Evolution Of Deformation During Oblique Rifting: Insights From Lithospheric-Scale Analog Models

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Oblique rifting, when the relative motion between two rigid plates is oblique to the deformation zone, results in a complex rift kinematics which is a combination of strike-slip and dip-slip motion. Rifting obliquity results in composite fault patterns, made of en-echelon fault systems with dip-slip and/or oblique-slip kinematics and variable orientation with respect to the stretching vector. Natural examples (such as the Main Ethiopian Rift, East Africa) show that oblique rifts are characterised by complex fault evolutions, with diachronous activation of different fault sets. In this contribution, the complex evolution of deformation resulting from oblique rifting is investigated through lithospheric-scale centrifuge models. Following the experiments by Corti (2008), the models are deformed in a large-capacity centrifuge and reproduce the upper 50km of the continental lithosphere (crust + upper lithospheric mantle) floating above a low viscosity material simulating the asthenosphere. To produce oblique rifting conditions, the models are characterised by a central zone of weakness, generated by a local increase in thickness of the crust; the trend of this weakness with respect to the extension direction is varied in different experiment, to reproduce different obliquity angles (i.e., angle between the orthogonal to the rift trend and the direction of extension), from 15° to 75°, at increments of 15°. The experiments also simulate the accumulation of sediments during progressive subsidence of the rift zone. Model results show complex fault evolution, which is mostly controlled by the obliquity angle. For obliquity <45°, there is a two-phase rift evolution, with diachronous activation of differently-oriented fault systems. The initial phase of rifting is characterised by activation of large boundary faults, which border a subsiding rift depression. Boundary faults are en-echelon arranged, and –as a group- they follow the orientation of the weak zone (i.e., they are oblique to the orthogonal to the extension direction). No deformation affect the rift depression during these initial stages of deformation, although marginal grabens form close to the boundary faults. Increasing extension results in the abandonment of the boundary faults and the development of faults within the rift depression (internal faults). These faults are orthogonal to the direction of extension and arranged in en-echelon segments that link with the boundary faults, resulting in sigmoidal fault zones. Obliquity of 45° still results in a two-phase rift evolution, although boundary fault activity is strongly reduced and deformation is soon transferred to the internal faults affecting rift depression. The orientation of boundary faults is still sub-parallel to the weak zone, whereas internal faults becomes oblique to the orthogonal to the direction of extension. For high obliquity (>45°), the dominance of the strike-slip component of motion over the extensional one, leads a different evolution and pattern of deformation. In this case, boundary faults do not form and the extensional deformation affects the rift depression since early stages of extension. The pattern of deformation is dominated by oblique-slip faults accommodating the (mostly) strike-slip deformation. The above results suggest that rift obliquity plays a major role in controlling rift evolution and architecture. These findings may have relevance for natural oblique rifts, such as the as the Main Ethiopian Rift in East Africa

(see Corti, 2008). There, two different sets of faults diachronously developed during extension: a system of late Miocene-Pliocene N30°-45° boundary faults and a set of Quaternary N0°-15° normal faults. These latter faults form the Wonji Fault Belt, a system of en-echelon, sigmoidal fault systems obliquely affecting the rift depression. Complex models invoking a change in rift (and plate) kinematics or magmatic processes have been applied to explain the two-phase rift evolution. The above model results suggest that a simple tectonic scenario may account for such a complex fault evolution and architecture. Modelling suggests indeed that the diachronous development of boundary faults and Wonji Fault belt may have resulted from a constant Late Miocene-rec ent ~N100°-directed extension phase. These findings well agree with both geological and plate kinematics data (see Corti, 2008). The model results have a general relevance and can be applied to other oblique rifts worldwide (e.g., Gulf of California), which may have experienced similar complex deformation histories driven by simple kinematics. Corti G.; 2008: Control of rift obliquity on the evolution and segmentation of the main Ethiopian rift. Nature geoscience, 1, 258-262

Thinning Of The Crustal Thickness Along The North Limit Of The Jalisco Block, Determined By Magnetotellurics

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The Jalisco Block (JB) is a tectonic unit in western Mexico limited by rifts to the north and east. In this work we try to show that rupturing of the continental lithosphere in the northern portion of the JB is accompanied by a thinning of the crustal thickness. The northern limit of the JB is commonly defined as the Tepic-Zacoalco rift, or graben, which extends along 216 km in the WNW-ESE direction from the coast of Nayarit to close to Chapala Lake. We reported recently results from a magnetotelluric (MT) survey along the N-S portion of the coast of Nayarit suggesting that at the NW end of the Tepic-Zacoalco rift the crustal thickness reaches a minimum. Herein we incorporate a second MT transect, 30 km to the east of the former transect, confirming the observed thickness decrement in the rifted region. Results from a seismic study, performed elsewhere, help constrain the interpretation of the resistivity derived from the MT survey to depths of 30-35 km; the seismic results s uggest that the crustal thickness decreases along a line that runs from Cabo Corrientes north to the NW portion of the Tepic-Zacoalco graben. At Cabo Corrientes the crustal thickness is ~28 km, whereas at the minimum thickness region, the rifted portion, the MT results suggest that thickness decreases to ~14 km. The second MT transect crosses the rift along a line that goes through Tepic and reaches to Aguamilpa dam, fed by the Río Grande de Santiago; the region of minimum crustal thickness is more clearly observed here, since the end of the transect shows a tendency of the crust to thicken where it penetrates Sierra Madre Occidental terrain; the width of the region determined by the two transects varies from ~20 to ~36 km and is densely populated by volcanic structures. Station separation defines the accuracy with which one can determine the width of the region of minimum crustal thickness at a given location; since this is a preliminary reconnaissance study, station separa tion at present ranges from 15 to 20 km, and thus we estimate an error of ±5 km in the location of each limit. Precision can obviously be improved by making denser the number of stations along the minimum thickness region. These results suggest that it is now possible to define the width of the rifted region not only on the basis of its topographic and surficial geological characteristics, but also on the thickness of the crust at those locations. With this methodology several questions regarding the west and east limits of the JB can be addressed, including the identification of another rift at the NW portion of the Jalisco Block, as well as determining their cortical characteristics.

Active faulting, sedimentation, and landscape evolution along a rift in a tropical monsoonal setting: Cabo fault and basin, Baja California Sur

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Studying the largest active fault and sedimentary basin exposed on land along the southwestern margin of the Gulf of California (the San Jose del Cabo Fault), adjacent footwall range (Sierra la Laguna), and the upper part of the associated hanging wall (San Jose del Cabo Basin) contributes to understanding the tectonic, surficial, and sedimentary processes active during the rift to drift transition along oblique-divergent plate margins. The fault system of the La Paz-Los Cabos region is an active left-stepping normal fault array with major offshore components. We are developing an integrated study of the topographic and basin development and sedimentary systems associated with active rifting in a setting of highly variable tropical storm-driven precipitation. Our research further north along the fault array, in which we have made detailed strip maps along the active faults and paleoseismological trench investigations with Optically Stimulated Luminescence age control, shows t hat the faults are slipping at 0.1 to 0.5 mm/yr. Along the San Jose del Cabo fault, we expect similar or slightly higher slip rates. In addition to the detailed characterization of the active fault zone, we have begun using geomorphic indices such as local relief and slope area scaling to show steeper middle and upper channel reaches consistent with westward footwall tilting. Gravity surveys indicate that the San Jose del Cabo Basin may be as deep as 3 km This project is built upon testing three hypotheses that have global implications for rupturing of continental lithosphere: (1) Faulting has continued along the plate margin after sea-floor spreading initiated, but at reduced rates driven mainly by the 3-5 km relief in topography formed during earlier rifting from the rift escarpment (Cabo fault footwall) to the spreading ridge. (2) The early rift basin sedimentary record is driven by tectonics (faulting & isostasy) with climate as a modulator, because footwall uplift enha nces erosion that is further enhanced by tropical storms, which results in an overfilled basin and bypass to the offshore marine. (3) Slowing of faulting at initiation of sea floor spreading dampens the positive feedback of uplift-erosion-storms, but slowing subsidence keeps basin filled; this system and sedimentary record are climate driven with minor tectonic modifications. A jump of faulting to the offshore as well as the slowing faulting has resulted in moderate uplift of the Cabo basin and left us with a superbly exposed record of the Quaternary history of the basin.

Law of the Sea: Considering the U.S. Margins

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Under the United Nations Convention on the Law of the Sea (UNCLOS), the United States would have the opportunity to delimit regions of extended seabed rights, consistent with international law, beyond the current 200 nautical mile U.S. Exclusive Economic Zone (EEZ). Although the United States has not yet acceded to UNCLOS, work has begun to assess the existing geophysical and geological data sources as well as the various scientific strategies that might be applied to a U.S. extended continental shelf (ECS) submission under Article 76 of this Convention. Significant portions of the U.S. margin have been preliminarily identified, in a Congressional Report published by the University of New Hampshire (Mayer et al., 2002), as having conditions for which an ECS submission might be made. These areas include portions of the U.S. Atlantic, Gulf of Mexico and Arctic passive margins, each of which involves a geologic framework shaped by a history of rifting continental lithosphere. Identified areas also include portions of the U.S. Pacific and Bering Sea margins, such that the U.S. Law of the Sea analysis will also involve margin settings shaped by convergence, transform tectonics, and even volcanic construction. Analysis of bathymetric data, morphologic and stratigraphic relationships, sediment thickness, crustal structure and potential field signatures may each play a role in the development of any prospective U.S. submission.

Continental fragmentation, lost Indian lithospheric roots and Deccan volcanism

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A recent seismic study (Kumar et al. Nature,449,894,2007)allowing unprecedented accuracy determined the thickness of the Indian lithosphere at 100 km, less than half the thickness of similar cratons. The cause of this thinness is proposed to be due to ponding beneath the craton by the plume material and thermal thinning of the lithosphere. This paper provides isotopic, geochemical and geochronological evidence for the remnants of the lost Indian lithospheric roots in the lower lava sequence of the continuous 3 km thick Deccan Traps in the western fragmented margin of the Indian craton. The combined major, trace element and isotopic ratios of Nd,Sr,Pb and Hf of the entire 3Km thick Western Ghats volcano-stratigraphic section of the Deccan , all acquired in our laboratory, can be interpreted to indicate the following. The upper sequence , especially the Ambenali formation is a product of low degree(16%) batch melting of the Reunion plume. The lower formations , such as Jawhar-Igatpuri to Bushe , are higher degree partial melts of eclogites that formed the roots of the craton by ancient subducted oceanic crust. The trace element geochemistry of these lower formations can be modeled by higher degree partial melting of eclogites. The isotopic characteristics of the lower formations , in addition, are indicative of the inherent characteristics of their heterogeneous sources, which are a composite of an ancient processed cratonic mantle root comprising metasomatized mantle peridotite and eclogitized oceanic crust. These sources provide a Pb-Pb isochro n age of ~ 2.6 Ga, as measured in the lower lava sequence of the Deccan in the Western Ghats. This age, interestingly, is the average age of the Archean Indian craton. Upon the arrival of the Reunion plume at the base of the Indian lithosphere these roots were incorporated in the ascending plume head. At shallower levels they melted to a higher degree, thus thining the lithosphere , and erupting to form the lower formations of the Deccan.

Influence of magmatism on rift initiation

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Over the last two decades increasing geologic and geophysical evidence has been collected indicating that most rifts and rifted continental margins are affected by massive basaltic intrusions and/or volcanic outflows. These observations may help to resolve a fundamental paradox in understanding of lithosphere rupture—namely that the tectonic force required for amagmatic extension is up to an order of magnitude greater than the force available for rifting. In this talk, I will show the results of new numerical models that incorporate the thermal and mechanical effects of magma intrusion during lithospheric stretching. We quantify the minimum volume of magma that is required to initiate rifting as a function of lithospheric thickness, stretching rate, and the available tectonic force. Our results show that relatively small amounts of magmatism can facilitate the rupture of thick, cold lithosphere, however, after rupture rifting can proceed with little or no additional input of magma. These results are consistent with the observation that much of the magmatism associated with rifting occurs immediately before or during the initiation of the rift.

Time and length scales of dike intrusions and associated faulting in the ongoing Afar rifting episode

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Although dike intrusions achieve plate opening along mid-ocean ridges and during continental rupture, the time and length scales of the intrusion process are poorly understood. Likewise, the role of dike intrusion in the creation of rift zone morphology, including faulting above and ahead of propagating dikes, is only loosely constrained by laboratory models and a few rare rifting events. Our temporary broadband seismic array deployed in the highly evolved Afar rift, Ethiopia recorded tectonic and low-frequency earthquakes associated with the ongoing diking activity in the region. Seismicity data March -December 2007 is analyzed to get an insight into these processes. In addition to the high levels of background seismicity, two large dike intrusions occurred in 2007: 12-13 August with a fissural eruption, and 11-13 November. Earthquakes were relocated using the double-differencing technique. Earthquake epicenters are located in a ~45-km long, 3km-wide zone at the southern end of the 60 km-long rift segment that opened in September 2005. The previously active northern end of the segment around Dabbahu volcano and the 2005 eruption site is now aseismic. The epicentral distribution shows a 2 km westward shift relative to the 2006 activity. The 3D distribution also shows a similar southward decrease in depth with most of the deepest events in the central part of the segment. The low-frequency volcano-tectonic earthquakes analyzed separately show a clear northward dike propagation direction, which is away from the largely aseismic eruption site. The November event comprised at least two discrete dike intrusions, each of which was preceded by tectonic earthquakes, followed by low-frequency earthquakes that propagated southward. We use seismicity, remote sensing and geodetic data to refine the dimensions and rates of dike emplacement both vertically and laterally, to identify magma source regions, and to understand the interaction between dikes an d brittle faulting within the regional tectonic context of an incipient spreading center.

Post-rifting relaxation processes in the Afar region (Ethiopia) from GPS measurements and numerical modeling.

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Accelerated deformations after major dike intrusion events such the 1975-1985 Krafla events in Iceland and the 1978 Asal-Ghoubbet events in Afar have been interpreted as the result of stress relaxation in a viscoelastic lithospheric mantle and/or continued magma injection. Separating these contributions, estimating mantle viscosity and quantifying the interaction with long-term stretching have however proven difficult in the absence of geodetic measurements immediately following the main dike intrusion. In September 2005, a 60km-long dike intrusion took place at the Dabbahu rift, Afar, Ethiopia, at the boundary between the Nubian and Arabian (Danakil) plates. Since this major event, 10 new intrusions have affected the central and southern parts of the 2005 dike. In order to measure post-diking deformation, we installed 19 continuous stations in the near-field of the 2005 intrusion and 20 survey sites in the mid- and far-field. Time series from continuous GPS stations outside of volcanoes show a combination of discrete diking events and quasi-constant velocity displacement. Continuous GPS stations on volcanoes show non-linear behaviour related to the feeding of shallow magma chambers. Survey GPS sites in the far-field (up to 150km from the rift) show current extension rates twice as fast as the secular divergence rate between Nubia and Arabia. We present the GPS results and propose a model that accounts for the combination of dike intrusions and viscoelastic stress relaxation in the upper mantle below Afar. We use a 3D elasticviscoelastic model with a constant crustal thickness of 17km and layered elastic properties derived from existing refraction experiments and recent seismic tomography. We use a Newtonian viscosity which we vary to minimize misfit to the data. The best fit is found for a viscosity of 4*1018 Pa.s. Residuals displacements are small but show a pattern that could be explained by the presence of melt reservoirs located below Ado Ale, Dabbahu and Gabho volcanoes, not accounted for in the model. Future work will involve testing a stress-dependent viscosity, accounting for known lateral variations in crustal thickness across Afar, and incorporating the magma chambers behavior.

Onset of transtensional rifting in the northern Gulf of California: Structural, Stratigraphic, Geochronologic, and Paleomagnetic constraints from coastal Sonora, Mexico

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Existing tectonic models differ as to when Baja California began to obliquely rift away from mainland Mexico. Addressing this problem is important for understanding how transtensional rifting may lead to successful rupture of continental crust. We conducted an integrated structural, stratigraphic, geochronologic, and paleomagnetic study of middle Miocene to Pliocene rocks associated with strike-slip faulting in coastal Sonora. Here, both the NW-striking, dextral Bahía de Kino and Sacrificio faults onshore appear to be linked to transform faults offshore (e.g. the De Mar fault) that accommodated Gulf opening. We mapped extensional basins overlying crystalline basement and middle Miocene andesitic rocks in a 160 km2 coastal region north of Bahía de Kino. Basins are floored by thick (>100m), high-grade deposits of the Tuff of San Felipe (Tsf), and contain thin (<20m) deposits of the Tmr3 cooling unit of the Tuffs of Mesa Cuadrada (Tmc) near their bases. Samples from these tuffs yielded ages of 12.50 ± 0.08 Ma and 6.39 ± 0.02 Ma, respectively, consistent with their ages determined from deposits in Baja California that now lie offset >250km across the Gulf. In coastal Sonora, modern-Gulf strata chiefly overlie Tmc and consist of non-marine conglomerate (Tcg) despite proximity of these basins to the Gulf of California. Pre-extension volcanic rocks in coastal Sonora are tilted to the east up to 90° and are bounded by N-striking normal faults. These normal faults and basins are typically cut by (1) sub-vertical NW-striking dextral faults and their conjugate NNE-striking sinistral faults, and (2) low-angle detachment faults with WNW-directed extension. These dextral and detachment faults may be coeval, simultaneously accommodating NW-directed transtension associated with the Pacific-North American plate boundary. Fault kinematic data are consistent with NW-directed transtension throughout the studied section. Tcg is dominated by debris-flow deposits with some sheet flood deposits, both interpreted to record deposition in an alluvial fan environment. Thicker sections of Tcg (>470 m) are found adjacent to the Punta Chueca fault, a large-scale NW-directed low-angle normal fault, that produced more extension and subsidence than other modern-Gulf faults in this region. After correcting for bedding dips and vertical-axis clockwise rotations determined from paleomagnetic analysis, restored paleocurrents in Tcg reveal consistent overall transport to the SSW. We interpret Tcg to record deposition in a 10- to 20-km wide coastal belt of coalesced alluvial fans (bajadas) that formed on the margin of the nascent northern Gulf of California. We obtained a SHRIMP 206Pb/238U weighted mean age of 6.53 ± 0.18 Ma (n=14; MSWD=1.3) on zircons from the newly discovered Tordillo Tuff (Tt). Tt is 80 m above the base of Tcg and 160 m below Tmc, yielding a sedimentation rate of 0.8 ± 0.2 mm/yr for lower Tcg. This isotopic age constrains the timing of basin initiation in coastal Sonora at ca 6.6 Ma. Utilizing a new reference vector for Tsf from stable Baja California, paleomagnetic remanence directions measured in Tsf in coastal Sonora

indicate variable amounts of clockwise vertical axis rotation from 0° to 55°. Where both Tsf and Tmc have been sampled, both tuffs are rotated by similar amounts. Taken together, the structural, stratigraphic, geochronologic, and paleomagnetic data suggest that the coastal Sonora basins record initiation of faults related to opening of the northern Gulf ca. 6.6 Ma. Future collaborative efforts will link onshore investigations on Isla Tiburón with offshore PEMEX seismic reflection data to further test the role of dextral shear in the development of a localized transtensional plate boundary within the Gulf of California.

Evaluating the role of climate forcing on sediment delivery in the Waipaoa catchment, Hikurangi subduction margin, New Zealand

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The Waipaoa River catchment (2150 km2), the onshore portion of the Waipaoa source-to-sink (S2S) sedimentary system, of the east coast of the North Island of New Zealand is a tremendously data-rich study area for obtaining insights into the form and function of fluvial systems in a temperate, tectonically active setting. Landscape change processes in the Waipaoa catchment are rapid as a consequence of easily eroded bedrock, major changes to vegetative cover through glacial-interglacial climate fluctuations, temperate contemporary climate, and tectonism. These combine to produce large perturbations with corresponding large landscape responses. We examine aspects of the response of the fluvial system brought about by the switch from sediment over-supply (valley filling/aggradation) during Marine Isotope Stage 2 (MIS 2) in the Waipaoa catchment to sediment under-supply (valley cutting/degradation) in late MIS 2 and MIS 1. The fluvial response is also influenced, in down-valley po rtions of the catchment, by the c. 100 m of sea-level rise that accompanied the transition to MIS 1, and by tectonic uplift. The field data constrains the temporal variation in rate of fluvial incision where Quaternary climate fluctuation is a prime agent of change. We are also able to isolate the role of tectonic uplift in driving fluvial incision from the role of sediment supply and runoff. We identify the extent and age of the widespread MIS 2 aggradation terrace throughout the Waipaoa catchment, and the general form of incision that swept through the catchment following reduction in sediment supply and possible increase in precipitation at about 17-20 cal. Ka, near the end of the glacial period. The location, and models of migration, of knickpoints through the Waipaoa River catchment are consistent with proposed controls on alternating aggradation and degradation phases in fluvial systems. That is, increasing aridity leads to a loss of vegetation cover, resulting in channel aggradation due to an increase in the sediment flux from side slopes. Incision occurs during more humid periods, when vegetation stabilizes the hillslopes, diminishing sediment supply, and increasing stream power. The sediment yield from threshold dominated basins may exhibit significant variability in response to relatively subtle environmental changes. Based on detailed mapping and dating of a suite of degradational terraces and meander channels along the Waihuka tributary of the Waipaoa River, about 17 km above the confluence of the Waihuka with the mainstem Waipaoa, we determine the charactersitics of fluvial incision below the MIS 2 aggradation level, and, coupled with present-day knickpoint location and evolutionary models, provide insights into whole catchment response.

