent-ocean transition, thickness of the sediment layer, and crustal structure beneath the Gulf of California. We used geophysical and geological data from previous studies in the area to constrain our models. The 2D gravity models show the cross-section of the basin and crustal structure of the segments including the new oceanic crust formed in the southern Gulf, highlighting the difference not only between the northern and southern parts of the Gulf but also the dissimilarity of rift widths between adjacent segments. The gravity models differ to some extent from earlier seismic cross sections in terms of margin (a)symmetry, structure and sediment thickness. We propose that rupture of the Gulf of California rapidly followed pull-apart basin formation. 3D geodynamic crustal models of pull-apart basin formation were constructed using the general purpose finite element package Abaqus to demonstrate that a situation favorable for continental breakup develops rapidly when the segments of the strike-slip faults overlap and tensional stresses rotate to become perpendicular to the strike of the master faults.

Our numerical models show how the new spreading centers of Gulf of California may have formed within a short period of geologic time. A modified evolutionary model for pull-apart rift formation includes an hour glass-shaped basin that represents an intermediate stage of pull-apart basin development.

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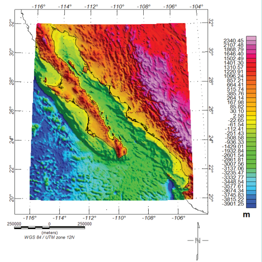
Abstract

The Gulf of California is a young sheared margin that began rifting 12 million years ago. It is characterized by differences in extensional style and sediment thickness between the northern and southern parts, and details of margin structure, the northward extent of oceanic crust and sediment thickness are debated. We have constructed two-dimensional cross-sections from gravity data using Geosoft montaj/GM-SYS software to understand the continent-ocean transition, sediment thickness and crustal structure beneath the Gulf of California. We used geophysical and geological data from previous studies in the area to constrain our models. The 2D gravity models show the cross-section of the basin and crustal structure of the segments including the new oceanic crust formed in the southern Gulf, highlighting the difference not only between the northern and southern parts of the Gulf but also the dissimilarity of rift widths between adjacent segments. The gravity models differ to some extent from earlier seismic cross sections in terms of margin (a)symmetry, structure and sediment thickness.

Moreover, 3D geodynamic crustal models of pull-apart basin formation were constructed using the general purpose finite element package Abaqus. We demonstrate that a situation favorable for continental breakup develops rapidly when the segments of the strike-slip faults overlap and tensional stresses rotate to become orthogonal to the strike of the master faults. Our numerical models show how the new spreading centers of Gulf of California may have formed within a short period of geologic time.



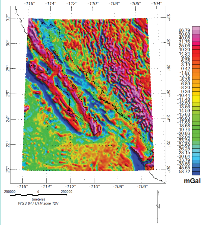
Topography/Bathymetry of the GoC

Brief Geologic and Tectonic History of the Gulf of California

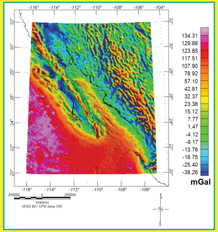
The Gulf of California is a young oblique rift system with long transform faults connecting short spreading segments. Rifting in the gulf began around 12 million years ago with the termination of the subduction of the Farallon plate. As the East Pacific Rise (EPR) approached the palaeo-trench, the subducting Farallon plate broke into a number of microplates; as subduction stalled, those microplates and the Baja California peninsula coupled to the Pacific plate, resulting in the onset of rifting and eventually the modern plate boundary within the Gulf of California in the vicinity of the former arc. The peninsula now moves nearly completely with the Pacific plate, with 48mm/yr of spreading across the Gulf of California. The relative plate motion is now almost entirely accommodated in the Salton trough and the Gulf extensional province.

Post–3 Ma magmas in the southern Gulf of California are largely tholeiitic basalts, and their associated vents are confined to the axes of en-echelon basins separated by NW-SE–trending right-lateral transform faults. Toward the mouth of the Gulf of California, there is clear evidence from magnetic striping for seafloor spreading in the Alarcon rise, whereas basins in the northern GoC are blanketed by thick deposits of sediments, which impede geomagnetic verification of oceanic spreading.