Feedbacks between lithospheric stress and magmatism in incipient continental rift zones

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The location, shape, and extent of magmatic injection in continental rift zones may be controlled predominantly by tectonic forces, lithospheric strength, resistance, and the orientation and strength of pre-existing structures (and hence lithospheric strength). Finite element models of continental scale rifting (Pangea) indicate that a 1-2 m.y. magmatic event that resulted in dike swarms over three continents, 1000's of kilometers, and 90 degree differential trends was controlled primarily by a steady tectonic motion of two plates, resistance, pre-existing weakness along sutures, and an evolving lithospheric strength. Specifically, models of the northwestward moving North American craton that left Africa and South America free to move with N America show some extensional stress diffused throughout the crust. However, when Africa was modeled as fixed, and therefore resistant to North America's motion, large areas of strong concentrated extensional stress were created. When a weak/thin boundary was modeled between the continents these areas of extensional stress became even more concentrated along their margins, but within the strong lithosphere. The orientation of both the weak margin and a thickened/strengthened area within the continent affected stress orientations, but only at the very margins of the strong areas. By inducing a southwesterly motion to South America, another resistance to the North American motion, the stress field within all the continents once again changed, further indicating that resistance to motion or stress is as important as the activation of motion itself. The final change in the stress field was created by creating a large area of weakened lithosphere between South and North America. Thus, while the tectonic motion created the continental scale stress fields, they were strongly affected by the strength of the lithosphere and the strength of the suture (and therefore resistance) between continental blocks. Finite element modeling reveals that Quaternary magmatism within the East African rift may be localized by crustal strengthening around the margins of cooled, mafic dike swarms that form ~50 km-long, 10 km-wide rift segments. Subsequent large volume, long duration dike intrusion events re-intrude these magmatic segments, weakening these zones. The weakened segments don't transmit the extensional stress, resulting in the concentration of stress at the margins of the bodies (and or dikes). Finite element models also suggest that any non-symmetrical magmatic injection into an extensional zone will likely cause the propagation and formation of a dike due to stress concentration around the weakened area. However, the dike may not initially form perpendicular to the regional extension direction because stress within the rift zone can become rotated due to strength differences in the rift zone and changes in stress brought about by other intrusions. These studies indicate that lithospheric strength and resistance, in combination with the large-scale tectonic stresses, may control the orientation, concentration, and location of the stress field at rifting continental boundaries, leading to along-axis variations in the orientation and location of magma intrusions. Further, it suggests that an evolving lithospheric strength profile as well as tectonic stresses account for changes in regional stress fields and styles of magmatic injection in continental rift zones.

Geodetic Activity detected at four volcanoes in the Kenyan Rift.

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Satellite geodesy provides a new perspective on the active processes which occur in continental rifts, and in nparticular shallow magma movements and dyke intrusions. Here we report inflation and deflation events at 4 volcanoes – Paka, Menengai, Longonot, and Suswa - in the Kenyan sector of the Eastern Rift for the time period from 1997 to present. This demonstrates the presence of active magmatic systems beneath and/or between these volcanoes with clear implications for medium range volcanic hazard. Similar episodes of inflation have been observed in the decade preceeding major dyke injection events at rift volcanoes, e.g. Dabbahu, Afar (Wright, 2008) and preceding eruptions at arc volcanoes e.g. Okmok, Alaska (Lu, 2008). Essentially all field and petrological study points to the importance of dike injection of mafic material to drive magma mixing and eruption (Macdonald et al, 2008). However, the short-term implications for eruption forecasts are less clear since many infl ation episodes do not culminate in eruption. The detection rate of volcanic activity in the Kenyan Rift is high suggesting that the magma flux in this area is significantly greater than previously believed.

Geomorphologic, paleoseismic, and geochronologic interpretation of the San Jose del Cabo Fault

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The San Jose del Cabo Fault is the largest active on-land fault in southern Baja, and its history and evolution are an important part of the development of the southern Baja region. In addition, paleoseismic evidence indicate that this fault is active and capable of producing >M7 earthquakes, which has significant seismic hazard implications for the area. This region also presents an opportunity to examine landscape response to both climate and tectonics, since the early landscape evolution was dominated by tectonic forces associated with rifting and was later dominated by climatically driven forces. Intensive mapping of Quaternary deformation, paleoseismic studies, and quantitative drainage analysis can lend insight into the seismic hazard potential of the SJdCF as well as to the regional landscape response to both climate and tectonics. This mapping will also help locate sites where we can interpret the geomorphology and the faulting history well enough to determine earthqu ake recurrence using paleoseismic techniques, and mapping the fault traces and determining the late Quaternary slip rate from dating of offset landforms will help to constrain these estimates. By using geomorphology, paleoseismology, geochronology and structural geology we hope to answer questions about the development and evolution of the San Jose del Cabo Fault and the role it plays in the story of both rifting and strain partitioning within the Gulf of California; the drivers of Quaternary deformation in the region; and the interaction of climate and tectonics and the role they play in landscape evolution.

Deformation History Beneath the Salton Sea, Southern California

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Seismic CHIRP data acquired in the Salton Sea provide new constraints on the interaction between the San Andreas, San Jacinto and Imperial fault systems. Detailed analysis of CHIRP profiles and sonar mosaics of seafloor sediments reveal several northeast trending en echelon faults. We combine data from Salton Sea borings and cone penetration tests with CHIRP profiles to identify facies changes in late-Holocene Lake Cahuilla sediments. High-amplitude horizons correlate with lowered lake levels and the consequent increased silt/sand components detected by cone penetrometer tests; the low amplitude horizons represent fine-grained high-stand lake deposits. These coarsening-up packages separated by flooding surfaces record fluctuations in Lake Cahuilla and have been correlated to radiocarbon dated lake sequences from the Coachella paleoseismic site. This chronostratigraphic control allows us to constrain the timing of paleo-earthquakes. We observe up to 13 events since ~3 Ka on a northeast trending fault near Bombay Beach. Preliminary analysis shows correlation between events on northeast trending faults beneath the Sea and events on the southern San Andreas Fault (SAF), suggesting stress interaction and potential triggering between secondary structures in the SAF-Imperial Fault step-over and large magnitude events on the southern SAF. Deformation beneath the sea is consistently down-to-the-southeast. Simply stated, differential subsidence and divergence to the southeast are evidence for rapid subsidence (> 10 mm/yr) and northwest-southeast oriented extension. These data provide the first direct observations of long-term kinematics and earthquake history beneath the Salton Sea.

Effects of Dike Intrusions on Continental Rifting

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Magma plays a major role in the development of many rifts and continental margins. This is particularly clear for some of the more recent continental rifts including the Afro-Arabian Rift System and the breakup of South America from Africa. We are interested in how magma, injected as dikes may lead to weakening of the lithosphere so that rifting can proceed even if the supply of magma wanes. We use a hybrid numerical model to simulate the effect of dike injection on continental lithopsheric rifting. We have developed a numerical diking simulation where the key diking parameters controlling the input of magma are the magma chamber size, minimum diking interval, and maximum tectonic force. The model includes a 2D finite difference code (FLAC) for tracking long-term stress build up and strain in a viscoelastic-plactic model lithosphere. A boundary element code is used to simulate the effect of short-duration dike intrusion events that are specified to occur periodicall y at the center of the model region. The stresses from the finite difference code are applied to the boundary element code to calculate how much a dike opens as a function of depth. If a dike is generated, basaltic-density magma is "injected" into the finite difference model based on the distribution of dike opening obtained from the boundary element code. Varying the diking interval and magma pressure changes the rate of magma input and lithospheric weakening. Several interesting results come from our models of diking and tectonic extension of "normal" continental lithosphere. By "normal" we consider lithosphere with crustal thickness of 30-40 km and surface heat flow of 40-50 mW/m2. In these models the rate of extension is limited by the rate of supply of magma until the lithosphere weakens to the point that tectonic extension can proceed without magmatic injection. These new results confirm results of simpler dike injection models showing that as little as 2-4 km of magmatic accommodation of extension is needed to weaken a rift by as much as an order of magnitude. Such weakening of "normal" continental lithosphere could allow tectonic extension to proceed at moderate force levels (say a few TeraNt/m2). The intrusion of magma also reduces the syn-rift subsidence and can increase the post-rift subsidence and we compare our subsidence results to several margins. The models allow for extrusion of magma when the magma pressure is sufficiently high after a dike has opened. Thus, we can simulate the development of "seaward dipping reflector" packages of lava flows. If the topography built up by such extrusions is not large then the extrusion has a small effect on the time required for a transition to tectonic rifting, when extension is no longer magma limited. This suggests that the evolution of "volcanic margins" and intrusive "magmatic" rifted may be similar. Thus, rifted margins with little or no surface volcanics may still have been greatly weakened by intrusion of hot basaltic dikes. A major geophysical challenge would be to detect and quantify the amount of magma intruded into magmatic and volcanic margins.

Dynamics of Slab Detachment Due to Ridge-Trench Collision: Implications for Baja California

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The approach of a buoyant spreading ridge to a subduction zone may lead to detachment of a subducted slab. Previous work has called upon the detachment process as an explanation for observed ridge abandonment and slab-window related magmatism (e.g. in Baja CA/western Mexico), but such a scenario has not been tested using fully-dynamic numerical models. We use dynamic two-dimensional models including a non-Newtonian rheology to study the approach of a spreading ridge to a subduction zone. In models exploring effects of subducted slab length, distance of the ridge from the trench, shear zone strength, and lithospheric yield strength, we find the following dynamics of ridge approach: (a) a decrease in subduction velocity as the ridge approaches the trench, (b) a shrinking surface plate that maintains a uniform subduction velocity, (c) ridge abandonment distances 100-275 km from the trench, and (d) slab gap distances 195-285 km from the trench. These results are consistent wit h observations in Baja CA, where detachment of the Cocos slab may explain abandonment of observed segments of the East Pacific Rise 50-200 km outboard of the trench (Lonsdale, 1991) and the presence of non-arc related magmatism located 100-250 km inboard of the trench with geochemical signatures separate from that associated with the normal subduction history for the Farallon plate (Pallares et al., 2007). Ridge subduction does not occur within any of our two-dimensional cases of ridge-trench collision.

Volcanic and Structural Response to Transtension in the Sierra Nevada Range Front (California) and Continental Arc Rifting in the Sierra Madre Occidental (Western Mexico)

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My major project for the past five years focuses on the structure, volcanology and landscape evolution of the Sierra Nevada, California, through Cenozoic time. Just as Hawaii is the type example of a mantle plume, the Sierra Nevada is now the archetype for lithosphere delamination, range uplift and associated volcanic activity. We have shown that the birth of the transtensional "future plate boundary" along the eastern side of the Sierra Nevada microplate (western Walker Lane belt) occurred in the axis of the Ancestral Cascades arc. This birth was recorded by a pulse of voluminous high-K magmatism that we interpret to record deep melting at a releasing stepover, rather than root delamination. Our new geologic data from the Sierra Nevada also confirm its position on the western shoulder of a Tibetan-type plateau for much of Cenozoic time, but also provide unambiguous evidence for three distinct Cenozoic magmatic and tectonic events that modified it. These events are part of th e continental lithospheric rupture process. My studies of continental lithospheric rupture have recently been extended to the Sierra Madre Occidental (SMO) of western Mexico, where three-fourths of the volume of the Late Eocene – early Miocene ignimbrite flareup of North America was erupted. All workers agree that this flareup represents the precursor of lithospheric rupture that eventually led to the formation of the Gulf of California. The SMO is the least deformed silicic large igneous province on Earth, as well as the largest Cenozoic one, and it hosts one of the largest epithermal precious-metal deposits in the world. Yet less than 10% of this vast terrane has been mapped. The massive ignimbrite volcanism in the SMO has been widely interpreted to record the onset of extension, but our new work shows that an Eocene extensional arc formed a precursor to the silicic large igneous province. Our study is focusing on the the "normal" arc to "flare-up" transition. We are determining the controls of normal faults and tran sfer zones, inherited from the precursory extensional andesite arc, on the siting and nature of silicic intrusions and vents. These include fissure-like silicic intrusions that pass upward into thick, extensive lava flows, interstratified with proximal ignimbrite facies, including co-ignimbrite lag breccias and surge-like ignimbrites. The silicic intrusions also appear to control the locations of at least some mineral deposits, especially along transfer zones. Graben calderas, rather than circular calderas, may be typical of this setting. All of these features are important for understanding the geodynamic evolution of a rifted continent. I will contribution to the workshop by presenting my unpublished geologic data from both areas, including geologic maps and cross sections, measured sections, photomosaics, outcrop sketches, outcrop photos and photomicrographs. I will also present geochronological, geochemical and petrographic data from the Sierra Nevada.

Late Quaternary Normal Fault System Behavior from Detailed Mapping and Gravity Analyses, BCS, Mexico

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Active normal faulting is well manifest along the southwest margin of the Gulf of California as a result of distributed deformation along an oblique-divergent plate margin. The southern end of the Baja California peninsula is ruptured by an array of roughly north-striking, left-stepping active normal faults. By characterizing normal-fault related deformation along the San Juan de los Planes fault zone southeast of La Paz and by using gravity to explore normal-fault-bounded basin geometries in the La Paz – Los Cabos transect of the Baja California Sur peninsula, we contribute to understanding the patterns and rates of faulting along the southwest gulf-margin fault system. Investigation of the San Juan de los Planes fault zone included a detailed geologic and geomorphic strip map of the active fault zone, including delineation of active scarp traces and geomorphic surfaces on the hanging wall and footwall; fault scarp profiles; analysis of bedrock structures to better understand how the pattern and rate of strain varied during the development of this fault zone; and gravity surveys across three major normal-fault-bounded basins. The footwall landscape along the San Juan de los Planes fault zone is characterized by a broad, gently-sloping, low-relief pediment surface with thin Quaternary cover, disrupted by inselberg-like hills. The young scarp-forming fault appears to have reactivated older faults to rupture this pediment, reflecting the episodic nature of slip along this fault zone. An age estimate of the youngest faulted deposit was obtained using optically stimulated luminescence dating techniques, and implies a Late Pleistocene-Holocene sli p rate of 0.1-0.5 mm/yr along the San Juan de los Planes fault zone. Whereas detailed mapping has improved our understanding of individual faults, the gravity surveys have aided in understanding the system more broadly, enabling us to estimate basin depths and geometries and make inferences about how the system is evolving and transferring strain. Gravity lines across the La Paz, San Juan de los Planes, and San Jose del Cabo basins reveal basin depths ranging from approximately 0.5 km (La Paz basin) to approximately 3 km (San Jose del Cabo basin). Based on the depth to bedrock and high adjacent footwall topography, it is likely that the San Jose del Cabo fault accommodates a greater slip rate than the other faults within this system. We infer that the San Juan de los Planes basin is a graben that serves to transfer strain between the larger Carrizal and Espiritu Santo faults and the San Jose del Cabo fault. An offshore CHIRP survey completed in late August, 2008 will provide further insight into the extent and interactions of faults within thi s system.

Origin of high-Nb and Nb-enriched basalts in Baja California, Mexico revisited

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The Quaternary alkali basalts in San Quintín and trachybasalts in Mesa San Carlos in Baja California, Mexico are compositionally similar to ocean island basalts (OIB). The eruption of such OIB-like basalts has been proposed to be due to upwelling of the Pacific suboceanic mantle through slab windows created underneath the peninsula after the cessation of subduction along the western margin of Baja California ca. 13 Ma (Pallares et al., JVGR 161, 2007; Castillo, GSAB 120, 2008). These basalts are compositionally the same as the rare, high-Nb basalts (HNB) that occur in a few volcanic arcs. Moreover, their composition greatly overlaps with that of the equally rare Nb-enriched basalts (NEB), which in turn are temporally and spatially related with silicic adakites that are purported to be products of melting of subducted basaltic crust. Adakites and NEB also occur as post-subduction lavas in Baja California. Interestingly, despite the consensus that Baja California HNB are direct ly coming from the Pacific asthenosphere, there is a difference in opinion as to the petrogenesis of NEB. On the one hand, Baja California NEB are due to melting of portions of the mantle metasomatized by melts from the subducted Farallon plate (e.g., Aguillón-Robles et al., Geology 29, 2001) whereas on the other, they are primary HNB magmas that have been modified through coupled fractional crystallization and contamination with tholeiitic mantle or lower arc crustal material (Castillo, GSAB 120, 2008). The possible presence of both HNB and NEB in the recently collected samples from the relatively thinner basement crust of the Gulf of California should help elucidate in more detail their petrologic and geochemical connection, and thus establish whether they are petrogenetically linked to a common source or not.

Seismicity And Seismic Attenuation In The Mexican Basin And Range Province In Sonora, Mexico

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We analyzed the seismicity that occurs along the western margin of the Sierra Madre Occidental, using records from the seismic network of northeastern Sonora, Mexico (Red Sísmica del Noreste de Sonora [RESNES]). This region is being extended in the east-west direction, particularly near the Gulf of California. In this part of the southern Basin and Range Province normal faults form on the margins of the Sierra Madre with a north-south strike. On May 3, 1887 a Mw 7.5 earthquake occurred in this region 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). We have located earthquakes that occurred between 2003 and 2007 in the Mexican Basin and Range Province using arrival times from the RESNES array and from stations of the USArray located within 150 km from the US-Mexico international border. We determined hypocenter coordinates of the earthquakes analyzed using the shrinking box Source-Specific Station Term (SSST) method of Lin and Shearer (2005). For events that occurred between April and December 2007 we also incorporated arrival times from stations of the USArray. We identify 3 swarms of earthquakes, one near Cananea, another near the fault segments that ruptured during the 1887 Sonora earthquake and a third swarm in the southern Sierra Madre Occidental. We also analyzed the spectral characteristics of local and regional earthquakes recorded by the RESNES array to determine empirical attenuation functions for P and S waves that describe how the spectral amplitudes decay with hypocentral distance. Then we used this attenuation functions to estimate the quality factor Q of the crust. We find that seismic rays traveling in the lower crust attenuate less than rays that propagate in the upper crust, where the rocks are more fractured due to surface faulting. These results suggest stronger scattering and internal friction near the surface. Acknowledgments.- This research was funded by the Mexican National Council for Science and Technology (CONACYT), grants 59216, 24507 and 62116. Technical support was provided by Alejandro Hurtado, Luís Inzunza, Antonio Mendoza and Arturo Pérez-Vertti.

3D Models of Faulting During Oblique Continental Extension

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We plan to use a newly developed 3D numerical modeling code to study the controls on deformation during oblique continental extension, a process involving rupturing continental lithosphere. The code is the only one we know of that can deal with 3D elasto-visco-plastic deformation and was developed by one of us (Choi). We first propose to focus on what controls the pattern of tectonic extension of continental lithosphere. More specifically, without worrying about the thermal evolution of an extended region, we would try to answer what fault weakening parameters are needed to match normal fault population statistics for natural and analog studies. Statistics that we would consider include the size frequency distribution and length offset ratios. In the next stage, we plan to consider natural type examples of oblique rifting, each of which extended with different initial conditions of thermal and crustal thickness. First, we would consider a region where the crust was likel y cold at the time of rifting. The focus of this effort would be: What degree of pre-heating of the rift zone needed to explain the along-axis segmentation and across axis structure of faulting in the Gulf of Suez? Next we would consider a region of moderately thick, warm crust, where highly oblique extension was apparently accommodated by two distinct geometries of transtension. Specifically, we would ask: Is magma needed to give the change in rift pattern seen at ~ 6 Ma in the Gulf of Calofornia? Lastly, we would consider extension of thick, hot crust that may have led to the formation of metamorphic core complexes in places like the Colorado River Extensional Corridor. Specifically we would ask: Is buoyant pluton emplacement needed for the formation of domal cores of Metamorphic Core Complexes?

Testing The Extensional Detachment Paradigm: A Borehole Observatory In The Sevier Desert Basin

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The Sevier Desert basin, Utah represents a world-class target for scientific drilling and for the development of an in situ borehole observatory of active faulting, with potential for establishing that normal-sense slip can occur along a brittle low-angle fault and, by determining the conditions under which that may take place, for resolving the mechanical paradox associated with such structures. The Sevier Desert detachment was defined in the mid-1970s on the basis seismic reflection data and commercial wells as the contact between Paleozoic carbonate rocks and Cenozoic basin fill over a depth range of ~0-4 km. Today, the interpreted fault is thought by most workers to root into the crust to the west, to have large estimated offset (< 47 km), to have been active over most of its history near its present 11° dip, and to be associated with contemporary surface extension (a 30-km-long zone of prominent Holocene fault scarps immediately west of Clear Lake). Although no seismicity has been documented on the detachment, its scale is consistent with earthquake magnitudes as large as M 7.0. The primary objectives of planned boreholes are to obtain critical core of fault rocks at a down-dip site where offset should be large, to establish more clearly the relationship between basin development and displacement along the interpreted fault, and to make in situ measurements at depth. The strategy currently being developed in a white paper, following a July, 2008 workshop in Utah, is: 1) to acquire new seismic reflection data in the vicinity of target sites; 2) to re-enter the ARCO Hole-in-Rock well in the southern Sevier Desert basin, to evaluate the character of the interpreted fault zone at a depth of 2.8 km; and 3) to core, log and make in situ measurements in a new hole offset downdip from ARCO Hole-in-Rock, intersecting the interpreted detachment at a depth of 3.2-3.5 km.

Fault activity, slip rates, and subsidence history of the Laguna Salada basin in northeastern Baja California, Mexico

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Analysis of the stratigraphy of sedimentary basins bounded by normal faults yield a wealth of information about how these brittle structures accrue displacement. However, mostly due to large uncertainties in the dating of sediments, little can be said about their slip rates and how slip is accommodated by individual faults. Cyclicity in sediments induced by Milankovitch climatic changes can be used as a very precise high-resolution stratigraphic chronometer, eliminating the problem of uncertainties in the dating. Here we present a cyclicity analysis from a series of gamma-ray logs from boreholes drilled in the Mexicali valley in north Mexico. This is an area of (i) rapid subsidence due to trans-tension along the San Andreas-Imperial fault system, and (ii) high flux of sediments transported by the Colorado River, and has a high potential of preservation of climatic information and tectonic activity. A time series analysis performed on two 42 m-long cores drilled in the depocen ter of the of the Laguna Salada basin reveal that the stratigraphy in the basin is modulated by cyclic variations in lake level as a result of changes in river discharge by Milankovitch forcing; we estimate the cores cover timespans of 50 Ka and 100 Ka. Based on these results we then obtain the long-term history of the faults surrounding the Laguna Salada basin using a series of gamma-ray logs recovered from a deep geothermal boreholes drilled by the Mexican Power Company. The deep boreholes reveal a history of activity pulses related to the initial breakage of the Laguna Salada fault and its interaction with neighboring faults. A first pulse started at 1.5 Ma and records initiation of the Laguna Salada fault and rapid uplift of the crystalline block of the Sierra Cucapa. A second pulse started at $\sim$1 Ma, which likely is related to the hard linking of the Laguna Salada fault with the Cañada David detachment by the Cañon Rojo fault. The onset of the Laguna Salada fault at 1.5 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 reorganization may have affected a large area from San Gorgonio pass to the northern Gulf of California.

Low Frequency Hybrid Earthquakes near a magma chamber beneath the Dabbahu volcano

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New broadband seismic data from the 2005-present Dabbahu, Afar rifting event offer unprecedented insights into the influence of magmatic fluids in the production of low frequency volcano-tectonic earthquakes. We analyze persistent low-frequency earthquakes recorded on a temporary array deployed three weeks after the intrusion of a 60 km-long 8 m-wide basaltic dike. The dike intruded and reheated existing silicic magma chambers beneath and surrounding Dabbahu and Gab'ho volcanoes. The multiple magma chambers and the large volume basaltic intrusion provide a diverse data set of volcano-tectonic eents, and he complementary seismic, geodetic, and structural data sets provide constraints on the source and path effects. We analyze the spectral characteristics of near source low-frequency earthquakes , and their spatial and temporal distribution to differentiate between competing models for their generation. Earthquakes from the three months following the intrusion are classifie d using their peak intensities in the frequency domain and by percentage of power below 2 Hz. We notice non-uniform increases in relative low frequency power on distance from station and wave propagation direction. Station north of Dabbahu volcano detect earthquakes with extreme attenuation at frequencies above 10 Hz over a distance less than 20 km, in many cases less than 5km, whereas the eastern instruments see a lesser change in distribution of power over a distance of over 70km. A small number of earthquakes require further calculation as they are dominated by low frequency power at all sites and are possibly due to a different type of mechanism entirely. Our data implies bodies that strongly attenuate high frequencies near and around Dabbahu volcano. The large impedance contrasts to explain our observations suggest the presence of melt in the crust from the initial dike intrusion. This study provides another approach to modeling the complexities in the Afar region and offers a unique chance to characterize the nature of low frequency events in a zone of sea floor spreading.

Sedimentary Basin Structure of the Hadar Formation's Lacustrine-Dominated Depocenter (Ledi-Geraru, Afar, Ethiopia) and its Relevance for Investigating Hominin Paleoenvironments

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Sedimentary sequences preserved in East African rift basins record the long-term response of past depositional environments to climatic and tectonic forcing. Motivations for recent field investigations at the Ledi-Geraru site, part of the greater Hadar sedimentary basin in the Afar region of Ethiopia, stem from a need to characterize local basin structure and expand and refine interpretations of the complex mid-late Pliocene history of local and regional-scale landscape change during a time of critical importance for understanding hominin evolution. Detailed geologic mapping (1:7,000), measured stratigraphic sections, and seismic reflection surveys provide the datasets necessary for basin evaluation. The Ledi-Geraru sedimentary sequence (>250m thick) exposes nearly the entirety of the hominin-bearing Hadar Formation of west-central Afar. Both primary unmodified lake deposits and intervals modified by subsequent subaerial exposure and pedogenesis are well-exposed. Whereas coev al fluvio-lacustrine sediments associated with hominin and archaeological sites west of Ledi-Geraru (e.g., Hadar and Gona) are marked by comparatively slow and episodic sedimentation, sedimentation rates in the Ledi-Geraru sequence are extremely high and consistent, on the order of ~0.9-1.0mm/yr. Laterally extensive tephra marker beds and paleomagnetic records provide excellent age control for sedimentation rate estimates and correlation to nearby fossil-rich sequences. As the Hadar basin sediments preserve a rich paleoanthropologic and archaeological record, this work provides the geologic framework necessary for a proposed (2011) continental drilling effort to obtain a near-continuous, ultra-high resolution terrestrial record of past climate variability from multiple paleo-lake basins in East Africa, including the Ledi-Geraru. A seismic reflection survey was completed there in spring 2008, below the planned drilling site. Gently east-dipping coherent reflections interprete d to be from the Ledi-Geraru sedimentary sequence are imaged in the seismic data to at least 0.2 to 0.3 s (two-way travel time). Preliminary average velocities of about 2000 m/s suggest a sequence thickness of 200-300 m. Furthermore, there is no indication of large-offset faults or of buried basalt ridges that would disrupt or reduce the stratigraphic column available for coring. The anticipated cores from Ledi-Geraru should yield a high-resolution chronostratigraphic framework and paleoenvironmental record from >3.5 to 2.9Ma. Combined geologic and seismic evaluations of depositional sequences are central for evaluating the geometry, tectonic evolution, and stratigraphic history of basins and facilitate interpretations of the space-time progression of evolving paleosurfaces.

Crustal Recycling by Surface Processes Along the Pacific-North America Plate Boundary: From the Colorado Plateau to the Salton Trough and Gulf of California

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Delivery of sediment from the Colorado Plateau to basins in the Salton Trough and northern Gulf of California exerts a major though poorly understood control on crustal thickness, composition, lithospheric mechanics and rift architecture. Synthesis of geomorphic, hydrologic, stratigraphic, and geophysical studies permits preliminary assessment of the timing, volume, and rate at which crust of the continent interior is moved as sediment and converted into new crust along the plate boundary. Recent work shows that the modern Colorado River was integrated by a series of catastrophic floods and lake-filling events that propagated down-river from Lake Mead to the Salton Trough between 6.0 and 5.3 Ma (Spencer et al., 2001, 2008; House et al., 2005; Dorsey et al., 2007). Thus, all transfer of sediment from the Colorado Plateau to the Salton Trough and northern Gulf post-dates 5.3 Ma.

The volume of rock eroded from the Colorado Plateau can be approximated by multiplying the pre-dam sediment discharge (1.2-1.5 x 10^8 tons/yr; Milliman and Syvitski, 1992) by the total lifetime of sediment output (5.3 m.y.), which gives a range of 235,000-294,000 km^3. The volume of sediment stored in subsurface basins of the Salton Trough and northern Gulf of California is estimated using geophysical and borehole data and crustal models based on seismic refraction studies (e.g. Fuis et al., 1984; Gonzalez et al., 2005; Pacheco et al., 2006; Aragon and Martin, 2007). According to one model, pre-existing granitic crust has been completely ruptured by oblique rifting, and the space is filled with new crust that consists of metamorphosed Colorado River sediment mixed with mafic intrusions from below. According to a second model, the middle and lower crust in these basins is made up of extended and thinned granitic rock that has undergone large-scale lower-crustal flow. Using these two end-member crustal models, and adding a small amount for Colorado River sediment exposed in eroding inverted basins, suggests that approximately 198,000 to 292,000 km^3 of Colorado River sediment is stored in basins of the Salton Trough and northern Gulf. Correcting for sediment porosity does not change this estimate much because the sediments are compacting and becoming rock at depth in the basins, and they were eroded largely from sedimentary rocks on the Plateau. Thus, despite the current large uncertainties, the volume of rock eroded from the Plateau appears to roughly match the volume of sediment stored in the receiving basins.

Using the equivalent rock volume (~183,000-281,000 km^3), age (5.3 Ma), and along-strike extent (~580 km) of sediment preserved in Gulf-Trough basins, the rate of crustal addition by sediment input to basins in the Gulf-Trough corridor is ca. 59-91 km^3 per km strike length along the plate boundary per million years. This is similar to the growth rate for western Pacific island arcs (25-95 km^3/km/m.y.; Dimalanta et al., 2002; Dimalanta and Yumul, 2003) and rates calculated for slow-spreading ocean ridges. It thus appears that crustal growth by delivery of sediment to basins along the plate boundary takes place at rates comparable to crustal growth by magmatic accretion at subduction zones and mid-ocean spreading centers. This process may be important at other rift and oblique-rift margins where a large continental river system is captured due to subsidence of a pre-existing orogenic highland.

Characterizing the evolution of plate margin shearing and major transtensional fault systems in northern Baja California, Mexico

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Northern Baja California is cut by an extensive array of faults that accommodate shearing between the North American and Pacific plates. The faults show systematic variations in orientations and together define a broad fan-shaped geometry. This portion of the plate margin is part of the complex transition zone associated with the “Big Bend” of the San Andreas where faults have broken across the mechanically competent Cretaceous batholith of North America. We present exciting new results of a multidisciplinary group of researchers that has been organized to characterize the slip history of each major fault zone on several time scales including modern, late Quaternary, and late Cenozoic. The main subdisciplines that we are employing include structural geology, geomorphology, paleoseismology, geophysics (gravity, magnetics and magnetotellurics), GPS geodesy, and earthquake seismology. Our work suggests that each fault has unique kinematics that varies systematically with orientation and that the faults operate together as a highly integrated and interdependent system to accommodate transtensional plate motion. New data allows us to compare and contrast the structural and geomorphic evolution of two distinct normal fault systems (San Pedro Martir fault and the Cañada David detachment), each of which controls major segments of the rifted margin of Baja California. This gives new insight into understanding the role and mechanical evolution of low-angle normal faults in the northern Gulf of California. This work also contributes significantly to understand questions related to the more regional perspective of the evolution of the Pacific-North American plate margin, such as (1) the origin of the “Big Bend” domain of the San Andreas fault system, which links transpressional shearing along coastal California with transtensional shearing in the Gulf of California, (2) the migration and localization of shearing in the northern gulf extensional province, and (3) regional models of finite strain and tectonic reconstructions of the Baja California microplate.

Dynamic Upwelling in the Mantle Beneath the Gulf of California

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We have completed a moderately high resolution study of the shear velocity structure of the crust and upper mantle beneath the Gulf Extensional Province and Baja California using Rayleigh waves propagating across the NARS-Baja, RESBAN, and southern California arrays. We employed finite frequency response kernels and take into account the complexity of the incoming wavefields using a multi-plane wave technique, yielding higher resolution and broader coverage than conventional approaches. We used vertical component fundamental mode Rayleigh waves ranging in period from 22 to 111 s generated by teleseismic sources. Surface waves traveling along the Gulf or Baja California have typically undergone waveform distortion before they reach the study area by propagating along continental margins and subduction zones that induce scattering and multipathing. Further waveform distortion is caused by heterogeneities in the extensional province. We employed a multiple two-plane-wave appro ximation to account for waveform distortion outside our study region and 2D finite frequency response kernels to represent scattering within the study area. There are two primary features of interest in the 3-D shear velocity structure: a series of low velocity anomalies in the shallow mantle beneath the Gulf of California and a deeper, high velocity anomaly that appears to be a remnant of the unsubducted Guadelupe and Magdelena microplates. There are three pronounced low-velocity anomalies in the 20-90 km depth range beneath the Guaymas basin, lower Delfin basin and west of the Wagner basin. Lesser low velocity anomalies in this depth range are located beneath the Salton trough and Farallon basin. We attribute these low velocity anomalies to dynamic, buoyancy-driven upwelling and melting initially triggered by extension in the gulf region, rather than strictly passive upwelling driven by the plate separation. The role of melting is suggested by the very low shear velocities (<= 4.0 km/s) and the fact that the maximum anomaly is at a depth of ~ 60 km, where petrological models indicate mantle melting should be at the greatest rate. The lack of a continuous low-velocity region, the spacing of the anomalies 200-250 km apart, and the offset of the centers of the anomalies from the current, nearby spreading centers suggest that shallow melt depletion buoyancy and melt retention buoyancy may have organized the initially passively driven upwelling into regularly spaced cells. The anomaly in the Wagner basin in particular is centered more beneath the young coastal volcanic province (< 3 Ma) and Roca Consag (0.12-1.2 Ma) than beneath the inferred current extensional center. The 200-250 km spacing is consistent with the characteristic dynamic segmentation length predicted for buoyant mantle instabilities in the numerical models of Magde and Sparks (1997) and others.

Thermal Processes, Fluid Production, and Crustal Deformation

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The thermal state of the lithosphere is closely coupled with crustal deformation and the production of fluids. Thus, the analysis of near-surface heat flow measurements can play an important role in characterizing the thermal, hydrologic, and tectonic processes associated with the rupturing of continental lithosphere. Along the San Andreas Fault, heat flow data in conjunction with other observations (geophysical, seismological, hydrological, etc.) have been used to effectively characterize both crustal and fault strength, as well as the thermal and tectonic history of the fault system. Additionally, recent work by myself and others, has shown how a general understanding of the thermal evolution of the lithosphere in this region can be used to calculate realistic fluid source estimates from crustal and mantle dehydration reactions. With these fluid flux estimates, we have used numerical models of coupled fluid flow and heat transport to evaluate their potential role in fault and crustal strength over time. Similar evaluations and detailed descriptions of the thermal state within rifted margins may prove useful in addressing many of the overarching themes within the RCL initiative, particularly: 1) How does the strength of the lithosphere evolve during rupturing? 2) How is strain partitioned during lithospheric rupturing?, and 5) How are fluid fluxes modified or controlled by lithospheric rupturing?

Seismicity and faulting in the southern Gulf of California from the Sea of Cortez Ocean-Bottom Array (SCOOBA) seismic experiment

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Accurate earthquake locations can help assess the mechanisms of faulting and deformation at rifted continental margins. The Pacific-North American plate boundary within the Gulf of California (GoC) provides a unique opportunity to explore such rifting, as continental extension in the north transitions to seafloor spreading in the south. From October 2005 to October 2006, an array of fourteen four-component ocean-bottom seismometers were deployed in the GoC to record earthquakes and other natural seismic signals as part of the Sea of Cortez Ocean-Bottom Array (SCOOBA) experiment. The array recorded 47 events with M>3 that were located by regional and global catalogs, including seven M > 5 events from the Global CMT catalog. Using an automated detection and location algorithm, we found over 850 additional events with M > ~1.5 Subsequent manual repicking of P-wave arrival times and relocation results in events that are tightly clustered on or near the major NW-SE strike-s lip faults that delineate the plate boundary. However, some events appear to be located on faults well away from the major plate boundary faults. The events are also clustered in time, with the largest events each accompanied by distinct foreshock and aftershock sequences. For sufficiently well-recorded and paired events, we plan to apply a double-difference algorithm to obtain high-precision relative locations. We anticipate that these locations will improve our understanding of the distribution of seismic deformation within the greater extensional zone in the southern GoC.

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In contrast to ancient rift margins where many of the mechanisms vital to the formation of the margin have long since been hidden, the Woodlark Basin of Papua New Guinea offers the opportunity to study active rift processes. Near the rifting-to-seafloor spreading transition the asymmetric rift system comprises large tilted fault blocks on the southern margin and a principally unfaulted northern margin that has subsided more than 3 km. As is often the case, estimates of extension derived by examining brittle faulting fall short of those calculated through subsidence. However, by including multiple phases of faulting and sub-resolution faulting, this gap can be closed – resulting in a total of 111+/-23km of extension. Assuming Airy isostasy, the extension calculated from subsidence along the same profile is 115+/-45 km. Though these estimates are in close agreement, it remains that locally a mechanism such as lower-crustal flow must be important. Extension can also be estimated by fitting Euler poles to fracture zones and magnetic chrons in the oceanic lithosphere. This gives an estimate of more than 200 km of extension since 6 Ma. Given that the basin has been opening since at least 8.4 Ma, this estimate far exceeds those predicted by brittle extension and subsidence. Can these extension estimates be reconciled? Estimates of brittle extension have so far ignored the potential role of metamorphic core complexes (MCC). At an MCC the upper crust has been removed - a 30 km wide MCC represents 30 km of extension. MCCs have not yet been identified along the study profile, but an MCC that has been dissected by normal faults may not be visible. The extension discrepancy may also be explained by a detachment between the mantle lithosphere and the upper crust. In this case estimates of extension from Euler pole kinematics should not agree with other estimates.

The role of dike injection in the evolution of continental rift systems

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Magma delivery through dike injection is an integral part of the extensional processes at rift systems. Many thermal and mechanical processes, including magma flux, topography, and melt crystallization rates limit the lateral propagation of dikes along a rift and affect the length scale of rift segments. Models of 2-dimensional dike injection at mid-ocean rifts have greatly increased our understanding of the physical and thermodynamic constraints that limit dike propagation [e.g., Fialko and Rubin, 1998; Buck et al., 2005; Behn et al., 2006; Qin and Buck, 2008]. At the center of rift segments, where extensional processes are primarily 2D, these models do a very good job of illustrating dike propagation during rifting and determining the thermal mechanical evolution of a rift. However, rift segmentation is an inherently 3D problem and the thermal edge effect of a rift offset may play a critical role in limiting dike propagation. Moreover, the dike propagation arrest dista nce may contribute to and or promote the segmentation evolution of continental rift systems. To better constrain the role of dike injection on the thermal-mechanical evolution of continental rift systems we are building on the 2D models of dike injection developed for oceanic lithosphere to investigate cases of dike injection into continental lithosphere using physical parameters specific to a given rift system. This will provide a first-order view of the limits of dike propagation in a uniform lithosphere and constrain the length scales possible for segment evolution. We are further developing these models in 3D to better understand the interplay between rift segmentation and dike propagation arrest distance and constrain the thermal-mechanical linkage between rift segments. Additionally, we are utilizing the high-resolution data coverage available for the East African Rift including local seismic arrays, InSAR, and GPS to model specific dike sequences. Synthesizing our coupled thermal-mechanical models with the physical parameters of Afar dikes will provide cons traints on the conditions for dike propagation and the linkage of faults in the system. Behn, M. D., W. R. Buck, and I. S. Sacks (2006), Topographic controls on dike injection in volcanic rift zones, Earth Planet. Sci. Lett., 246, 188-196. Buck, W. R., L. L. Lavier, and A. N. B. Poliakov (2005), Modes of faulting at mid-ocean ridges, Nature, 434, 719-723. Fialko, Y. A., and A. M. Rubin (1998), Thermodynamics of lateral dike propagation: Implications for crustal accretion at slow spreading mid-ocean ridges, J. Geophys. Res.-Solid Earth, 103, 2501-2514. Qin, R., and W. R. Buck (2008), Why meter-wide dikes at Oceanic Spreading Centers?, Earth and Planet. Sci. Lett., 256, 466-474.

Reactivation Of The Levant Passive Margin Prior To Localization Of Deformation Along The Dead Sea Transform

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During the late Tertiary the paleogeography of the Middle East region changed significantly. Whereas in the Senonian and most of the Eocene times Israel and its surroundings was completely flooded, after the Middle Eocene the sea retreated hundreds of km westward and a huge area, including parts of Saudia Arabia, Jordan, Israel, Sinai, and parts of Egypt, was subaerially exposed. The massive land exposure was associated with enhanced fluvial transport into the southeast Mediterranean Sea and enhanced sedimentation rates in the basin. Noteworthy, modern seismic data reveals that the thickness of post Mid-Eocene section in the Levant Basin is about 4 km (Gardosh et al., 2008; Gvirtzman et al., 2008), which is about one third of the basin's total sedimentary column. We distinguish between two tectonic phases that reshaped the continental-oceanic transition at that time. The first phase of activity occurred in the Late Eocene (~35 Ma), during which three large structural steps with a total vertical displacement of 1.5-3 km formed between the Arabian Plateau and the eastern Mediterranean (Bar et al., EGU 2008). This was followed by erosional and incisional processes that yielded several planation surfaces in the inland region cut by deep channels across the steps while depositional processes filled the subsiding Levant basin. A second phase consisting of N-S extension occurred in the Mid-Late Miocene (10-5 Ma). Whereas Late Miocene volcanism in the Israeli coastal plain was described many years ago, extensional faulting was recognized only in recent years. Our work describes a 70 km long margin-parallel fault running along the Israeli coastal plain with a vertical displacement of 200-400m (Steinberg et al., 2008) and a sub-normal EW fault with a vertical throw of up to 1000m just south of Mt Carmel (Steinberg et al., in prep.). Both faults are traced below the mostly undisturbed Plio-Pleistocene section. We suggest that in conjunction with the Suez rifting (Oligocene-Miocene), a left-lateral fault system was formed along the Levant continental margin connecting the northern tip of the Red Sea-Suez Rift to the northern tip of the Sirhan-Yizreel-Qishon Rift. This left-lateral fault system allowed Arabia to slip northward relative to the Mediterranean lithosphere producing transpressional deformation mainly along the NE trending Pelusium Line offshore Israel. In Mid-Late Miocene times deformation wandered to the Israeli coastal plain and produced some transtensional faulting; and finally, from the Pliocene to date motion is localized along the Dead Sea Transform. Attributing a strike slip motion to a fault along the Levant margin is a new paradigm suggested here. It suggests the Suez Rift initially continued northward around the margin of the oceanic Mediterranean lithosphere and provides a mechanism for the subsidence of the Jaffa basin that was formed between two segments of the left-lateral margin-parallel fault. Eventually, plate motion jumped inland to the Dead Sea Transform. Then, both the Suez Rift and the Jaffa Basin, a pull-apart basin along this fault system, were gradually abandoned and buried by Plio-Pleistocene sediments.

Geodetic observations of new dyke intrusions in the Dabbuhu Rift segment (Afar, Ethiopia) between 2006 and 2008.