Data and Methodology



Free Air Offshore-Bouguer Onshore Anomaly

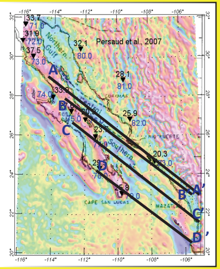


Bouguer Anomaly

The EGM08 Free Air anomaly data from International Gravimetric Bureau (BGI) has been processed up to the Bouguer correction using a value of 2.67 g/cc. Seismic refraction data (Persaud et al., 2007; Phillips, 1964) have been used to constrain the moho depth and sediment thicknesses. In addition, seismic reflection study (Lizzaralde et al., 2007) has been used to constrain the crustal layers beneath the various basins in the Gulf of California.

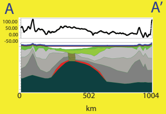
The gravity data are projected to X and Y coordinates on UTM 12N. The differences between the model response and the observed gravity field are reduced by refining the model structure and/or density.

Results and Discussion



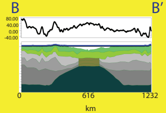
The transects in the southern GoC are shown in this figure. Moreover, the location of the refraction control stations (Persaud et al., 2007) are depicted on the gravity data.

Layers	Density
Unconsolidated sediments	2.2 g/cc
Consolidated sediments	2.3 g/cc
Upper crust	2.7 g/cc
Middle crust	2.8 g/cc
Lower crust	2.9 g/cc
Mantle	3.3 g/cc



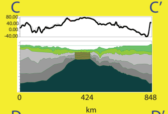
Guaymas

Guaymas is a narrow volcanic basin with an over 5-km-thick oceanic crust. There are also igneous intrusions with a high gravity anomaly at both sides of the margins at about 90 km and 907 km on the transect. There is a dense, high-velocity lower crustal body, possibly a magmatic underplating, under the basin. The continent-ocean transitions look asymmetric with widths of ~ 120 and ~230 km.



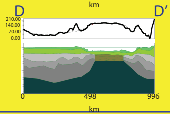
Farallon

This basin has almost 200 km wide, 6-km-thick oceanic crust. The continent-ocean transitions are symmetrical with a length of ~ 270 km.



Alarcon

Alarcon is a wide rift with an oceanic crust ~ 5 km thick. Here also, the transitions seem symmetrical with ~ 170 km width. Moreover, there is a ridge jump and continental crust thinning at the Tamayo trough (at about 510 km on the model).



San Jose del Cabo to Puerto Vallarta

This southernmost transect has produced ~ 220 wide, ~ 6 km thick oceanic crust. Like most of the segments, igneous intrusions seem to exist in the continent-ocean boundary. The transitions in this basin also look long and symmetrical, having a width of about 300 km.

Summary

The 2D gravity models show the cross-section of the basin and crustal structure of the segments including the new oceanic crust formed in the southern Gulf.
In addition, the 2D models highlight the dissimilarity of rift widths between adjacent segments and the continent-ocean transition. Our 2D gravity models show a ridge jump in the Alarcon segment, and magmatic underplating below the Guaymas basin.

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Overview

Pull-apart basins are topographic depressions formed as a result of crustal extension associated with either right-lateral right-stepping or left-lateral left-stepping en-échelon strike-slip fault systems. The purpose of this study is 1) to understand the role of strike-slip fault separation and length of overlap on the development and evolution of pull-apart basins, 2) to understand how the evolution of pull-apart basins leads to rapid continental break-up, and 3) to understand how pull-apart basin flank uplift develops. ABAQUS, which is a general purpose finite element software package, is used to simulate the evolution of pull-apart basins in three dimensions.

Model setup

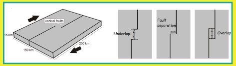

Figure 1. Model setup. Master strike-slip faults cut through the entire upper crustal model domain. Black arrows denote direction of plate motion, prescribed as velocity boundary conditions at the left and right sides of the model domain.

The models consist of a brittle upper crust which is 15 km thick. A series of strike-slip faults cut the entire brittle crust. The faults are defined as 100-m-wide shear zones along which displacement is allowed parallel to the fault plane in both horizontal and vertical directions. The crust has an elastic rheology with Young's modulus of 70 GPa, density of 2700 kg/m3, and Poisson's ration of 0.25. The finite element model is discretized by 60,000 tetrahedral elements. All the models are set up with uniform dimensions with a length of 150 km and a width of 200 km. Velocity boundary conditions are prescribed to the left and right sides. Parameters such as fault overlap and separation are varied.

Results and Discussion

Vertical displacements predicted by the models are compared and analyzed to study the effects of fault separation and overlap on subsidence, depocenter migration, and uplift of basin flanks. In all models, master-fault parallel movement of the tectonic plates results in the formation of depressions (depocenters, or pull-apart basins) on the inside of the step-over, and flank uplift at the outside fault tips.