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The 60-km-long Dabbahu segment of Nubia-Arabia plate boundary lies in the Northern Ethiopian region of Afar. In September 2005 a major rifting episode resulted in the injection of a 60-km-long dyke with a maximum thickness of ~8m (Wright et al., 2006). Subsidence observed at Dabbahu and Gabho volcanoes implied that some of the magma was sourced from shallow reservoirs beneath the volcanoes. Between June 2006 and November 2008 a further 10 dykes were intruded in the Dabbahu segment, in the vicinity and to the south of Ado'Ale - a dissected, silicic volcanic complex at the centre of the rift segment. On June 17 2006 a swarm of ~50 earthquakes were detected near Ado'Ale. Modelling of radar interferometry (InSAR) data indicates the injection of a ~2 m thick, ~10-km-long dyke in accordance with the observed seismicity. Additional dyke intrusions were detected in July, September and December of 2006 and in January, August and November of 2007. InSAR suggests that a ~ 1 m thick, ~9 -km-long dyke was intruded in July 2006 followed by a ~ 1m thick, ~8-km-long dyke in September, with both dykes showing a southward migration. Dykes in December 2006 and in January and August 2007 re-intrude previous dykes with lower amounts of opening. A basaltic fissural eruption occurred with the August 2007 dyke. Modelling indicates that the dykes are confined to the upper 10 km of crust, and are located near the Ado Ale complex. InSAR shows no deflation at either of the volcanoes at the northern end of the segment, in addition, seismicity associated with the June and July dykes propagates to the north and south of Ado'Ale, respectively, implying an alternate source is feeding the ongoing rifting at depth. The apparent migration sequences seen so far appear to be similar to those seen in Iceland during the 1975-1984 Krafla rifting episode. Repeated dyke intrusion in the Dabbahu segment implies that tectonic stresses in the lithosphere were not relieved during the Septemb er 2005 dyke event. It is likely that, with a continued magma supply, additional dykes will be intruded until the tectonic stress is relieved.

Neogene Chronostratigraphy In The Northern Gulf Of California

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Geologic models locate Baja California next to mainland Mexico before the Oligocene and propose opening of the Gulf of California during Miocene times. Outcrop information in the northern part of the Gulf indicates late Miocene marine sedimentation on a continental platform. However, the earliest marine sediments in the region are present in basins sampled by oil exploratory wells in the area, which drilled as much as 5 591 meters of marine sands to silty clays. Stratigraphic and paleontological data in these wells indicate almost continuous marine sedimentation from middle Miocene times, in maximum water depths of approximately ~200 meters. The presence of the dinoflagellates Cribroperidinium tenuitabulatum, Diphyes latiusculum and Spiniferites pseudofurcatus, together with the nannofossil Cyclicargolithus floridanus in samples from some of these wells, indicate marine deposition during middle Miocene times in Tiburón Consag and Wagner basins in the northen Gulf of California.
Resume

Controlled-Source Seismic Imaging of Rift Processes and Earthquake Hazards in the Salton Trough

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The NSF MARGINS program, the NSF EarthScope program, and the U.S. Geological Survey have funded a large seismic refraction and reflection survey of the Salton Trough in southern California and northern Mexico, including the Coachella, Imperial, and Mexicali Valleys. The purpose of this abstract is to communicate plans for the seismic project and encourage synergy with piggyback and complementary studies. Fieldwork is tentatively scheduled for January 2010. The goals of the project include both rifting processes at the northern end of the Gulf of California extensional province and earthquake hazards at the southern end of the San Andreas Fault system. In the central Salton Trough, North American lithosphere appears to have been rifted completely apart. The 20-22 km thick crust is apparently composed entirely of new crust added by magmatism from below and sedimentation from above. The seismic survey will investigate the style of continental breakup, the role and mode of magmatism, the effects of rapid Colorado River sedimentation upon extension and magmatism, and the partitioning of oblique extension. The southernmost San Andreas Fault is considered at high risk of producing a large damaging earthquake, yet structure of the fault and adjacent basins are not currently well constrained. To improve hazard models, the seismic survey will image the structure of the San Andreas and Imperial Faults, structure of sedimentary basins in the Salton Trough, and three-dimensional seismic velocity of the crust and uppermost mantle. The seismic survey will include two refraction / wide-angle reflection lines 200-250-km long along the entire Salton Trough and across the Imperial Valley and adjacent ranges. These lines will constrain structure and seismic velocity of the entire crust and upper-most mantle. In addition, several lines 30-50 km long will cross the Imperial and Coachella Valleys and adjacent faults. These shorter lines will provide detailed seismic velocity in the upper crust, including basin and fault structure, and low-fold seismic reflection images of the entire crust. The project web site is: http://www.geophys.geos.vt.edu/hole/salton/

Mapping seismic velocities to viscosity beneath divergent margins

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The rupturing of continental lithosphere and subsequent progressive development of new oceanic lithosphere require dramatic changes in the viscosity structure beneath the plate boundary. Towards understanding this time dependent process, we need the highest possible resolution inversion of seismic data for 3-D anisotropic velocity structure, and then a method to map from elastic properties to a spatial distribution of viscosity. I will present recent progress in mapping from seismic velocities to viscosity developed by and in collaboration with Y. Takei (U. Tokyo), with an emphasis on the perturbations due to melt. The mapping methods are based on the elasticity model by Takei (JGR, 1998) and Takei & Holtzman (JGR, in press). Effective viscosity is very sensitive to the detailed aspects of melt distribution, much more so than is elasticity. In collaboration with Y. Takei, M. Kendall (U. Bristol) and J. Gaherty (LDEO), we are applying these methods to velocity models from Northern Ethiopian Rift and the Gulf of California RCL site.

Passive Margins of the United States: Rifting, Drifting, and the United Nations Convention on the Law of the Sea

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The U.S. Law of the Sea (LOS) project provides an opportunity to re-examine the morphology, geology, tectonics and evolution of the passive margins of the United States: the Atlantic, the Gulf of Mexico, and the Arctic. Although LOS is a legal treaty, science plays a significant role in determining how to apply or justify applying the sometimes ambiguous formula and criteria of LOS to identify those areas of continental margin beyond 200 nautical miles where the United States can exercise sovereign rights. Specifically, the nature of the ocean-continent transition is of potential relevance in determining natural prolongation, one of the fundamental concepts used in justifying the LOS legal seafloor boundary that extends beyond 200 nm. Although rift basins associated with breakup and the post-rift stratigraphy are reasonably well known on the three passive margins, the loci of continental rupture remains poorly imaged and largely unsampled, owing to burial deeply beneath thick sedimentary packages (Atlantic and Gulf of Mexico) or lack of data (Arctic). A review of existing data and literature prepared for LOS indicates that very little quantitative information is known about the width, segmentation, structural fabric and compositional heterogeneity of the deepest basement rocks on the three margins, despite knowledge about the general location of the break-up from magnetic or refraction information. The breakup has been most extensively studied on the Atlantic margin in the 1970's – 1990's from large experiments in the Baltimore Canyon trough and Carolina trough, where rift-related volcanism is well documented. The Georges Bank and Blake Plateau basins lack meaningful deep velocity or crustal thickness m easurements; only a few studies shed light on the ocean-continent transition in the Gulf of Mexico; and paucity of data makes the Alaskan Beaufort margin a frontier area for understanding breakup. LOS studies may make it possible to revisit and reevaluate existing models for the break up history of the passive margins of the U.S. and to apply new ideas about breakup to understand the deepest parts of these margins.

Seismic slip on an oblique detachment fault at low angles: >1 m thick pseudotachylytes generated by the Pliocene-Pleistocene West Salton detachment fault

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Pseudotachylyte is one of the few accepted indicators of seismic slip along ancient faults because frictional melting does not occur within a creeping fault. Low-angle normal faults have produced few large earthquakes in historic times and low-angle normal faults (detachment faults) are severely misoriented relative to a vertical maximum compressive stress. As a result many geoscientists question whether low-angle normal faults produce earthquakes at low angles. Relationships in southern California show that a major low-angle normal-dextral fault slipped at low angles and during large paleoearthquakes. The exhumed Pliocene-early Pleistocene West Salton detachment fault preserves some of the world's most spectacular fault-related pseudotachylytes along its fault plane and injected into both its hanging wall and footwall in southernmost California. Damaged fault rocks and pseudotachylyte comprise ~15-20% of the clasts of Pliocene syndetachment conglomerates. In the fault core, composite pseudotachylyte-ultracataclasite zones are up to 1.25 m thick and persists over lateral distances up to ~400m. Pseudotachylyte is common in most thin sections of damaged fault rocks with more than 20% of cataclasite. Metasedimentary rocks host the thickest and most voluminous pseudotachylyte, which occur in the most exhumed exposures of the detachment fault at the tip of Yaqui Ridge. We recognized the presence of original melt using numerous criteria: abundant spherulites in thin sections, injection structures at both the thin-section and outcrop scale, black aphanitic textures, quenched vein margins, variation in microcrystallite textures and/or size with respect to the vein margin, tiny vesicles and amygdules, and glassy textures in hand sample. Multiple earthquakes likely produced the thickest pseudotachylyte-ultracataclasite lenses in the fault core. Kairouz (2005) documented the late Cenozoic age of the pseudotachylyte-ultracataclasite le nses in the fault core. The late Cenozoic West Salton detachment fault is strongly guided by the late Cretaceous Eastern Peninsular Ranges mylonite zone and, in the area of thickest pseudotachylyte at Yaqui Ridge, nearly perfectly reactivated the older thrust-related mylonite zone at the kilometer scale. We infer that the West Salton detachment fault formed and slipped at low angles because it nearly perfectly reactivates a Cretaceous ductile thrust system and is currently a low angle structure with dips between ~10 and 45°, averaging about 30° at Yaqui Ridge. These relationships indicate a low dip on the detachment fault when the detachment was active, when it produced voluminous pseudotachylyte during earthquakes, and when the supradetachment basin above it received a large volume of sediment eroded from the pseudotachylyte-bearing parts of the damage zone. To interpret the pseudotachylyte as the product of slip across a detachment when it was dipping at least 45° requ ires the following improbable sequence of events: Formation of the Eastern Peninsular mylonite zone within a low-angle top-to-the-west ductile thrust zone, tilting to steep dips by an unknown and undocumented structure, reactivation of the steepened thrust zone by the West Salton detachment fault, seismic slip across the West Salton detachment fault at moderate to steep dips, untilting of roughly equal magnitude but opposite sense to a dip of less than 30° by a second undocumented and unknown

structure, followed by small amounts of local steepening within a Quaternary contractional stepover of a younger dextral fault zone. This alternative is so unlikely that we conclude there must have been seismic slip at low angles across the West Salton detachment fault. Our conclusion agrees with prior studies by B. John and G. Axen in the Chemehuevi and Whipple metamorphic core complex and increases the published catalogue of detachment faults that sport pseudotachylytes.

Spatial and Temporal Variation in Extensional Strain in Response to a Tectono-Magmatic Cycle: Insights from an Obliquely Spreading Ridge Segment, SW Iceland

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Rifting in continental lithosphere commonly involves an interplay between tectonic and magmatically assisted extension, characterized by spatial and temporal cyclicity. In the case of oblique extension, transtension models can be used to ascertain the instantaneous strain orientation, which can then be compared to field observations of the orientation of deformation features (normal faults, joints, and dikes) and any kinematic indicators to see if theory and observation can be reconciled. Where magmatic events are episodic, a secondary state of stress may be superimposed on a region of the lithosphere during dike intrusion, resulting in variable kinematic behavior along rift zone faults from magmatic to amagmatic periods. Punctuated magma-assisted extension episodes may ultimately result in a transition to transform-like (or highly oblique) motions during later amagmatic periods in order to average out the long-term oblique displacements across the rift zone. In response, the instantaneous extensional strain axis may oscillate as magmatic episodes come and go, greatly affecting fault activity. As similar extensional processes and tectono-magmatic cyclicity exist along oblique spreading centers, they may provide insights into the long-term effects of magmatic influences during continental rifting. The Reykjanes Peninsula of SW Iceland is one potential analog. As the Mid-Atlantic Ridge comes onshore at the Reykjanes Peninsula, it bends towards an 075 trend that is about 30 degrees oblique to the 105 degree NUVEL-1A plate motion direction. The Reykjanes Peninsula ridge segment is composed of normal, oblique-slip, and strike-slip faults, gaping vertical fractures, and eruptive fissures. Much of this deformation is localized within four NE-trending fissure swarms, each associated with its own magma system, and comprised of an assemblage of closely related fractures and normal faults. The last eruption on the peninsula occurred in the 13th century. De spite the long-term plate motion direction, current motions along the rift axis deduced from GPS-derived velocities and seismic data are distinctly transform-like. The presence of large normal fault scarps despite the lack of contemporary normal fault motions provides evidence for a temporal partitioning of strain into transform (strike-slip fault) and extensional (normal fault) components. Most of the left-lateral component of the oblique spreading is taken up by NNE-trending, right-lateral strike-slip faults (bookshelf faulting) that span the full length of the peninsula with no correlation to the locations of fissure swarms. These are the faults that have been historically active. The fissure swarms trend perpendicular to the long-term strain direction associated with plate motion, implying that the broad-scale structural fabric of the lithosphere is directly related to the spreading obliquity. Nonetheless, at the 100s of m scale, fault traces have a zigzag pattern compri sed of two orientations (30 degrees different in strike) where they broke through postglacial lava flows that covered the faults, implying two distinct strain directions. At the 10s of m scale, faults and fractures display left-stepping, en echelon segments oriented 10–15 degrees clockwise from the general trend of the array, but this pattern is not consistent in the eruptive fissures, which may thus have been the cause of these fault geometries. The left-stepping geometry suggests a rotation of the stress field that induced right-lateral oblique slip events. Interestingly, opening vectors across these left-stepping fractures

often indicate left-lateral motion. The faults thus have a complex, oscillatory kinematic history. As there has been minimal recent slip on normal faults having up to 10 m of throw in 2–12 ka lava flows, there must have been periods of time in the past 12,000 years when normal faulting dominated. Eruptive fissures (dikes) are consistently found in close proximity and subparallel to the fault traces. The field observations, combined with numerical models of dike effects on faults, imply that normal faulting predominates during the extensional strain field characteristic of magmatic periods (with right-lateral oblique slip partially due to perturbations of the stress field by the intruding dikes), whereas strike-slip faulting predominates during amagmatic periods. As normal fault activity decreases, there is also a transition to left-lateral oblique motion due to the rotation of the extensional strain axis as the magmatic influences wane. These oscillations repeat on the time scale of magmatic episodes on the peninsula, perhaps every 1000-2000 years.

Velocity structure of the Arabian Shield crust and upper mantle from body and surface wave tomography

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The P and S wave velocity structure of the shallow upper mantle beneath the Arabian Shield had been modeled by inverting body wave travel times and Rayleigh wave phase velocity measurements between 45 and 140 s together with previously published Rayleigh wave group velocity measurements between 10 and 45 s. The velocity models show a broad low-velocity region to depths of 150 km in the mantle across the Shield and a narrower low-velocity region at depths greater than 150 km localized along the Red Sea coast and Makkah-Madinah-Nafud (MMN) volcanic line. The velocity reduction in the upper mantle corresponds to a temperature anomaly of 250– 330 K. These findings, in particular the region of continuous low velocities along the Red Sea and MMN volcanic line, do not support interpretations for the origin of the Cenozoic plateau uplift and volcanism on the Shield invoking two separate plumes. When combined with images of the 410 and 660 km discontinuities, body wave tomographi c models, a S wave polarization analysis, and SKS splitting results for the Arabian Peninsula, the anomalous upper mantle structure in our velocity models can be attributed to an upwelling of warm mantle rock originating in the lower mantle under Africa that crosses through the mantle transition zone beneath Ethiopia and moves to the north and northwest under the eastern margin of the Red Sea and the Arabian Shield. In this interpretation, the difference in mean elevation between the Arabian Platform and Shield can be attributed to isostatic uplift caused by heating of the lithospheric mantle under the Shield, with the significantly higher elevations along the Red Sea coast possibly resulting also from lithospheric thinning and dynamic uplift.

Relationships Between Crustal Structure and Extension in the Basin and Range Province and East Africa

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The Basin and Range Province of the western United States is an unusually wide continental rift zone, and its structure and evolution have been the topic of much debate. Large scale Cenozoic extension has exhumed mid-crustal rocks (from 10-20 km depth) along low angle detachment faults to create metamorphic core complexes. In contrast to the extreme amounts of extension and internal deformation of the Basin and Range, the Colorado Plateau has remained a relatively rigid block, with a crustal thickness of 40-50 km that was resistant to Laramide compression and Basin and Range extension. Integrated studies undertaken using seismic refraction/wide-angle reflection, gravity, remote sensing, and geologic data have delineated a relatively uniform crustal thickness of 27-31 km within the Southern Basin and Range, 32-36 km thick crust in the Transition Zone, and 37-42 km thick crust in the southwesternmost Colorado Plateau. However, the velocity of the lower crust rarely exceeds 6.5 km/s indicating that mafic material is volumetrically insignificant. There are areas of thickened lower crust that correlate with regions of greatest extension (Death Valley, Lake Mead, and Colorado River extensional corridor) and the long wavelength (100-400 km) component of the Bouguer gravity anomaly field. The seismic velocity and density of these lower crustal features indicate that they are either intruded by mafic material, the result of the intrusion of intermediate composition rocks directly from the mantle or the result of lateral ductile flow. In contrast, the crust in along the Eastern arm of the East African rift varies greatly axially in a way that correlates with the amount of extension. Here and in the Main Ethiopian rift, the magmatic modification of the crust is significant, but the crustal column is still that of a modestly extended cratonal area. The magmatic modification of the crust is primarily mafic and correlates with volcanic events and features in a logical way.

The Main Ethiopian Rift: A narrow rift in a hot craton?

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The Main Ethiopian Rift (MER) is a classic example of a narrow rift, but the MER may not have developed in initially thick, strong continental lithosphere as is commonly thought and as might be expected from the Buck model of modes of continental lithospheric extension. We present a synthesis of our results from the EAGLE (Ethiopia-Afar Geoscientific Lithospheric Experiment Phase I broadband experiment) and from the EBSE experiment (Ethiopia Broadband Seismic Experiment). Our joint inversion of receiver functions and Rayleigh-wave group velocities for crust and upper-mantle velocity indicates that the MER is a narrow rift that developed in thin, hot, weak continental lithosphere. The shear-wave velocity of the lowermost crust across the MER and the Ethiopian Plateau is 3.6-3.8 km/sec, 0.2- 0.4 km/sec lower than the shear-wave velocity of the lowermost crust in the Eastern and Western branches of the East African Rift System. The shear-wave velocity of the uppermost mantle ben eath the MER and the Ethiopian Plateau reaches a maximum of 4.3 km/sec, 0.3 km/sec lower than the maximum value of 4.6 km/sec in Tanzania. The very low shear-wave velocity in the upper-mantle, high electrical conductivity in the lower-crust, and high shear-wave splitting delay times beneath a very broad region of the MER and the Ethiopian Plateau indicate that a hot lower-crust with partial melt is responsible for the low lower-crustal velocities we find in our receiver function and surface wave joint inversion. The MER developed as a narrow rift at the surface, likely following the Neoproterozoic suture that joined East and West Gondwana, along which it could localize in the upper- and middle-crust. However, a far broader region (~400 km wide) of the lower crust and uppermost mantle apparently remains thermally weakened since the Oligocene formation of the flood basalts by the Afar plume head or a broad thermal upwelling. The ductile lower-crust and thermally-weakened upper mantle significantly reduce the vertically integrated strength of the lithosphere. The development of both the Eastern/Western branches of the East African Rift System to the south and of the MER in the north as narrow rifts, despite vastly different lithospheric strength profiles, indicates that inherited structure, rather than rheological stratification, is the primary control on the mode of extension in these continental rifts. The MER has developed as a hybrid rift mode, with a narrow zone of strain accomodation in the upper and middle crust and a much broader zone in the lower crust and upper mantle.

Plaeomagnetic evidence for Rift-ward dipping Volcanic rocks at a nascent passive margin, Kereyou Lodge Section, Main Ethiopian Rift (MER) and their possible correlation to Seaward dipping reflectors (SDR).

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Twenty-four cooling units from the over 110 meters Early Pleistocene extrusive volcanic rocks were sampled for magnetostratigraphic studies at the Kereyou Lodge Awash River Valley section, Awash National Park, Main Ethiopian Rift. Seven to ten samples were collected from each unit and only seven were enough for both Thermal (TH) and Alternating Field (AF) paleomagnetic analyses. The Natural Remanent Magnetization (NRM) direction reveals two simple and straightforward components. The first and low stability component is generally isolated by heating to 100ºC-250ºC or by AF of 10-15mT. The magnetization direction after these steps has defined a straight line that is directed towards the origin, which is interpreted primary NRM or ChRM (Characteristic Remanent Magnetization). Paleomagnetic site mean directional analyses revealed, top 17 flows are reversed, 3 are transitional and bottom 4 flows are normal magneto-zones. Using available age information the normal interval is co rrelated to the Olduvai subchron on the Geomagnetic Polarity Time Scale (GPTS) of Cande & Kent (1995). Hence the three transitional flows are dated to be 1.77 Ma and the overall section is dated to be between 1.6—1.8 Ma. The overall mean direction calculated for the entire section excluding one of the most removed transitional directions resulted in N=23 D=355.20, I=14.70, K=37, a95=50. When this value is compared with expected Geomagnetic Axial Dipole (GAD) Field obtained from Apparent Polar Wander Path (APWP) Curve (Besse & Courtillot, 1991, 2003), a difference in declination DD = -5.80 ± 5.70, and an inclination difference of DI = 1.70 ± 5.50 were obtained. The negative declination difference reflects counterclockwise rotation about a vertical axis, in agreement with oblique rifting geometry and associated transtenssional structures described by Casey et al. (2006). The positive inclination difference, on the other hand, which is negligible taken the uncertainty, might re flect small inclination shallowing. However, when site-mean inclinations versus flow positions are plotted a systematic inclination change with flow position. The top reversed flows have a progressive inclinations shallowing where as the bottom normal flows have a progressive inclination steepening. This change can only be achieved by a progressive rotation about a horizontal NE-SW oriented axis viewing towards Northeast. For the Kereyou Lodge magnetostratigraphy section, this would mean that the beds are progressively dipping towards northwest or toward the rift in this case. The systematic inclinations change with depth could be linked to continuity of the fault slip during the emplacement of the volcanic rocks similar to growth faults in sediments. This observation is similar to reports of rock tilting in well-developed Seaward Dipping Reflectors (SDR) in mature margins where they are recognized mostly through seismic study. The present study suggests that the tilting observed in SDR might also have a similar progressive tilting nature and therefore, magnetostratigraphy study along this nascent passive margin in the Main Ethiopian Rift might be instructive as a

comparison to those in well-developed SDR in mature margins, which are buried several hundred meters deep and are situated under waters.

Geologic and Hydrologic Role of Sill Intrusion and Delineation of the Oceanic Crustal Boundary in the Central Gulf of California

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High-resolution multichannel profiles recently shot in the central Gulf of California display concordant and discordant (concave-upwards) sills intruded shallowly within (I) young sediments in the axial troughs of Guaymas, Carmen and Farallon Basins, (II) off-axis in the basin floors, and (III) within the sediment cover of subsided and extended continental crust. We interpret some imaged sills as 3D saucer-shaped intrusions based on their concave-upward profiles, the overlying circular and elliptical plans of domal uplifts of the present multibeam-mapped seafloor, and their striking resemblance to field-mapped and 3-D seismically imaged saucer-like sills. Vertical zones of high-amplitude, disturbed reflectors leading up from sills are probably "blow-out pipes" acting as conduits for hydrothermal fluids and gases migrating up and away from the heated sill-sediment contact aureole, forming pockmarks on the present seafloor. Seismic evidence of sill intrusions into the shallow c rust throughout the central gulf suggests melt is being delivered not just to spreading centers, but to a much broader area of oceanic and continental crust. We have improved the delineation of the oceanic/continental crustal boundary in the central and southern gulf by sampling igneous basement (tholeiitic basalt and gabbro = oceanic; granitic = continental), by identifying the extent of magnetic stripes diagnostic of seafloor spreading, by interpreting multichannel reflection profiles, and by geomorphology. Although the "boundary" is somewhat smeared by the intrusion of shallow sills (some known to be tholeiitic, most inferred to be) into the cover of both granitic and oceanic basement, we find no evidence of "transitional zones" of hybrid crust; at those sheared and rifted margins where basement is accessible, granite commonly abuts tholeiitic flows and sills. Seafloor spreading magnetic anomalies, with low amplitudes and broad transition widths, can be read out to C2Ar i n Alarcon Basin, and C2An.1 in Guaymas Basin (but only on profiles that avoid major off-axis seamounts and intrusions); in both cases they indicate significantly slower accretion during the first 1 m.y. of spreading, presumably because of concurrent continued extension of the rifted margin. Widespread sill intrusion over continental basement does hamper identifying the ocean/continental boundary on seismic reflection profiles, and because the already thin Cordilleran crust was clearly highly extended during prolonged rifting we do not think that crustal thickness is a reliable criterion for the extent of oceanic crust.

New investigations of an ultra-slow continental rifting revealed from hydroacoustic monitoring in the Bransfield Strait, Antarctica

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From November 2005 to December 2007, we have operated an Autonomous Underwater Hydrophone (AUH) array in the Bransfield Strait and the Drake Passage, Antarctica. The array takes advantage of the efficient propagation of sound in the oceans to detect, locate and analyze the temporal and spatial distribution of small- to moderate-size earthquakes along the South Shetland Islands, Bransfield Strait and Scotia Sea. During the mooring period, a total of 3,146 earthquakes occurred in the Bransfield back-arc basin, while 3,900 total earthquakes were located from throughout the region including the South Shetland Trench and the Drake Passage. The seismic activity included eight space-time earthquake clusters, or swarms positioned along the central rift zone of the young Bransfield back-arc system implying the swarms are likely due to magmatic activity. During a recent cruise, KOPRI personnel dredged several continental rock samples from the eastern Bransfield basin. These samples inc luded granites and gneiss as well as a few volcanic rocks, indicating the region may be undergoing passive continental rifting. In addition to the occurrence of earthquake swarms, this evidence is consistent with a transition from volcanic to fault driven rifting from the SW to NE within the Bransfield. A total of 122 earthquakes were located along the South Shetland trench, indicated continued deformation and possibly ongoing subduction along this margin. Given the extinction of the Phoenix-Antarctic Ridge (Lawver et al., 1996), seismicity in the trench and back-arc is likely a result of slab rollback. Earthquake swarms, combined with the ~10 mm/yr spreading rate from GPS measurement (Dietrich et al., 2001), demonstrate that the Bransfield Strait is in an ultra-slow continental rifting regime.

Along-strike variations in margin width and magmatism in the eastern Gulf of Aden: A combined MCS-OBS-Heat flow survey (Encens experiment)

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Fundamental characters of rifted-margins are commonly related to the large-scale processes prevailing during rifting: volcanic margins are for instance attributed to the interaction between regional extension and mantle plumes. However, more local variations have been identified at the scale of margins segments, but not been yet investigated in details. Here we present new observations from three sub-segments of the eastern Gulf of Aden that evidence clear relationships between the structure of the crust, the thermal regime and the development of the Ocean Continent Transition (OCT). Over short lateral distances (10 kilometres), OCT can evolve from wide, highly deformed and non-magmatic domains to narrow and volcanic domains, which characterize usually end-members of rifted-margins. However, such rapid transitions cannot be attributed to similar large scale characters but more likely to local heterogeneities in the pre-existing crust, mantle fertility and from the obliquity of rifting.

Cenozoic continental margin rifting and break-up along the Xisha Trough and the northwest sub-basin of the South China Sea

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The Xisha Trough is often regarded as a failed rift located to the west of the northwest sub-basin, which itself is a narrow and short-lived oceanic basin of the South China Sea. The main phase of seafloor spreading later occurred to the south of these features from approximately 25 Ma to 16 Ma. This mechanism of multiple episodes of opening of the South China Sea as well as the tectonic link between the Xisha Trough and the northwest sub-basin are rather vaguely understood. In this presentation, we use newly acquired multichannel reflection seismic data in this area to better delineate the styles and dynamics of Cenozoic rifting, subsidence, and seafloor spreading.

Initial emplacement of oceanic crust in the Central Red Sea

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For over two billion years the Earth's internal engine has triggered a cyclical process (period about 500 m yrs) whereby continents assemble in a single super continent and then gradually fragment and disperse again. A major step in this "Wilson Cycle" is the splitting of a continent and the birth of a new ocean, with the consequent formation of passive plate margins, such as those found today along the edges of the Atlantic and Indian oceans. Nowhere in today's Earth is this process better displayed than in the Red Sea, where Arabia is separating from Africa. The transition from continental to oceanic rifting in the Red Sea appears to start in discrete "cells" and to proceed by axial propagation from south to north. We obtained multibeam, magnetics, and seismic reflection data as well as bottom rock samples from the two northernmost axial segments of clear initial oceanic crust injection in the Red Sea. They are the Thetis Deep and the Nereus Deep. Thetis Deep is actually ma de of three subbasins: the emplacement of oceanic crust started about 3 million years ago in the southern subbasin; between 1 and 2 million years ago in the central basin, and less than 0.7 million years ago in the northern basin, with a clear northward propagation. Zero age intensity of magnetization and mantle degree of melting (obtained from basalt chemistry) are highest in the northern, youngest subbasin. These data not only confirm that oceanization starts in discrete axial cells, but reveal a strong "active" initial burst of oceanic crust generation and sea floor spreading at each cell as soon as the continental lithosphere lid breaks, followed by along-axis propagation and more "passive" emplacement of oceanic crust.

Tectonic controls on the Waipaoa Sedimentary System N.

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The Waipaoa Sedimentary System is situated in the northern part of the active Hikurangi Subduction Margin, where the total Pacific-Australian plate convergence rate is ~55 mm/yr. The Waipaoa River catchment drains the uplifted Mesozoic basement-cored backstop and overlying Paleogene passive margin sediments and Neogene forearc basin. The offshore part of the Waipaoa Sedimentary System is situated on the Neogene accretionary wedge. The first-order tectonic controls on the geometry and behaviour of the Waipaoa Sedimentary System are relatively well understood. Rapid erosion in the headwaters is driven in part by rapid regional scale uplift (>3 mm/yr) occurring in response to deep-seated subduction processes such as sediment underplating. Erosion in the middle reaches is partly driven by passive uplift at moderate rates (approx. 1 mm/yr), although higher incision to the NE may reflect a down-to-the-SW tilting, which has also resulted in subsidence and deposition beneath the lower floodplain (Poverty Bay and Flats). The mechanism for this tilting is less well understood, but may relate to a stepover in the currently locked part of the subduction interface. The continental shelf and upper slope are characterised by fault-controlled synclines and anticlines, which have produced a series of subsiding sedimentary basins and uplifting Neogene sediment-cored structural highs. The lower continental slope is chara cteristically steep and cut by a series of eroding canyons and is largely shaped by seamount impact and tectonic erosion at the Hikurangi Trough. New work has recently been completed to quantify the magnitude and frequency of large (>Mw6) earthquakes impacting the Waipaoa River Catchment, as the first step towards understanding the relative role of tectonic perturbations on the sedimentary system. This was undertaken using standard probabilistic seismic hazard analysis methodologies: 1. compile earthquake sources (active faults and historical or distributed seismicity), 2. calculate Mw and RI (using regressions for historic earthquakes calibrated by field data for the active faults and Gutenberg-Richter relationships for distributed seismicity), (iii) calculating Modified Mercalli Intensity (MMI) using attenuation relationships, (iv) compiling all the results to calculate combined magnitude and frequency estimates. The results indicate that earthquakes impacting relatively large areas (750 km2) of the Waipaoa River catchment could produce MM7 approximately every 7 years, MM8 every 37 years, and MM9 every 230 years. The se calculated earthquakes are more frequent than previously appreciated and evidence from historical earthquakes indicate they could produce significant landsliding. The calculated dominant earthquake source is the distributed seismicity, followed by the offshore Gable End Fault (Mw7.2, RI 760 yrs) and the Hikurangi subduction interface (Mw8.2, RI 970 yrs). The magnitude and frequency of earthquakes impacting the NW half of the catchment are similar to those impacting the SE half, although the sources are slightly different, with faults of the North Island Dextral Fault belt providing a greater contribution in the NW. Faults within the catchment (e.g., the Repongaere Fault) have relatively low magnitudes and long recurrence intervals, and thus are not a significant source of large earthquakes.

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This work has involved a large number of Mexican and U.S. collaborators who would have been listed as coauthors if I'd had the time to coordinate it; notable are T. **Orozco** and L. **Ferrari** (UNAM); M **Lopez**, A **Gonzalez** and A. **Martin** (CICESE); P. **Castillo** (Scripps), B. **Eakins** (NOAA), D. **Kimbrough** (San Diego State U.) and M. **Grove** (Stanford U.). I'm not sure how many of them plan to attend the meeting. My planned presentation forms a "group" with the one planned by my graduate student J. Kluesner Exploration of eruptive volcanism on continental and oceanic crust flooring the central Gulf of California Two sampling campaigns, one using precision dredging and one with the JASON ROV, have collected lavas and volcaniclastic rocks from several hundred outcrops located by multibeam reflectivity in this generally muddy MARGINS focus area. Dating and even geochemical analysis of this diverse suite of rocks is incomplete, so any interpretations are provisional. Available results do clarify the pattern and nature of subaerial and submarine volcanic activity on now submerged continental crust during (pre-Gulf) mid-Miocene "arc" volcanism, post – 11Ma proto-Gulf rifting and post -8Ma (?) flooding, and on both continental and oceanic crust during Plio-Pleistocene seafloor spreading. Outcroups include erosional remnants of the pre-Gulf arc exposed (together with underlying Cretaceous and mid-Miocene granitic plutons) at major fault scarps, uneroded (submarine-erupted) seamounts on continental and oceanic crust, and small pillow cones among the many intrusive mounds in the axes of some spreading centers (North Pescadero, Carmen, Sal si Puedes). These axial pillow cones, and young probably intrusive basalt from oceanic fault scarps in South Pescadero and Farallon Basins, are tholeiitic in composition, and remarkably similar to lavas on the crest of the EPR. Small seamounts that have grown off-axis through the thick sediment of Farallon and Guaymas Basins have both tholeiitic pillow basalt and more fractionated dacitic to rhyolitic lavas, the latter closely resembling the (subaerial) Salton Buttes. Some young volcanoes that have grown on submerged continental crust have the same range of fractionated sub-alkalic lavas, but some are highly alkalic, with almost phonolitic compositions (11% Na2 0+K20). Alkalic basalts and more silicic tuffs are the commonest volcanic rocks from the proto-Gulf period, but there are also extensive outcrops of Pliocene rhyolite from ocean/continent boundary sites adjacent to rifted and sheared margins. We hope that when analyses and dating of this large suite of volcanic rocks is more complete, speculation about the changing amounts, patterns, and chemistry of Gulf volcanism (derived from extrapolation from the subaerial margins of the flooded depression, theoretical models, or analogies to other rifting/spreading provinces) can be replaced by direct geological interpretation of stones from the seafloor.

Landscape evolution at a young rifted margin, near Loreto, Baja California Peninsula, Mexico

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High-relief escarpments developed along rifted continental margins are some of the most dramatic landforms observed on the Earth's surface. They rim the coastlines of Southern Africa, SE Australia and the Red Sea. The origin of these escarpments has been one of the most debated and controversial topics in studies of landscape evolution. However, numerous questions remain about their evolution, and in particular hypotheses for their mode of retreat are polarised between two opposing views. The aim of this project is to focus on one of the youngest developed rift margins – the western margin of the Gulf of California - to investigate the processes of landscape evolution at a young rifted margin. The Main Gulf Escarpment, located in the Mexican states of Baja California and Baja California Sur, is a superb example of a young passive margin escarpment. Generally considered to be no older than twelve million years, the escarpment offers an opportunity to gain insights into the early tectonic and erosional development of rift margin escarpments. The aim of this project is to reconstruct the geomorphic evolution of the escarpment in the Loreto area of Baja California. Here, the escarpment has retreated several kilometres away from the Loreto fault. The project aims to determine how the escarpment retreated and at what rate, and what processes controlled the retreat. As such it provides an excellent opportunity to test recent numerical models of escarpment retreat. In the Loreto region of Baja California the Main Gulf Escarpment exhibits west-draining beheaded valleys of enigmatic origin, ranging up to ~7 km in cross-sectional width. Incised into pre-rift volcaniclastic material, such valleys may be relics of the drainage system prior to Late Miocene rifting of the Protogulf of California. Our initial study will seek to use U-Pb and fission track analysis on detrital heavy minerals within the sediment fill of these valleys to constrain depositional age and provenance. This will allow an increased understanding of the relationship between rifting and drainage within the Gulf of California extensional province, including an enhancement of the chronology of early rifting. Future work will investigate the exhumation history of the Main Gulf Escarpment in the Loreto area using low-temperature thermochronology.

Structure, Stratigraphy, and Recent Volcanism in the Northern Gulf of California: Implications for the delay of sea-floor spreading

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Along-strike variation of rifting in the Gulf of California and Salton Trough region is distinctively marked by thick (>6 km thick) sedimentary sequences in the northern Gulf basins, whereas across-strike variation of rifting is manifested by an asymmetric locus of volcanism and recent seismicity along the western rift margin. Interpretation of several exploratory wells, seismic reflection (from PEMEX), magnetic and gravity data indicates that the northern Gulf of California contains two parallel, north-south trending rift-basin systems separated by a basement-high. In both basin systems the lower sequence (A) is composed of marine mudstone-siltstone, has parallel reflectors with a maximum thickness of 1.5 km, and gradually pinches out toward the lateral margins. Marine microfossils from borehole samples from sequence A in the Tiburon and Consag basins indicate mid-Miocene to late Miocene (>11.2 Ma) proto-Gulf conditions. This age indicates that subsidence could be related to either plate margin shearing beginning in the middle Miocene or a different phase of early extension. Sequence B conformably overlies sequence A, and is characterized by up to 2 km growth strata with a fanning geometry that clearly shows a genetic relationship to the major transtensional faults that control the segmentation of the two basin systems. Microfossils from sequence B indicate a late Miocene to Pliocene age. Sequence C in the Tiburon and Tepoca basins is comparatively thin (<800 m) and includes several unconformities, but is much less affected by faulting. In contrast, sequence C in the active Wagner, Consag and Upper Delfin basin towards the NW is a much thicker growth sequence (up to 2 km) with abundant volcanic intrusions. Marked variations in sequence C in the different basin systems and abandonment of the Sonora and Sinaloa clearly demonstrate a major westward shift of plate-margin shearing, which is thought to have occurred in the last ~2 Ma.

Volcanoes and shallow intrusions are conspicuous within the active rift basins and western margin and provide a unique opportunity to characterize crustal accretion beneath the thick sedimentary sections and/or thinned continental crust. Most Quaternary volcanoes in the northern Gulf basins are rhyolite to andesite lavas with depleted (relative to CHUR) Nd isotopes. Basaltic xenoliths and rhyolite from Salton Buttes have eNd values of +8.5 and +6.3, respectively (Herzig and Jacobs, 1994). Andesite, dacite and rhyolite rocks from Roca Consag, Lower Delfin and Isla San Luis yield marginally lower values (eNd +6.5 to +4.1). Rhyolite from the Upper Delfin basin and dacite from Cerro Prieto yielded Nd of +2.2 and +0.5, respectively. These values are consistent with overall depleted $^{87}Sr/^{86}Sr$ ratios (0.70353-0.70382). Only rhyolites from Lower and Upper Delfin basin, Salton Buttes and dacite from Cerro Prieto have higher $^{87}Sr/^{86}Sr$ (0.70492-0.70661) compared to coexisting dacites and andesites, which suggests that these rocks may have experienced hydrothermal alteration and/or contamination of continental crust. In general, the isotope data indicates recent differentiation of dominantly mantle-derived young crust. The preponderance of intermediate to felsic volcanism in the northern Gulf of California suggests that only low-density magmas can reach shallow levels and may form a significant volume of new crust within the active rift basins. Our goal is to understand the thermal affects associated with abundant volcanism along the western rift margin that likely controlled the asymmetric partitioning of plate shearing.

Subduction-generated mantle chemical heterogeneity and effects on continental rifting: insights from back-arc basins.

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In continental rifts, large variations in magma production and tectonic extension are observed and are increasingly attributed to modifications of mantle composition by earlier subduction events. In the Gulf of California, recent studies [Lizarralde et al., 2007] show large and abrupt variations in magmatic productivity and tectonic extension across individual spreading segments. Because of the short spatial scales involved mantle compositional variations are proposed to control these variations, rather than mantle temperature changes which are inferred should be more gradational and regional in extent. In the Newfoundland margin exposures of exhumed serpentinzed mantle indicate high degrees of depletion by prior melt extraction, [Müntener and Manatschal, 2006]. In both these cases the chemical pre-conditioning of the mantle in a subduction zone setting prior to rifting is indicated, however, the subduction itself is long extinct. To more directly examine how mantle chemic al heterogeneity is generated in a subduction setting and its effects on crustal accretion we present geophysical observations from several active back-arc basins. In these basins, strongly subduction-influenced mantle has interacted with back-arc spreading centers and generated a diverse assemblage of terrains providing a window into how upper mantle chemical heterogeneity is produced, evolves and affects crustal production above an active subduction zone. Subduction introduces water and other volatiles into the mantle wedge, lowering the solidus temperature and thereby increasing melt productivity. Subduction and trench rollback also induce melt extraction processes from the mantle wedge in back-arc spreading centers, at the volcanic arc and in rear-arc volcanic chains. Melt extraction produces a strong and refractory mantle thereby decreasing its subsequent magmatic productivity. Thus subduction can both increase or decrease melt productivity and produces related rheological effects. Subduction-modified mantle shows a variety of spatial patterns in active arcs and back-arc basins. The loci of arc magma production are spaced at intervals of 10's of km along the volcanic front and in rear-arc chains. At backarc spreading centers magmatic productivity can be robust or deficient over distances on the order of 100 km along axis but change abruptly with only a few km separation of the spreading axis from the volcanic front. We pr esent a compilation of geophysical observations from the Bonin, Mariana, Tonga, Manus and Scotia arc/backarc basins showing how active subduction processes influence magmatic crustal accretion. As the Wilson Cycle implies that continental rifts form over previously sutured subduction zones, modern supra-subduction setting may provide important insights into controls on magmatism and rheology in active as well as ancient continental rifts. References: Lizarralde, D., G. J. Axen, H. E. Brown, J. M. Fletcher, A. Gonzalez-Fernandez, A. J. Harding, W. S. Holbrook, G. M. Kent, P. Paramo, F. Sutherland, and P. J. Umhoefer (2007), Variation in styles of rifting in the Gulf of California, Nature, 448(7152), 466-469. Müntener, O., and G. Manatschal (2006), High degrees of melt extraction recorded by spinel harzburgite of the Newfoundland margin: The role of inheritance and consequences for the evolution of the southern North Atlantic, Earth Planet. Sci. Lett., 252(3-4), 437-452.

FEMs of transient volcano deformation: Accounting for rheologic contrasts.

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InSAR data reveal that the caldera of Okmok volcano, Alaska, subsided more than a meter during its eruption in 1997. The large deformation points to a shallow magma chamber beneath Okmok. Seismic tomography using ambient ocean noise reveals a significantly deeper magma chamber (>4 km), compared to previous geodetic-based estimates (3 km), and a low velocity zone corresponding to a region of weak, highly saturated materials within the caldera. This shallow low velocity zone extends from the caldera surface to a depth of 2 km. The deep low velocity zone associated with the magma chamber suggests magma remains in a molten state between eruptions. We construct finite element models (FEMs) to simulate deformation caused by mass extraction from a magma chamber that is surrounded by a viscoelastic rind and embedded in an elastic domain partitioned to account for the weak caldera materials observed with tomography. This configuration allows us to reduce the estimated magma chamber de pressurization to within lithostatic constraints, while simultaneously maintaining the magnitude of deformation required to predict the InSAR data. More precisely, the InSAR data are best predicted by an FEM simulating a rind viscosity of 7.5x10^16 Pa s and a mass flux of 4.2x10^9 kg/d from the magma chamber. The shallow weak layer within the caldera also provides a stress regime that supports dike arrest and lateral magma propagation to the rim of the caldera, which explains the lateral offset of magma extrusion compared to the location of the magma chamber beneath the center of the caldera.