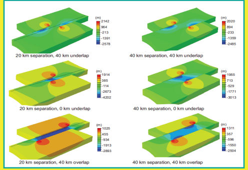

Figure 2. Predicted uplift and subsidence after 5 million years of model evolution. Blue colors indicate depressions (basins); red colors indicate uplift. Initial fault geometries are indicated.

Results and Discussion (cont.)

In the 20-km fault separation models, separate depocenters form at the ends of the master faults when the faults underlap. With continuing fault overlap these dual depocenters connect, and one pull-apart basin develops with a center deep. When a fault overlap exceeds fault separation, an elongated rhomboidal-shaped pull-apart basin forms. Similar models with 40-km fault separation show the development of more pronounced dual depocenters which can be recognized even after considerable fault overlap. In all tested models of fault separation, most subsidence is observed for no underlap/overlap geometries. Flank uplift is predicted in all models with two strike-slip faults. This uplift occurs along the entire pull-apart basin, but is largest in amplitude near the fault tip. Here, the underlap geometries result in maximum uplift of the flank.

The elongated rhomboidal-shaped pull-apart basin that is bounded by strike-slip faults experiences localized orthogonal extension. This orthogonal extension takes several million years to develop in our models, dependent on the relative velocity of the crustal blocks and the amount of fault overlap. It would thus take several million years of pull-apart basin formation to evolve into a setup favorable for continental breakup.

Sheared or transform margins form when the extension direction is highly oblique or transform. During this phase of continental deformation, a master strike-slip fault system develops that is discontinuous, consisting of multiple shorter segments that may be arranged en echelon.

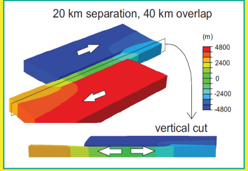

Figure 3. 20-km separation, 40-km overlap model. The vertical transect through the pull-apart basin shows deformation in opposite directions (indicated by white arrows).

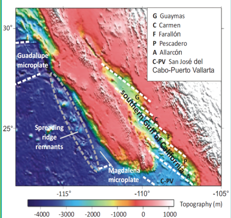

Figure 4. Topography of the southern Gulf of California region. Indicated are transform faults of the Gulf of California spreading ridge and rift system, remnants of the Guadalupe and Magdalena microplates, and the extinct spreading ridges between the microplates and the Pacific plate. Dashed white lines indicate transform faults and fracture zones.

The first stage is the continental rift stage during which pull-apart basins form at discontinuities in the strike-slip fault system. With ongoing extension and overlap of the master faults, stresses rotate in between the master faults, and a configuration favorable for rupture is achieved (stage 2). The crustal region that has been rifted varies, depending on the geometry of the discontinuity. After breakup, short spreading segments are linked by long transform faults and fracture zones. At this young margin stage (stage 3), the initial length of the spreading centers corresponds to the separation of the continental master fault segments, and the continental rift/fault geometry is inherited. The margin subsequently matures by thermal cooling, subsidence and sedimentation, and the continent-ocean boundary of the resulting sheared margins (stage 4) is often zigzagged with transform segments alternating with rifted segments .

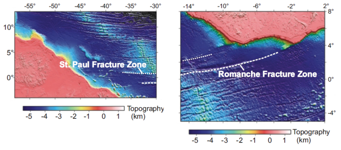

Figure 5. Topographic map of the Atlantic equatorial region of South America (left) and Africa (right). St. Paul (white dots) and Romanche Fracture Zones (white dashed line) are indicated. The edge of the continental shelf shows a zig-zag pattern, whereby corners correspond to continent-ward continuations of fracture zones.

Transects across sheared margins may show a sudden transition from undeformed continental crust to oceanic crust at transform. Here, the zone of crustal stretching is very narrow and the continent-ocean boundary is sharp. Transects that cross older pull-apart rifts intersect a wide zone of deformed and stretched continental crust and possibly remnants of transform faults. Transects parallel to the transform faults are expected to show some asymmetry in crustal deformation. This results from the asymmetric pull-apart basin development between the fault tips.

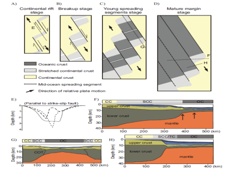

Figure 6. Evolutionary stages of sheared margins (A-D) modified after Mascle and Blarez (1987) and transects from numerical models (E), Gulf of California (Lizarralde et al., 2007, G), French Guiana (Greenroyd et al., 2008, F and H).

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