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Global Positioning System (GPS) measurements broadly distributed around the Arabian and Nubian plates constrain present-day plate motions and intra-plate deformations, and quantify patterns and rates of deformation along the Red Sea rift. Broad-scale motion of the Arabian plate indicates coherent plate motion (wrms residuals = 0.6 mm/yr) with internal deformation below the current resolution of our measurements. The GPS-determined Euler vector for Arabia-Nubia is indistinguishable from the geologic Euler vector determined from marine magnetic anomalies (Chu and Gordon, 1998). Agreement between broad-scale GPS rates of extension (i.e., determined from relative plate motions) and those determined from magnetic anomalies along the Red Sea rift imply that spreading in the central Red Sea is at present primarily confined to the central rift (±10%). This deduction is supported by GPS profiles oriented perpendicular to the Red Sea in Saudi Arab ia that indicate no resolvable deformation of the uplifted rift flanks. In addition, the relationship between plate motion rates and the width of the Red Sea along strike from the Sinai micro plate to the Afar Triple Junction suggests that rifting initiated simultaneously (± 0.5 Myr) along the full length of the Red Sea at 25±3 Ma, consistent with independent geological estimates of the timing (Garfunkel and Beyth, 2006) and kinematics (Omar and Steckler, 1995) of the separation of Arabia from Nubia. The GPS measurements also indicate that the Red Sea rift bifurcates south of 16°N latitude with one branch following a continuation of the main Red Sea rift (~150° Azimuth) and the other oriented roughly N-S traversing the Danakil Depression/Afar volcanic province. These two rift branches account for the full Arabia-Nubia relative motion. Within the resolution of our observations, the partitioning of extension between rift branches varies linearly along strike; north of ~ 16° N, extension (~ 15 mm/yr at 16°N) is confined to the main Red Sea rift while at the latitude of the Afar Triple Junction (~12°N) extension (~ 20 mm/yr) has transferred completely to the Danakil-Afar Depression. The Danakil block separates the two rifts and rotates counterclockwise, accommodating extension along the rifts and developing the triangular geometry of the Danakil/Afar Depression. Extrapolating the geodetic rates to the time of initial rifting of Arabia from Nubia (25 ± 3 Ma) suggests that extension was initially confined to the main Red Sea rift along its full length with the presently observed bifurcation south of 16°N initiating at about 17 Ma BP.

Interest statement (no abstract)

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As a micropaleontologist, I have been working on the Proto-Gulf and Gulf of California region for many years now, developing a cohesive picture of the age and environmental interpretations based on microfossils. The challenge of this work is integrating the tectonics with the microfossil interpretations as the microfossil ages suggest increasingly older marine incursions in the Proto-Gulf. Recent work has documented the presence of middle Miocene marine microfossils. The distribution, age, and ecological significance of in situ middle Miocene strata presents problems for current tectonic models and needs to be addressed. This is why I would like to participate in the MARGINS workshop this spring

Mantle-crust interactions during different zonal and temporal evolutionary stages of VRM formation.

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The Eurasian–Greenland continental breakup during the Paleocene-Eocene transition marked the culmination of a continental rift system and the development of volcanic rifted margins (VRM) (Meyer et al. 2007). Up to the end of the Danian, the early geodynamic history of this continental breakup is marked by widespread extensional basin formation and localised minor magmatism. A first peak of volcanic activity around 60 Ma caused widespread continental-flood-basalt eruptions and formed numerous large central volcanoes whose eroded remnants now outcrop as igneous centres in West and East Greenland, NE Ireland and NW Scotland. A second "pulse" of high magma eruption rates at ca. 55 Ma coincided with the final breakup of the continents and the initiation of seafloor spreading and emplaced the volcanic seaward-dipping wedges. Different VRM structural zones characterise distinct time-space episodes of the rift-to-drift evolution history : (a) VRM continental flood basalt (CFB) areas mark the late stage of a continental rift. (b) The seaward-dipping wedges are extrusive rock units from the rift to drift transition. (c) High velocity lower crustal bodies (HVLC) presumably reflect massive intrusive complexes near the continent-ocean boundary (COB). Unfortunately, even with state of the art drilling techniques the HVLC will remain an unreachable drilling target for the time being (Meyer et al. in press A). The Paleocene magmatism of the Isle of Rum in NW Scotland forms an integral part of the pre-breakup NAIP continental-flood-basalt tectono-magmatic zone. The igneous rocks of Rum comprise early felsic magmas, that are crosscut by later plutonic ultrabasic to basic Layered Suite. The felsic magmas are considered to originate from melting of gneissic crust (Meyer et al. in press A) by ascending voluminous basic mantle melts. Such associations of "early felsic–later mafic" rocks have also been recovered in cores of ocean drilling campaigns at the North Atlantic seaward dipping wedges, e.g., at the Norwegian Sea (ODP Leg 104; Meyer et al. in press B). At the Vøring Plateau crustal melts (the 'Lower Series', 133 m drilled, total thickness not known) are covered by a 770 m thick sequence of tholeiitic basalts ('Upper Series'). Rum and the Vøring Plateau, however, represent different zonal and temporal evolutionary stages of VRM formation and the here presented comparison of the crustal melting differences in these two locations can contribute to a better understanding of the interactions between ascending mantle melts and crust during continental breakup. References: Meyer, R., Nicoll, G., Hertogen, J., Troll, V. R., Ellam, R. E., Emeleus, C. H. (in press A) Trace element and isotope constraints on crustal anatexis by upwelling mantle melts in the North Atlantic Igneous Province: example from the Isle of Rum, NW Scotland. Geological Magazine Meyer, R., Hertogen, J., Pedersen, R.-B., Viereck-Götte, L., Abratis, M. (in press B) Interaction of mantle derived melts with crust during the emplacement of the Vøring Plateau, N.E. Atlantic. – Marine Geology Meyer, R. van Wijk, J., Gernigon L. (2007) The North Atlantic Igneous Province: A review of models for its formation . – In: G. R. Foulger, D. M. Jurdy (eds.) Plates, Plumes, and Planetary Processes – Geological Society of America Special Paper, 430, 525 – 552.

Upper-mantle Seismic Anisotropy and Salt in the Central Gulf of California

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We will present newly processed multichannel (MCS) reflection and coincident wide-angle seismic data from the 2002 PESCADOR experiment. We use data from the central-Gulf to model crustal seismic structure across the continent-ocean transition on line azimuths oblique to a previously modeled profile across the Guaymas spreading segment. A preliminary model suggests an azimuthal dependency in upper-mantle velocities, constrained by the travel-times of the upper-mantle refraction phase Pn. We interpret this apparent anisotropy as evidence for a lattice preferred orientation in the upper-mantle that developed during near-axis corner flow and remained largely unchanged as upper-mantle material flowed off-axis. This observation may provide important information about the orientation of strain in the upper-mantle during rifting and subsequent spreading. We also interpret a smooth basement reflector in stacked MCS data from the east-central Gulf as the top of a largely autochtho nous salt body. The salt underlies ~2 km of sediments and appears to sit directly on the igneous basement. Mapping of salt volume and areal extent may help constrain the Gulf's sea-level and upper-mantle thermal histories.

Spreading and traps magmatism: a new model on the basis of the concept of the nonlinear lithospheric medium and whirling motions in it

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The evolution of the structural geometry of the different segments of the global mid-ocean ridge system and geological-geophysical data on the most detailed studied spreading zones and trap provinces which connected with evolution of oceanic rift-spreading systems of tectonosphere are analysed. It is shown that whirling movements do take place in the solid Earth during ocean formation and create scale-invariant rifting and spreading systems, where the spreading axis tends to undergo whirling. The size of these systems differs by more than two orders of magnitude. Many geotectonic phenomena that accompany the formation of oceans, including segmentation of the ocean floor and passive continental margins, folding of the sedimentary cover at these margins, tectonic diving into layers of the oceanic lithosphere, may be explained by whirling movements of different dimensions. The whirling movements are realized only in a nonlinear, nonequilibrium medium. In accordance with concept of the nonlinear lithospheric medium its main peculiarities are nonlinearity of proceeding processes and physical properties, richness of energy, discreteness of it structure, instability, high sensitivity to the external influence. According to offered model, the primary centres both spreading, and trap magmatism appear as a result of dissipation of energy in the nonequilibrium nonlinear lithospheric medium owing to influences on it, due to whirling motion of lithosphere. Specific character of these movements which promote rock melting is change of geodynamic conditions from a compression (with shear) to tension (with shear) in each point of accretion zone of lithosphere, and the gradient of transition from compression to a tension increases in process of a whirling of whirl system. The primary trap magmatic centres are formed as in the field of their greatest whirling (provinces of Northern Atlantic, East African and Deccan), also near of the continental margin ledges whic h formation is connected with whirls (Parana- Etendeka). Our model explains formation of the majority of trap provinces near to zones of splitting of continents, short duration of episodes of trap magmatism, and also presence of rotating litospheric microplates in trap magmatism areas.

Particle dynamics simulations of passive margin processes: Controls on gravity tectonics and salt tectonics

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Sediments accumulated on passive continental margins are subject to gravitational sliding and spreading, leading to coupled regions of up-slope extensional and down-slope contractional deformation. The stratigraphy of the slope sediments, and the underlying structure play a strong role in defining the modes of deformation that occur. The presence of weak interlayers, such as salt or shale, allows for significant basinward transport of slope sediments leading to the formation of pronounced deep-water fold and/or thrust belts. These features closely resemble fold and thrust belts that form along convergent margins, but result from gravitational rather than tectonic driving forces. High resolution particle dynamics simulations allow the effects of various stratigraphies, strength contrasts, and sediment loading patterns to be explored. The resulting fold and thrust belt geometries compare well to physical analog models and natural systems. The widths and intensities of the deformed belts are strongly influenced by the thickness, extent, and number of weak interlayers, their strength contrasts with the surrounding materials, and underlying basement structures. The numerical simulations provide preliminary constraints on the mechanical structures and growth histories of documented upper slope extensional systems and deep water fold and thrust belts.

Stress and Strain at the Brittle–Ductile Transition of a Major Strike-Slip Shear Zone: The Kern Canyon Fault, Southern Sierra Nevada, CA

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The Kern Canyon fault (KCF), an ~150-km-long dextral strike-slip shear zone of the southern Sierra Nevada batholith, is analogous to the modern-day San Andreas fault or the Sumatra-Java fault. The KCF began activity at the western edge of North America during Cretaceous time, in response to obliquely directed forces imparted during Farallon plate subduction. Transpressional environments such as this are common in both continental and oceanic settings, and are associated with large strike-slip earthquakes. Geodetic data from modern transpressional faults can be used to assess the relative components of shortening and strike-slip shear in transpressional faults. However, understanding the rheology of deep rocks from modern and ancient settings requires knowing the geologic context of the fault. One particularly valuable feature of the KCF is that it traverses exposure levels of ~25 km, allowing investigation of structures and microstructures of ductile deformation that provide constraints on the distribution of stress and strain from ductile through brittle conditions, including the transition zone. A regional geobarometric database of >200 locations through the batholith, from Al-in-hornblende igneous barometry, constrain the paleodepths of modern KCF exposures. The fault is ~2 km wide in most places—typical of mid-crustal shear zones—and across its width, different rock types including marble, phyllite, quartzite, granodiorite, and amphibolite are variably deformed. Thus, the KCF thus provides a natural laboratory to investigate stress and strain distribution as a function of 1) temperature, 2) depth, and 3) composition. Shear strain analyses of S-C mylonites indicate ~15 km of ductile dextral slip along the KCF. Grain sizes of dynamically recrystallized pure quartz mylonites from ~10 km depth within the shear zone were used to estimate flow stresses of 20-40 MPa. Petrographic observations of surrounding high-strain igneous rocks suggest that dextral ductile shearing started at temperatures of 400-450° C and continued through cooling to ~300° C. These observations match 40Ar/39Ar cooling histories of deformed hornblende, mica, and K-feldspar, which indicate deformation temperatures were ~400–350˚ C in this section of the shear zone from 90–86 Ma. Applying this deformation temperature range and lithostatic pressures of 350–400 MPa yields paleo-strain rates along the PKCF of ~10^-13 to 10^-15/s. Shape-preferred orientations (SPO, or rock fabrics/foliation) give map-scale insight into the distribution of ductile shear across the KCF. At one margin of the shear zone, thickly bedded quartzite with well-preserved original bedding features remained unfoliated, even while interbedded mica-rich layers became pervasively foliated. On the opposite margin, a large-volume igneous body that pre-dates KCF activity has little to no shear fabric. In between these end members, different rock types are weakly to strongly mylonitic. Crystallographic preferred orientations (CPOs), determined through electron backscatter diffraction (EBSD) imaging, gives further insight into which minerals played key roles in localizing stress. Even rocks with no apparent SPO/foliation can have a pervasive CPO indicating (dynamic) recrystallization under applied stress. However, the thickly bedded quartzite has a random CPO, confirming it really did "arrest" shear stress at one margin. Quartz in the apparently unfoliated igneous body at the other margin, in contrast, has a strongly developed CPO

indicating basal slip under greenschist facies conditions. This supports views that in quartz-rich, mixed-phase rocks, quartz is often the weak mineral. Further studies of CPO patterns of mixed-rocks across the KCF will provide insight into the relative development of CPOs for different minerals and identify which minerals localize stress and accommodate strain within the fault zone. Additional EBSD data, as well as quartz piezometry applied to quartzite and to quartz-rich regions of mixed-phase rocks, and calcite piezometry on marble mylonites, should provide further constraints on stress and strain rates along the length and depth exposures of this major strike-slip shear zone.

Changes in the ocean-continent transition along the Nova Scotia margin

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When continental lithosphere rifts apart and new ocean basins form, a transition region is created between the old, thick continental crust and young, thin oceanic crust. Based on the amount of volcanism that occurs during rifting, two primary classes of this transitional region at continental margins can develop, volcanic and non-volcanic. The Nova Scotia margin is located in a unique position bounding volcanic margins to its south and non-volcanic margins to its north. Previous investigations of the structure of this margin on three long crustal MCS reflection and wide-angle refraction (WAR) transects show that there are significant variations between the profiles: from a volcanic-type margin in the south, to a non-volcanic margin in the center, and finally to an extremely amagmatic margin in the north. These zones of transitional crystalline crust appear to coincide with northward transitions within overlying sedimentary structures, from salt-free to salt bodies in the south, and from autochthonous salt diapirs to allochthonous salt tongues in the north. We obtained access to the 2003 GXT's NovaSpan 9-km-long streamer MCS dataset and will gain access to the 2007 GSC's UNCLOS dataset. The high quality NovaSpan profiles allows us to look in much more detail at the transitional structures both along and across the Scotia margin. The UNCLOS MCS data provide an opportunity to determine whether structural variations within the oceanic crust further offshore can be linked to the margin segmentation. In June 2010, two new WAR profiles will be collected. Both profiles are positioned along the NovaSpan 5100 strike line, are about 150 km long, and cross major structures in the basement that we believe represent important crustal transitions. One line will examine the transition from volcanic to non-volcanic rifting, indicated by the disappearance of seaward dipping reflectors on adjacent margin-normal MCS profiles. The other line will examine the transition from non-volcanic to extreme amagmatic rifting, associated with the major change in crustal reflectivity. These data will be acquired using 22 OBS instruments fr om the DAL-GSC pool spaced at about 7 km, and using the new Sercel G-gun array from GSC. Coincident OBS and long-streamer MCS data are highly complementary. The combination of deep velocity control from the OBS data, and shallow velocity control and overall structural information from the MCS data provides a powerful tool for regional subsurface studies. We will iteratively process MCS and OBS data to extract maximum possible structural and velocity information. Our goal is to image and explain the character of the large variations in the ocean-continent transitions that appear to occur over small margin-lateral distances within just one rift segment, as suggested by the earlier studies in this region but not yet documented using seismic data.

Active Transtensional Basin Formation in the Northern Gulf of Aqaba/Eilat, Dead Sea Rift System

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A high-resolution, marine geophysical survey in the northern part of the Gulf of Aqaba/Eilat (GAE), Dead Sea Rift was carried out during October and November 2006. The survey led by an international research group (Israel, Jordan, and USA) funded by MERC aims to provide the municipalities of Aqaba and Elat with a base map of active faults for seismic hazard assessment. The survey collected multibeam and side-scan sonar, Sparker seismic reflection, and magnetic data in two phases—a deep-water survey in water depths of 10 to 700 m onboard the Israel Oceanographic and Limnologic Research vessel R/V Etziona, and a shallow water (< 50 m) survey onboard the Danny-Boy (a locally-owned, Israeli fishing vessel that was modified to accommodate operation of the research equipment). A total of 263 seismic reflection profiles with a total length of more than 370 km were collected. The northern GAE shelf developed along the transition between the deep marine basin to the south and the subaerial transform basin to the north. The stratigraphic architecture of the northern GAE shelf is similar to the early drift phase of continental opening with relict fossil reefs defining the shelf-slope break. However, the GAE late Quaternary sedimentary sequence developed during multiple depositional and erosional cycles in response to climate-driven sea level rise and fall. Each sedimentary cycle is defined by a basal erosional surface that truncates underlying reflector sequences that are inclined or tilted. Coral reefs that develop during stillstands and highstands are subsequently buried by aggrading and prograding sediments. The GAE shelf is oriented at a high angle to the main trend of the Dead Sea transform boundary. The shelf sedimentary sequence is cross cut by several, subparallel faults that flank the east and west margins of the basin and faults that trend obliquely across the basin. These faults divide the gulf head into the Eilat and Aqaba subbasins separated by the Ayla high. West of the high, the Eilat subbasin receives a large amount of sediment that is transported to the deep basin by slumping and gravity sliding along the Eilat submarine canyon. Seafloor lineaments defined by slope angle analyses suggest that the Eilat canyon and the eastern boundary of the Ayla high align along northwest-striking fault systems. The shelf-slope break that lies along the 100 m isobath in the Eilat subbasin and shallower in the Aqaba subbasin is offset by approximately 150 m along the east edge of the Ayla high. Our preliminary interpretations of these data suggest interesting block deformations with localized depocenters that migrate as the blocks adjust to changes in the localized strain. The presence of fossil coral reefs that provide chronological control as well as recording both changes in sea level/climate and tectonic strain makes the northern Gulf of Aqaba/Eilat an excellent site for future MARGINS research.

Velocity structure of the Arabian Shield crust and upper mantle from body and surface wave tomography

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The P and S wave velocity structure of the shallow upper mantle beneath the Arabian Shield had been modeled by inverting body wave travel times and Rayleigh wave phase velocity measurements between 45 and 140 s together with previously published Rayleigh wave group velocity measurements between 10 and 45 s. The velocity models show a broad low-velocity region to depths of 150 km in the mantle across the Shield and a narrower low-velocity region at depths greater than 150 km localized along the Red Sea coast and Makkah-Madinah-Nafud (MMN) volcanic line. The velocity reduction in the upper mantle corresponds to a temperature anomaly of 250 – 330 K. These findings, in particular the region of continuous low velocities along the Red Sea and MMN volcanic line, do not support interpretations for the origin of the Cenozoic plateau uplift and volcanism on the Shield invoking two separate plumes. When combined with images of the 410 and 660 km discontinuities, body wave tomographi c models, a S wave polarization analysis, and SKS splitting results for the Arabian Peninsula, the anomalous upper mantle structure in our velocity models can be attributed to an upwelling of warm mantle rock originating in the lower mantle under Africa that crosses through the mantle transition zone beneath Ethiopia and moves to the north and northwest under the eastern margin of the Red Sea and the Arabian Shield. In this interpretation, the difference in mean elevation between the Arabian Platform and Shield can be attributed to isostatic uplift caused by heating of the lithospheric mantle under the Shield, with the significantly higher elevations along the Red Sea coast possibly resulting also from lithospheric thinning and dynamic uplift.

Onset of transtensional rifting in the northern Gulf of California: Structural, Stratigraphic, Geochronologic, and Paleomagnetic constraints from coastal Sonora, Mexico

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Existing tectonic models differ as to when Baja California began to obliquely rift away from mainland Mexico. Addressing this problem is important for understanding how transtensional rifting may lead to successful rupture of continental crust. We conducted an integrated structural, stratigraphic, geochronologic, and paleomagnetic study of middle Miocene to Pliocene rocks associated with strike-slip faulting in coastal Sonora. Here, both the NW-striking, dextral Bahía de Kino and Sacrificio faults onshore appear to be linked to transform faults offshore (e.g. the De Mar fault) that accommodated Gulf opening. We mapped extensional basins overlying crystalline basement and middle Miocene andesitic rocks in a 160 km2 coastal region north of Bahía de Kino. Basins are floored by thick (>100m), high-grade deposits of the Tuff of San Felipe (Tsf), and contain thin (<20m) deposits of the Tmr3 cooling unit of the Tuffs of Mesa Cuadrada (Tmc) near their bases. Samples from these tuffs yielded ages of 12.50 +/- 0.08 Ma and 6.39 +/- 0.02 Ma, respectively, consistent with their ages determined from deposits in Baja California that now lie offset >250km across the Gulf. In coastal Sonora, modern-Gulf strata chiefly overlie Tmc and consist of non-marine conglomerate (Tcg). Pre-extension volcanic rocks in coastal Sonora are tilted down to the east up to 90 degrees and are bounded by N-striking normal faults. These normal faults and basins are typically cut by (1) sub-vertical NW-striking dextral faults and their conjugate NNE-striking sinistral faults, and (2) low-angle detachment faults with WNW-directed extension. These dextral and detachment faults may be coeval, simultaneously accommodating NW-directed transtension associated with the Pacific-North American plate boundary. Fault kinematic data are consistent with NW-directed transtension throughout the studied section. Tcg is dominated by debris-flow deposits with some sheet flood deposits, both interpreted as an alluvial fan environment. Thicker sections of Tcg (>470 m) are found adjacent to the Punta Chueca fault, a large-scale NW-directed low-angle normal fault, that produced more extension and subsidence than other modern-Gulf faults in this region. After correcting for bedding dips and vertical-axis clockwise rotations determined from paleomagnetic analysis, restored paleocurrents in Tcg reveal consistent overall transport to the SSW. We interpret Tcg to record deposition in a 10- to 20-km wide coastal belt of coalesced alluvial fans (bajadas) that formed on nascent northern Gulf margin. We obtained a SHRIMP 206Pb/238U weighted mean age of 6.53 +/- 0.18 Ma (n=14; MSWD=1.3) on zircons from the newly discovered Tordillo Tuff (Tt). Tt is ~80 m above the base of Tcg and 160 m below Tmc, yielding a sedimentation rate of 0.8 ± 0.2 mm/yr for lower Tcg. This isotopic age constrains the timin g of basin initiation in coastal Sonora at ca 6.6 Ma. Utilizing a new reference vector for Tsf from Baja California, paleomagnetic remanence directions measured in Tsf in coastal Sonora indicate variable amounts of clockwise vertical axis rotation from 0° to 55°. Where both Tsf and Tmc have been sampled, both tuffs are rotated by similar amounts. Taken together, the structural, stratigraphic, geochronologic, and paleomagnetic data suggest that the coastal Sonora

basins record initiation of faults related to opening of the northern Gulf ca. 6.6 Ma. Future collaborative efforts will link onshore investigations on Isla Tiburón with offshore PEMEX seismic reflection data to further test the role of dextral shear in the development of a localized transtensional plate boundary within the Gulf of California.

Preliminary Plio-Pleistocene stable-isotope and paleosol data from the Fish Creek-Vallecito basin, southern California: Implications for timing of uplift of the Peninsular Ranges

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The Peninsular Ranges of southern California form the faulted western margin of the Salton Trough and are a major physiographic feature in the region. Understanding the evolution of this mountain range is important for understanding the history of this part of the Pacific-North America plate boundary. The timing of Peninsular Range uplift is not known, although recent work suggests it could have occurred as recently as early Pleistocene (Mueller et al., 2006). This hypothesis is based on modeling of uplifted marine terraces along the Pacific Coast, and has not been tested with geological data. In this study we use detailed measurements and isotopic analyses of Plio-Pleistocene paleosols in the Fish Creek-Vallecito basin (FCVB) to test for the onset of a rain shadow created by the uplift of the Peninsular Ranges. The FCVB currently lies in a hyperarid rain shadow (MAP = 10-15 cm) formed by the Peninsular Ranges. In the FCVB, abundant paleosols are exposed in a thick, tilted stratigraphic section that accumulated in the hanging wall of the West Salton detachment fault. New high-resolution magnetostratigraphic dating allows us to determine the age of paleosol horizons to within an average uncertainty of +/- 0.06 m.y. Pedogenic carbonate nodules from 23 horizons ranging in age from 3.7 to 1.0 Ma, spanning a thickness of 2.5 km, were analyzed for oxygen and carbon isotopic compositions on a Gasbench and MAT 253 mass spectrometer. The data reveal an increase in carbonate d18O values at about 2.5-3.0 Ma, from -10.5 +/-1.5 ppm to -9.2 ppm +/- 1.8 ppm (VPDB). Carbon isotope values in pedogenic carbonate vary between -10.4 ppm and -3.8 ppm (VPDB) with no apparent trend. A total of forty-nine paleosols were described in the study interval. Most paleosols have shallow carbonate (Bk) horizons and thin, poorly-developed A horizons. Our finding of an increase in d18O is opposite of the change that would be produced by the onset of a rain shadow in the FCVB. These data therefore indicate that uplift of the Peninsular Ranges occurred before 3.7 Ma or after 1 Ma, or perhaps took place in two stages before 3.7 Ma and after 1 Ma. The increase in d18O at 2.5-3.0 Ma coincides with a global climate change caused by the onset of northern hemisphere glaciation, and may reflect (1) an increase in enriched Pacific Ocean-derived storms and decrease in the concentration of isotopically depleted monsoonal sources, (2) a change in the source of Pacific Ocean atmospheric water vapor, or (3) an increase in soil water evaporation driven by an increase in local temperature or summer precipitation. Measurements of depth to the soil carbonate (Bk) horizon reveal an average decompacted depth to Bk of 19.7 +/- 10 cm, which corresponds to a mean annual precipitation of approximately 25 cm (Retallack, 2005). This is similar to mo dern annual rainfall in coastal San Diego and is 10-15 cm more than in the present-day FCVB. While there is considerable scatter in depth-to-Bk measurements, clear trends are not apparent, suggesting no major changes in climate regime in the basin between 3.7 and 1.0 Ma. We tentatively interpret the

paleoprecipitation estimates to record either initiation or strengthening of a rain shadow due to Peninsular Ranges uplift after ca. 1.0 Ma.

BAJA transfer by partial coupling with the Pacific plate

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The Baja California (BAJA) microplate was ruptured from the North American (NAM) plate ~ 12 Ma ago and since then translated with the Pacific (PAC) plate. The microplates' transport mechanism has been explained by partial coupling with the PAC plate. According to this theory, the young oceanic lithosphere from the Farallon-Pacific spreading center approaching North America was too buoyant to be subducted. Therefore a zone of increased lithospheric coupling developed between the partially subducted Farallon slabs and the overlying NAM margin. In consequence both, the subduction and the seafloor spreading slowed down and ceased. With the development of this coupling region west of BAJA the main PAC-NAM plate boundary jumped inland east of BAJA, first delocalized in the Protogulf extensional province, and later localized along the Gulf of California. Having analyzed the present day rigid plate motion and deformation of the Baja California microplate, and its relative motion to the Pacific and North America plates, we now use a numerical model to test the dynamic conditions of BAJA transport. Using the kinematic data we test the necessary coupling forces for BAJA transport, as well as, geometrical constraints along the PAC-BAJA coupling zone. Evaluating the transport conditions at different stages of the plate boundary evolution, we want to learn about the long-term behavior of the interplate coupling, and estimate fault slip rates west of BAJA prior to the Gulf of California rupture.

Rupturing lithosphere in the Sea of Okhotsk: the ancient subduction processes and formation of back- arc basins in the Sakhalin Island.

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In the Sea of Okhotsk in Eastern Sakhalin an ancient (Upper Cretaceous-Paleogene) subduction zone is distinguished. On the surface it is manifested by an ophiolite complex, which separates North Sakhalin oil and gas basin from Deryugin basin of the Sea of Okhotsk. These sedimentary basins formed after the subduction ceased. They have the anomalous deep structure. Their features are rift structures in the basement; active magmatism at the initial stage of formation; active hydrothermal processes; the heat flow high density caused by the rise of the asthenosphere to the crust; and the location of asthenospheric diapirs beneath sedimentary basins. Geodynamic constructions showed that Deryugin basin in the Sea of Okhotsk was formed at the place of an ancient deep trench after the subduction of the Okhotsk Sea plate under Sakhalin ceased in the Early Paleogene. Deryugin basin is located above a hot plume that is asthenosphere diapir revealed at a depth of approximately 25 km. In the Cenozoic, thick sandy-clayey sediments accumulated in Deryugin basin. The North Sakhalin basin is located above the ancient subduction zone. The basin may have formed in the following way. Approximately 100 million years ago, the oceanic lithosphere of the Sea of Okhotsk subducted under Sakhalin, the eastern part of which was an island arc. Behind it, in western Sakhalin, there was a back-arc basin where sandy – clayey deposits accumulated in the Late Cretaceous- Paleogene, which subsequently formed the basement of Neogene North Sakhalin basin. The Neogene sediments consist of marine terrigenous and volcanic rocks.

Dynamic Upwelling in the Mantle Beneath the Gulf of California

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We have completed a moderately high resolution study of the shear velocity structure of the crust and upper mantle beneath the Gulf Extensional Province and Baja California using Rayleigh waves propagating across the NARS-Baja, RESBAN, and southern California arrays. We employed finite frequency response kernels and take into account the complexity of the incoming wavefields using a multi-plane wave technique, yielding higher resolution and broader coverage than conventional approaches. We used vertical component fundamental mode Rayleigh waves ranging in period from 22 to 111 s generated by teleseismic sources. Surface waves traveling along the Gulf or Baja California have typically undergone waveform distortion before they reach the study area by propagating along continental margins and subduction zones that induce scattering and multipathing. Further waveform distortion is caused by heterogeneities in the extensional province. We employed a multiple two-plane-wave appro ximation to account for waveform distortion outside our study region and 2D finite frequency response kernels to represent scattering within the study area. There are two primary features of interest in the 3-D shear velocity structure: a series of low velocity anomalies in the shallow mantle beneath the Gulf of California and a deeper, high velocity anomaly that appears to be a remnant of the unsubducted Guadelupe and Magdelena microplates. There are three pronounced low-velocity anomalies in the 20-90 km depth range beneath the Guaymas basin, lower Delfin basin and west of the Wagner basin. Lesser low velocity anomalies in this depth range are located beneath the Salton trough and Farallon basin. We attribute these low velocity anomalies to dynamic, buoyancy-driven upwelling and melting initially triggered by extension in the gulf region, rather than strictly passive upwelling driven by the plate separation. The role of melting is suggested by the very low shear velocities (<= 4.0 km/s) and the fact that the maximum anomaly is at a depth of ~ 60 km, where petrological models indicate mantle melting should be at the greatest rate. The lack of a continuous low-velocity region, the spacing of the anomalies 200-250 km apart, and the offset of the centers of the anomalies from the current, nearby spreading centers suggest that shallow melt depletion buoyancy and melt retention buoyancy may have organized the initially passively driven upwelling into regularly spaced cells. The anomaly in the Wagner basin in particular is centered more beneath the young coastal volcanic province (< 3 Ma) and Roca Consag (0.12-1.2 Ma) than beneath the inferred current extensional center. The 200-250 km spacing is consistent with the characteristic dynamic segmentation length predicted for buoyant mantle instabilities in the numerical models of Magde and Sparks (1997) and others.

Large Scale Mass Wasting after Breakup at the Galicia Rifted Margin

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I have been reinterpreting the formation of the Galicia rifted continental margin in terms of explaining the last phase of continental extension as one or more large scale mass wasting events. This interpretation is motivated by the relative paucity of syn-rift sediments documenting clear rotation of the underlying fault bounded blocks during an extended period of crustal extension. I see evidence for large scale slumping off of the Galicia Bank to the west in the area of the prominent S reflector, which separates faulted and rotated blocks of continental crust and pre-rift sediments above from serpentinized upper mantle rocks below. In terms of the mass wasting hypothesis, the material above the S reflector is interpreted as the foot of the west directed slump, while the material below the S reflector is interpreted as upper mantle rocks that were exhumed to the seafloor and then later covered by the slump foot material. I suggest that the extensive serpentinization of the upper mantle under S is easier to explain if it was once exposed to water at the seafloor than if it was always covered by a 2-3 km thick layer of rotating fault blocks. Unfortunately, in this location, the unambiguous direction of rifting and the direction of my hypothesized slumping are both roughly east/west. Therefore, it difficult to distinguish among these processes. I also see evidence for south directed mass wasting off of the Galicia Bank at the margin segment boundary between the Galicia Bank segment and the Iberia Abyssal Plain segment. There the direction of primary rifting is east/west, perpendicular to the inferred direction of slumping. There I observe rotated fault-bounded blocks, similar to those described above, showing extension to the south. The foot of this inferred slump seems to cover an area in the Iberia Abyssal Plain that has been shown to consist of post-rift segments overlying exhumed and serpentinized upper mantle rocks. These interpretations, if borne out by further evidence, suggest that large scale mass wasting may be an important process for modifying the end-of-rifting configuration of magma starved rifted continental margins.

Along-strike variations in magmatism in the Black Sea and consequences for the style of extension

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The amount of magmatism that accompanies the extension and rupture of the continental lithosphere varies dramatically at rifts and margins around the world. Based on widely-spaced geophysical transects, some margins (e.g., Gulf of California) are known to preserve a transition from magmatically-robust to magmatically-starved rifting along strike, but the nature of the transition itself is unknown. Wide-angle seismic data from the Black Sea provide the first direct observations of such a transition and show that it is abrupt, occurring over only ~20-30 km, and coincides with an interpreted transform fault. This abrupt transition cannot be explained solely by gradual along-margin variations in mantle composition or temperature, since these would be expected to result in a smooth transition from magma-poor to magma-rich rifting over hundreds of kilometers. We suggest that the abruptness of the transition results from the development of 3D melt migration due to along-strike vari ations in extension and thus the thickness of the lithosphere at the time of rifting. Localized magmatic addition attributed to melt focusing has been observed in modern mid-ocean ridges and active rift environments, but here we show that such processes can also produce abrupt along-strike changes from magma-poor to magma-rich rifting. Variations in the amount of magmatism along strike are also accompanied by changes in the style of thinning at the southern margin. For example, a wide zone (>70 km) of highly thinned continental crust (beta of ~4-5) is present in the magma-poor part of the basin, while the continental crust thins abruptly beneath the continental slope in the magma-rich part of the basin with magmatic and thick oceanic crust immediately seaward. We will present new constraints from crustal velocity models supported by gravity modeling and discuss different models to explain these variations and their relationship to magmatism. These results together with recent findings from other rifted margins (i.e., North Atlantic) illustrate the contribution of passive margin research towards addressing MARGINS RCL themes, particularly those concerning the role of magmatism, the transition to seafloor spreading and the stratigraphic response to lithospheric rupture. Because passive margins are the final product of deformation and magmatism throughout the life of a rift, they complement studies of early-stage and 'teenage' active rifts.

The Salton Trough Seismic Project

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The Salton Trough Seismic Project, funded by NSF (Margins/Earthscope) and the USGS, involves an active-source seismic study of the Salton Trough, including the Mexicali, Imperial, and Coachella Valleys, to take place in January 2010. This major project addresses the processes of rupturing a continent through a seismic reflection and refraction survey at the Salton Trough in southern California. In the Salton Trough, however, the 20-22 km thick crust is composed entirely of new material added by magmatism from below and Colorado River sedimentation from above. The adopted model of magmatic addition to the crust is from A. Schmitt and J. Vazquez (2006), where mafic magma reaches neutral buoyancy in the lower to middle crust. Hydrothermal circulation transmits the heat, preventing massive melting of overlying sediment but also allowing re-melting of altered basalts. For the Salton Trough project, we are analyzing the microseismicity from the SCSN database of the region around the Salton Buttes, five rhyolite domes, at the southern end of the Salton Sea and near the Brawley seismic zone. In fall 2009, we will install five digital seismographs to supplement the existing network for a more detailed study related to subsurface structures. Then in January 2010, we will participate in the main north-south seismic reflection/refraction line. In addition, samples of the rhyolite will be collected with Jorge Vazquez and students for petrologic and P wave velocity analyses.

Recent dynamics of the western part of the Eger Rift, Central Europe: earthquake swarms triggered by magma intrusions

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The Eger Rift is a geodynamically active area in the northwestern part of the Bohemian Massif, the easternmost outcrop of the Variscan orogenic belt in the Alpine foreland in Europe. The Eger Rift is part of the European Cenozoic Rift System (ECRIS); its formation and development is supposed to be related to Alpine collision. However, the geodynamic causes underlying the formation of the Eger Rift are a matter of controversial interpretations, from small-scale mantle plume activity to the induction of extension by development of the Alpine orogenic root and associated changes in mantle flow and regional crustal palaeostress fields. Although sharing many common features with other dominant structures (e.g., the Rhine Graben and the Bresse-Rhone grabens) of the ECRIS, i.e. anomalous upper-mantle structure, thinned crust, abundant intra-plate basaltic volcanism carrying lower-crustal and mantle xenoliths to the surface, moderate seismicity, mantle-derived fluids approaching the surface, typical graben morphology, and graben-related sedimentary basins, the western part of the Eger Rift stands out because of a number of unique signatures highlighting the recent dynamics in this particular area: (a) weak to moderate earthquake swarms occur uncommonly frequently (3 years in average); (b) high proportions of mantle-derived 3He (5.9 Ra) comparable to values characterizing the European Subcontinental Mantle (ESCM) and demonstrating the deep origin of these gases; (c) the post-rift uplift of the Krusne Hory Mts. involving the NW margin of the Eger Rift, represents one of the largest neotectonic uplifts in the Alpine foreland. The driving forces of the geodynamics of the rift, including the magmatic/fluid, thermal, and earthquake activity, are not well understood and demand significant research. The time-space pattern of seismicity during recent earthquake swarms in the region of interest demonstrate the gradual and ordered migration of micro-seismic activity, suggesting the step-by-step penetration of fluids into a small fractured volume. This scenario is supported by the similarity of the source mechanisms of the natural events of the January 1997 swarm with artificial injection-induced micro-earthquakes during the German Deep Drilling Project (KTB) in neighbouring NE Bavaria. Also the comparison of the West Bohemia region with other intraplate earthquake swarm regions and with earthquake swarms induced by current volcanic processes indicates a role of intrusions of magma and related fluids in generation process of West Bohemian earthquake swarms.

Present-day strain rates and dynamics of the East African Rift D.

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The forces and physical processes at work during continental rifting remain to be fully understood and quantified. We investigate the balance of large-scale forces affecting present-day rifting in East Africa using a thin sheet approach to quantify strain rates and deviatoric stresses. We develop a strain rate model constrained by a combination of GPS-derived kinematic models and seismic moment tensors (CMT catalog) for our region of interest. We estimate a total deviatoric stress field by combining (1) stresses caused by gravitational potential energy (GPE) gradients within the crust and (2) a buoyancy signal present in the topography that we use to compute stresses. To estimate internal body forces, we assume crustal thicknesses and lateral density variations modeled in Crust 2.0 (G. Laske and G. Masters, http://mahi.ucsd.edu/Gabi/sediment.html, 2000). In our preferred model of deviatoric stresses, we estimate and remove the dynamic topography buoyancy signal by allowing th e mantle lithosphere density to vary, compensating the lithosphere to a given reference depth. To test the reliability of our total deviatoric stress field, we compare tensor patterns of deviatoric stresses, with and without contributions from the mantle, to tensor patterns from kinematic deformation indicators. Our results to date suggest that horizontal buoyancy forces arising from variable crustal thicknesses and lateral density variations within the lithosphere contribute significantly to the diverging plate boundary forces of the EAR but do not account for the entire budget of force needed to produce present-day deformation.

Seismic-Stratigraphic Framework for the Northern Gulf of California

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In 1999 we collected a grid of 3500 km of high-resolution multichannel seismic data in the northern Gulf of California on board the B/O Ulloa operated by CICESE. These data record the stratigraphy in the vicinity of the Wagner, Consag, and Upper and Lower Delfin basins with penetration averaging ~1 sec and resolution of better than 5 m. The seismic data revealed widespread faulting reflecting the active tectonics of a region covered by a thick sediment fill. However, the close spacing of the innumerable faults made correlation of seismic reflectors a challenging task. We have now created a seismic-stratigraphic framework for interpreting the Pleistocene evolution of the basins. The seismic survey was divided into four subareas in which multiple horizons were mapped. However, only a limited number of reflectors could be tied between subareas due to difficulties correlating across regions of gas wipeout or active rifting. Southeast of the Upper Delfin basin, the reflectors exhibit a repetitive pattern of more reflective and more transparent layering that we ascribe to the 100,000 yr glacio-eustatic cyclicity. We have tentatively correlated the reflectors back to OIS 22 (875 ka). All but the oldest reflector outcrops at the sea floor due to the uplift of the most southeastern part of the field area. Within the SE part of the field area, a number of features such as acceleration of subsidence or rate of displacement along some faults, sealing and abandonment of others, channeled erosion surfaces, and angular unconformities can be correlated and mapped, indicating periods of tectonic change or basin reorganization. There are indications of reorientation of rifting near the Lower Delfin Basin in the deeper part of the section. We will present the interpreted seismic data and the seismic-stratigraphic interpretation, together with its implications for the evolution of rifting in the northern Gulf of California.

MARGINS needs to Study US Passive Margins

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Understanding "passive" margins – the transitional lithosphere that forms during rifting and becomes the juncture between continental and oceanic lithospheres, as well as the sdeiments that rest on this lithosphere - has far-reaching economic and societal implications. Passive margins underlie the coastal regions of most of the conterminous US, extending continuously from Texas eastward to Florida and northward to Maine. They hide most of the undiscovered hydrocarbon reserves of the USA, are potential geothermal resources, and are excellent sites for sequestering carbon dioxide. Natural hazards of hurricanes, tsunamis, sealevel rise, and rapid subsidence, and concerns related to the UN Law of the Sea also make it imperative to better understand how "passive" margins form and evolve. Economic and societal concerns provide natural avenues for explaining the importance of this and other "hypothesis-driven" geoscientific research efforts to US taxpayers and political leaders, e specially because much of the US population lives on or near our passive margins. Furthermore, the economic potential of passive margins invites joint study and sharing of data by industrial and academic scientists. Understanding US "passive" margins should be a high priority of both. The following are a few of the scientific questions that studying US "passive" margins should strive to answer: 1) How can we best determine which segments of US "passive" margins formed as "Volcanic Rifted Margins" (VRM) and which formed as "Non-volcanic Rifted Margins" (N-VRM)? What are the best explanations for such segmentation? 2) How does the evolution (early uplift/subsidence; later subsidence) of "passive" margins that formed as VRM differ from those which formed as N-VRM? 3) What are the most important controls that these endmembers exert on subsequent evolution of passive margins, including subsidence, thermal structure, and fluid flow? The NSF-MARGINS initiative recognizes the importance of understanding incipient passive margins through its RCL (Rupturing Continental Lithosphere) experiment. MARGINS-RCL has focussed on "active" systems, which has been defined as tectonic settings where plate convergence or divergence can be measured. "Passive Margins" are in fact very active systems, with active subsidence, sedimentation, fluid flow, and metamorphism and should be treated as active systems, suitable for the next generation of MARGINS-RCL research. It will not be easy to study the deeply-buried lithospheric structure beneath passive margins. Next-generation MARGINS-RCL should partner with USArray (focused on land studies), and provide the programmatic vehicle that steps across the shoreline, which has traditionally marked an operational boundary between land and marine geoscientific efforts.

Extent of new, non-oceanic crust in the northern Gulf of California: constraints and controversies

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The excellent geological exposures of the conjugate margins of the northern Gulf of California provide key kinematic constraints, with consequently important implications regarding processes of rifting. Within the Upper Delfin Basin and Lower Delfin Basin segments, numerous marker units, both pre-rift and syn-rift in age, constrain the offset on individual faults. Paleomagnetic measurements constrain the timing and amount of rotation of small crustal blocks within the extensional province. One fortuitously distributed pre-rift marker horizon (the ca. 12.5 Ma Tuff of San Felipe/Tuff of Hermosillo) is preserved in various fault blocks, spanning the rift system from the stable Peninsular Ranges of Baja California, on Pacific plate, to the interior of Sonora on the North America plate. Reconstruction of this and other geological marker units constrains the total displacement across the rift and the relative motion of two continental blocks now isolated as large islands (Tibur on and Angel de la Guarda) within the Gulf of California. This leads to three important conclusions: 1) within the northern Gulf basins, approximately 250 km of post-6.1 Ma plate separation is accommodated by new crustal area within the rift. The nature of this new crust is debated and deserves further study; its geophysical characteristics imply a thickness and average density differing from both traditional oceanic crust and the intrusive and metasedimentary new crust along the plate boundary to the north in the Salton Trough. In other rifts (e.g., the Ross Sea and Sea of Japan), regions of similar new crust may lie unrecognized. 2) The amount of rift opening, constrained by the geology of the basin margins, is nearly identical to the plate circuit displacement since ca. 6 Ma but exceeds displacements implied by several other data types. Seismic reflection data have been interpreted to indicate less net extension in these basins, but this data may not be able to imag e the oldest phases of deformation here. The age of marine sedimentary rocks in the basins has been interpreted to conflict with the geological constraints from the margins, suggesting a high priority for future drilling and coring studies. 3) The history of pre-6 Ma rifting and its relationship to plate motion in this region is controversial, and not yet reconciled with the magnitude and timing of extension inferred for rift segments farther to the south.

Geo- and thermochronometric constraints on Tertiary normal faulting and basaltic volcanism along the central Arabian flank of the Red Sea rift system

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The Red Sea rift system is one of the best exposed examples of continental rifting and has significantly contributed to our understanding of rupturing modes and mechanisms of continental lithosphere. To improve our understanding of this system, this study investigates the timing of development of extensional structures and rift-related Tertiary basaltic volcanism along the central Saudi Arabian flank of the rift system, using apatite and zircon (U-Th)/He thermochronometry on the exhumed rift flank and magnetite (U-Th)/He and whole-rock 40Ar/39Ar dating of harrat basalts that interact with rift-related extensional faulting. Constraints on the dynamics of rift flank deformation are achieved through the collection of long-baseline thermochronometric transects that traverse the entire Arabian shield from the coastal escarpment to the inland sedimentary cover sequences and short-baseline elevation transects in the footwall of major normal faults along the main rift border and with inland extensional basins. Long-baseline transects aim to resolve the timing of rift flank uplift and exhumation and are coupled with new geophysical models predicting the pattern of lithospheric modification during the rupturing of continental lithosphere. One such transect partially traverses the main rift-margin escarpment near the coastal city of Yanbu, allowing for a characterization of the complex border-fault system which juxtaposes exhumed Precambrian rocks in fault-bound footwall blocks against Oligo-Miocene syn-rift strata. Conversely, short-baseline elevation transects are used to constrain the spatiotemporal evolution of rift-related, fault-bound structures such as the NW-trending Hamd-Jizil basin, a prominent extensional basin comprised of two distinct half-grabens and located north of Medina. This unified collection technique permits the reconstruction of early rift architecture, strain distribution during progressive rifting, and subsequent whole-scale modifications of the rift flank due to thermal and isostatic factors. Preliminary (U-Th)/He apatite and zircon analysis of samples from both short- and long-baseline transects within the central portion of the Arabian rift flank in the Yanbu and Medina regions reveal a temporally-distinct cooling history. A leucotuff intercalated within the uppermost syn-rift sedimentary sequence in the Hamd half-graben yields a zircon (U-Th)/He age of 13.6 ± 1.1 Ma. Jabal Samar, an exhumed footwall block, yields a mid-Miocene apatite (U-Th)/He cooling age of 14.7 ± 0.9 Ma. This age is doubly-significant since it not only reveals a Red Sea rift signal far inboard from the modern rift margin but it also underscores the importance of fault reactivation during progressive rifting since Jabal Samar is structurally delineated by faults formed within a Neoproterozoic shear zone. Apatite (U-Th)/He ages from Jabal Radwa, a pluton exhumed within the border fault complex, show a Red Sea rift signal strikingly similar to exhumation signals observed in the Gulf of Suez. In both areas, footwall exhumation commences ~23 Ma prior to regional strain redistribution from the onset of the Dead Sea transform fault. In stark

contrast to these Oligo-Miocene ages, analysis of apatite and zircon grains from many areas within the study region reveal two populations of Permo-Triassic apparent cooling ages (210 – 240 Ma & 250 – 350 Ma). Preliminarily, these background cooling ages, found throughout the Arabian Shield, are attributed to tectonic processes associated with Variscan and Neo-Tethyan events. In addition to bedrock thermochronometry, this study also employed magnetite (U-Th)/He and whole-rock 40Ar/39Ar dating of syn- and post-kinematic basalt flows, to determine eruption ages of Harrat volcanism, constrain the timing of rift-related normal faults, and shed light on the post-rift geomorphic evolution of the originally internally-drained Hamd-Jizil basin. Summarily, early Red Sea rifting affected a wide area well inboard from the prominent modern Red Sea escarpment and the main border-fault system. Geo- and thermochronometric constraints illustrate that during early to middle Miocene times extensional faulting occurred in the Hamd-Jizil half graben system contemporaneously with faulting along the main border fault complex in the central portion of the Saudi Red Sea margin. Faulting appears to have stopped in the Hamd-Jizil basin region and the main border complex and migrated basin-ward in the middle Miocene, contemporaneously with rift reorganization and the establishment of the Dead Sea-Gulf of Aqaba transform. New apatite and zircon (U-Th)/He ages from the unextended Arabian Shield appear to be related to well-recorded global tectonic events including widespread denudation of the Arabian-Nubian Shield during Neo-Tethyan rifting.

Breakup of Orogenic Continents

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The spatially and temporally varying rheologies of deforming continental and oceanic lithosphere are a function of strain rate, temperature, (fluid) pressure, and material properties including composition, fabric and inherited weaknesses. In the absence of mantle temperature and composition anomalies, the rupture of continental lithosphere is not attended by excessive volcanism and is preceded by variable combinations of upper crust faulting, lower crust flow and, in active orogens, core complex exposure associated with arc magmatism. The Gulf of California, South China Sea, Goban Spur, NW Australia and Woodlark Basin provide examples. There is evidence for depth-dependent stretching but how/where it is balanced remains a subject of debate. At sufficient strain rates (10-14/sec) and opening velocities (2 cm/yr), the continent-ocean boundary is typically narrow, occasionally as thin as one fault zone or intrusive contact. On the other hand, spreading reorganization short ly after breakup sometimes produces continental slivers within oceanic crust. Exhumed mantle on the oceanic side of ruptured continental crust is only documented at very slow opening rates and this may be a spreading rather than breakup characteristic. In the Woodlark Basin: (i) Continental rifting does not cease when seafloor spreading begins. Rather, active rifting of the conjugate margins continues for ~1 m.y. after spreading has separated them. This is shown by present overlap between the western spreading segments and earthquake seismicity on the margins, and by conjugate magnetic anomalies and seafloor fabric that curve symmetrically towards the spreading axis. (ii) In most cases oceanic transform faults do not develop from transfer or transform faults within continental rifts, but link offset spreading segments at/after continental break-up. (iii) Continental transform margins that are or were juxtaposed against the ends of spreading centers show no evidence for thermal uplift or igneous underplating. (iv) Linear magnetic anomalies do not necessarily mark the onset of seafloor spreading; they may mark large faults that localize intrusions and/or juxtapose alternately magnetized rifted continental crust. (v) Stepwise spreading center nucleation in order to remain within a rheologically weak zone, rather than rupturing of the lithosphere by stress concentration at the tip of a propagating ridge axis, is the dominant form of the continental rifting to seafloor spreading transition. Many more orogens/arcs have rifted (e.g., Gulf of Corinth) or broken apart during the Tertiary than cratons. They provide a rich diversity of rifted margin examples to consider magmatism, strain partitioning and sedimentation/surface processes.

Geochemical, Sr-Nd-Hf isotope composition of mantle xenoliths and host lavas from Assab, Eritrea: implication for the composition and thermal structure of the lithosphere beneath Afar Depression.

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The Afar Depression offers a rare opportunity to study the geodynamic evolution of a rift system, from continental rifting to sea floor spreading. A detailed study of host lavas and crustal- and mantle xenoliths from the Assab area of the Afar Depression provides important constraints on the evolution of magmatic activity in this geodynamically-active region. The host lavas are alkali basalts having enriched rare earth element (REE) patterns ((Ce/Yb)N = 6.2 - 10.3) and trace element characteristics similar to those of ocean island basalts (OIB). They show limited ranges in Sr-Nd-Hf isotope ratios: 87Sr/86Sr = 0.70336-0.70356, eNd = +6.42 - +6.81and eHf = +10.43 - +11.16. Mixing of enriched and depleted Afar plume is proposed to account for the geochemical and isotopic compositions observed in the host lavas. The gabbroic crustal xenoliths show wider ranges in their Sr-Nd-Hf isotopic ratios: 87Sr/86Sr = 0.70437-0.70791, eNd = -8.29 - +2.36 and eHf = -10.01 - +5.34. They have trace element characteristics and primitive mantle-normalized geochemical patterns similar to those of Neoproterozoic rocks from the Arabian-Nubian Shield and modern arc rocks suggesting that the lower crust beneath Afar Depression contains Neoprotrozoic mafic igneous rocks. The Assab mantle xenoliths comprise protogranular dunites, spinel-lherzolites, plagioclase-free pyroxenites and plagioclase-spinel pyroxenites and contain a primary assemblage of fresh ol+opx+cpx+sp±pl, with no alteration or hydrous minerals. Clinopyroxene-rich bands as well as spinel-rich layers and euhedral spinel crystals are also present in some samples. Equilibration temperatures and pressures calculated using two pyroxene thermometry and clinopyroxene barometry range from 870 to 1040°C at 0.7 to 2.7 GPa. The estimated P-T ranges for the mantle xenoliths from the Assab region follow a steeper geothermal gradient than that expected from continental shields, in agreement with the tectonic environment of the Afar Depression. The vast majority of the clinopyroxene, orthopyroxene and plagioclase grains from Assab xenoliths display a narrow range in their isotopic compositions: 87Sr/86Sr = 0.70310-0.70409, eNd = +4.23 - +7.88 and eHf = +10.64 - +20.41. The forste rite content of olivine (92-79) correlates positively with the Mg# of orthopyroxene (90-80), clinopyroxene (92-81) and spinel (73-59). The systematic variations in major and trace elements among the Assab mantle xenoliths and their isotope ratios largely reflect the relative degree of fractional crystallization that affected the peridotites and show that the Assab peridotites suggests that they represent a sequence of variable evolved layered cumulates formed during fractionation of a relatively enriched picritic melt related to the Afar plume that was emplaced prior to the eruption of the host lavas. The xenoliths and the host lavas thus likely represent a sequence of samples that record an earlier magmatic history (cumulates) and a younger volcanism (host lavas), respectively.

Paul **Umhoefer**

Work relevant to the Workshop: Overall: I can participate in two ways: (1) All of my work in the Gulf of California focus site is relevant to the goal of reviewing this focus site. (2) I was also one of the major players in formulating the three forward themes of RCL that will be discussed at the workshop and helped write the MARGINS statement on the Sedimentation, Climate and Surface Processes theme. One of many possible summaries of southern Gulf of California: A review of the patterns of upper crustal faulting in the SW Gulf of California in space and time Paul Umhoefer 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. 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; the main plate boundary has ~85 – 90% of the plate motion, ~10% is on faults west of Baja California, and a few percent in the SW Gulf margin. The SW Gulf is a complex zone of tens of potentially active faults, 3-4 appear to be active across any latitudinal transect. Onshore fault scarps, uplifted marine terraces, earthquakes, and seismic reflection data confirm active faulting, and suggest individual faults move at tenths of mm/year. The coastal belt has three rift segments along the Gulf escarpment, 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 faulting 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. The SW Gulf faults 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 run s 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 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 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 fundamenta l framework for the geometry of the developing plate boundary.

Implications of mantle-lithosphere interactions below rift margins: surface elevation, depth dependent extension, seismic wave velocity anomalies, and melt chemistry

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Many passive rifted margins are characterized by depth dependent thinning whereby the mantle lithosphere seems to have been thinned more than the crust. Examples include the Exmouth Plateau and North Atlantic margins. Here we propose an explanation for this observation that is supported by numerical models. The models consist of a lithosphere overlying the upper mantle, and solve for visco-plastic deformation. Instabilities of the lithosphere develop during the late syn-rift stage below the margins of the rift zone. The instabilities develop preferably around heterogeneities in the lithosphere such as rift margins, where lateral thermal variations promote the development of small-scale convection cells. Our models show that the drips (the instabilities) that are formed consist of lower lithosphere material. When the drips detach and sink into the upper mantle, they actually remove base lithosphere material from the lithosphere. The lithosphere thus experiences additional thin ning. Because the drips do not develop until the rift zone is well developed (late syn-rift to early post breakup), continental rifts such as the North Sea Basin did not experience depth dependent thinning. Another consequence of this process is that the detachment of the drips provides a way to recycle lithosphere material into the upper mantle below passive rifted margins. This could help explain the chemistry of some melts that have a lithospheric component. When the lithosphere is extended to the point of continental breakup, the models predict ~1500 m of uplift of the margins. This is dynamic uplift; i.e. uplift caused by mantle flow below the rift. This dynamic uplift is not necessarily the actual surface elevation of the margins at breakup time; it is an added component to the existing elevation at the time. It could help bring the surface up to or above sea level, and explain sub-aerial emplacement of basalts in for example the North Atlantic. The temperature structures predicted by our models are converted to synthetic seismic wave velocities that can be compared to seismic tomography. Passive upwelling of mantle material occurs below the rift during rifting, and is always confined to the asthenosphere. Warm asthenosphere replaces cooler lithosphere below rifts, and results in a low seismic wave velocity anomaly. These low seismic wave velocity anomalies are shallow features (<200 km). A case study of the Rio Grande rift in the southwestern US shows that temperature variations explain the first order tomographic structures, and compositional variations are required to explain the finer details.

Rupturing continental lithosphere above a subduction zone, the Taupo Rift, New Zealand: an overview

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Extension in the continental lithosphere inboard of the Hikurangi subduction margin, North Island, New Zealand, comprises two inter-dependent components – a volcanic arc known at the Taupo Volcanic Zone (TVZ), and a tectonic rift known as the Taupo Rift. These two components are co-existent at regional scale, but in detail tend to be anti-correlated, suggesting that the extension is largely accommodated by alternate processes within the region (magmatic intrusion, tectonic and volcanic faulting). A consequence of plate boundary kinematics in the Hikurangi subduction margin is rapid rotation of eastern North Island, diminishing southward with a resulting "fan-shaped" opening of the Taupo Rift. Extension rates across the rift range from c. 15 mm/yr in the northeast to perhaps 3-5 mm/yr in the southwest. These rates occur within an active fault belt that varies from 14-40 km wide, similar in dimension to the Corinth Gulf of Greece, and in rate to the whole Basin and Range extension of western North America. Volcanism varies compositionally along the axis of the onshore TVZ with andesites dominant the northern (Whakatane) and southern (Tongariro) domains and rhyolite in the central (Ngakuru) domain. Offshore andesitic and rhyolitic volcanism coexists. Volcanism and normal faulting terminate about 200 km short of the transition from subduction to collision in central New Zealand. The Taupo Rift has evolved in the past c. 2 Myr in concert with the development of the arc. The initial development of faulting is now difficult to determine because of later overprinting of structure and burial by more recent volcanic products. However, theoretical studies and some field data indicate crustal thinning and doming probably preceeded both faulting and volcanism. Gravity data provides some clue of initial rift structure indicating linear rift boundaries occasionally coincident with old caldera structures (e.g., Mangakino caldera). During the mid-late Quaternary, faulting in all but the 40 km wide Tongariro domain, show a localisation (inward migration) with time. This localisation of faulting is especially marked in the central and northern parts of the Rift, and coincides broadly with the spatial evolution of volcanism in the TVZ. The Tongariro domain is a recent (c. 400 kyr) extension of the rift and the volcanic arc to the south. Interpretation of gravity data at the southern end of the Rift suggests the arc may have localised on the Mesozoic suture mapped today as the Waipapa-Torlesse terrane boundary. A contractional tectonic regime exists adjacent to the southern termination of the Taupo Rift, such that further southward propagation requires a major rearrangement of the stress field, which is more likely to be achieved at the time of a major event (such as large ignimbritic eruptions) than as an incremental process. We present results from studies of active faulting (tectonic geomorphology and paleoseismology), gravity, and numerical and analogue modelling that allow us to define the spatial and temporal evolution of the rift and insights into strain partitioning between volcanic and tectonic processes.

Dynamic Upwelling in the Mantle Beneath the Gulf of California

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We have completed a moderately high resolution study of the shear velocity structure of the crust and upper mantle beneath the Gulf Extensional Province and Baja California using Rayleigh waves propagating across the NARS-Baja, RESBAN, and southern California arrays. We employed finite frequency response kernels and take into account the complexity of the incoming wavefields using a multi-plane wave technique, yielding higher resolution and broader coverage than conventional approaches. We used vertical component fundamental mode Rayleigh waves ranging in period from 22 to 111 s generated by teleseismic sources. Surface waves traveling along the Gulf or Baja California have typically undergone waveform distortion before they reach the study area by propagating along continental margins and subduction zones that induce scattering and multipathing. Further waveform distortion is caused by heterogeneities in the extensional province. We employed a multiple two-plane-wave appro ximation to account for waveform distortion outside our study region and 2D finite frequency response kernels to represent scattering within the study area. There are two primary features of interest in the 3-D shear velocity structure: a series of low velocity anomalies in the shallow mantle beneath the Gulf of California and a deeper, high velocity anomaly that appears to be a remnant of the unsubducted Guadelupe and Magdelena microplates. There are three pronounced low-velocity anomalies in the 20-90 km depth range beneath the Guaymas basin, lower Delfin basin and west of the Wagner basin. Lesser low velocity anomalies in this depth range are located beneath the Salton trough and Farallon basin. We attribute these low velocity anomalies to dynamic, buoyancy-driven upwelling and melting initially triggered by extension in the gulf region, rather than strictly passive upwelling driven by the plate separation. The role of melting is suggested by the very low shear velocities (<= 4.0 km/s) and the fact that the maximum anomaly is at a depth of ~ 60 km, where petrological models indicate mantle melting should be at the greatest rate. The lack of a continuous low-velocity region, the spacing of the anomalies 200-250 km apart, and the offset of the centers of the anomalies from the current, nearby spreading centers suggest that shallow melt depletion buoyancy and melt retention buoyancy may have organized the initially passively driven upwelling into regularly spaced cells. The anomaly in the Wagner basin in particular is centered more beneath the young coastal volcanic province (< 3 Ma) and Roca Consag (0.12-1.2 Ma) than beneath the inferred current extensional center. The 200-250 km spacing is consistent with the characteristic dynamic segmentation length predicted for buoyant mantle instabilities in the numerical models of Magde and Sparks (1997) and others.

The sediment source-to-sink patterns in large drainage basins and marginal seas: the Changjiang (Yangtze) example

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In the past decades one of the research highlights of global changes is Tibetan Plateau uplift and the corresponding global climate changes during the Cenozoic. The mega-rivers originated from the Himalayan-Tibetan Plateau transport huge amount of particulate and dissolved matters eroded from the plateau and its surrounding regions into the marginal seas of Asia and, therefore, exert a great control on source to sink process of terrigenous materials. Geochemical tracing studies of these rivers provided important constraints on the uplift history of the Tibetan Plateau, weathering intensity and atmospheric CO2 sink in the drainage basins, and chemical flux change of global ocean. The Changjiang is the third longest river in the world and the fourth largest one in terms of its water discharge. Different from those South and Southeast Asian rivers, the Changjiang has much more complex drainage systems, source rock geology, and stronger anthropogenic impacts in its large basins . The recognition of flux and fate of the Changjiang sediment into the East Asian marginal seas is therefore of great significance for the understanding of the global S2S pattern of terrigenous materials into the sea and the river-sea interactions. Over the past decade, we have investigated the sediment production and transport in the Changjiang drainage basin at present and in the Quaternary, and tectono-climate control on the river sediment S2S process. The sediment S2S processes in the present-day's Changjiang drainage basin and marginal seas were examined, and the ultimate sources of the fluvial sediments were identified by using various geochemical proxies including REE and Sr-Nd isotopic compositions and age patterns of detrital zircon and monazite grains. Our research results revealed that the modern Changjiang sediments yield variable chemical compositions among different tributaries and locations along the mainstream. Source rock compositions and chemical weathering intensities in the drainage basin account for the compositional variations. Climate is the predominant factor controlling silicate weathering in the Changjiang drainage basin, while controls by source rocks and relief are subordinate. The specific source rocks such as the large Emeishan Basalt Province and Himalayan igneous rocks in the upper basin and the metamorphic rocks in the middle-lower reaches contribute significantly to the sediment supply of the Changjiang. The bulk Sr-Nd isotopic compositions and age spectrum of zircon and monazite from the Changjiang sediments provide good constraints on sediment recycling and evolution of weathered upper continental crust in the Yangtze Craton. The core data from the East China Sea revealed that the Changjiang-derived sediments played an important role in the formation of sedimentary strata in the East China Sea during the late Quaternary, forming one of the largest deltas and of the widest continental shelf in the world. The combined influences of natural climatic variability, sea-level changes and anthropogenic activities on the production, transport, deposition and preservation of terrestrial sediment and organic matter in the Changjiang Delta and adjoining East China Sea were recognized. The changes of the Kuroshio Current mainstream during the late Quaternary greatly influenced the dispersal patterns of terrestrial sediments sourced from the surrounding landmasses, producing unique sedimentary architecture in the delta area and marginal sea.