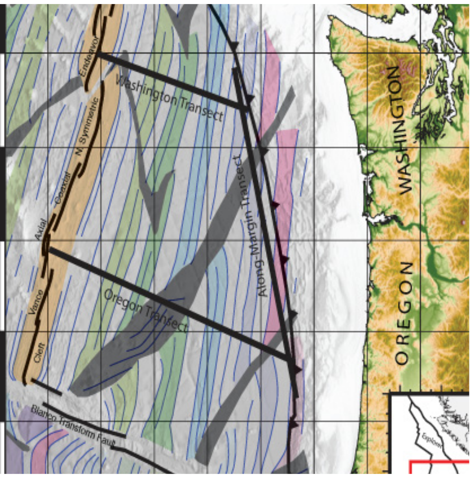
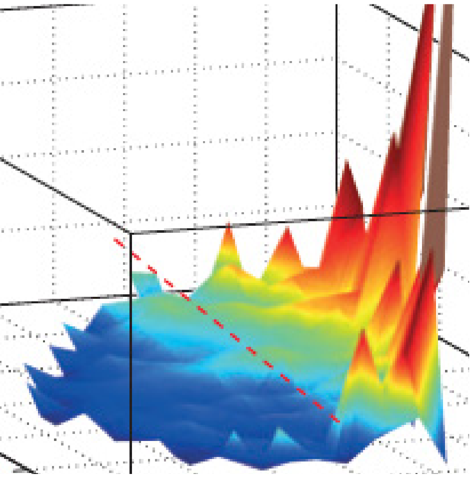
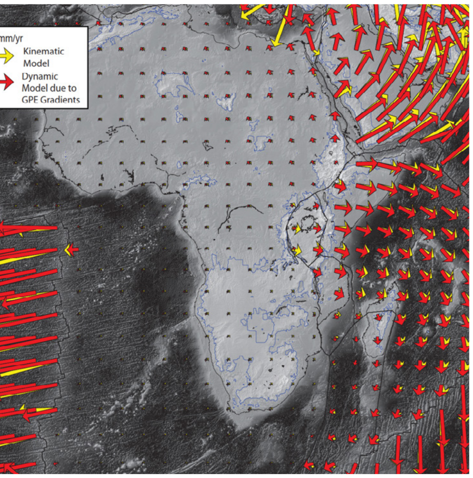
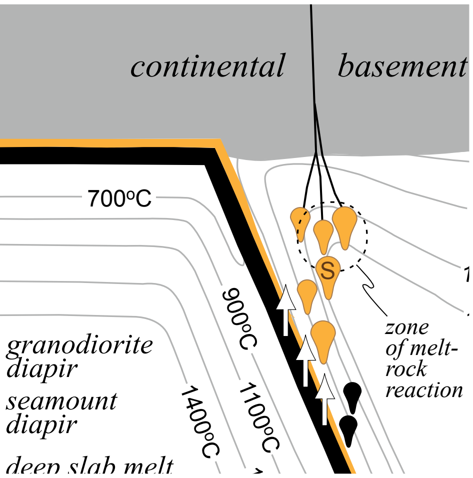
B3. GeoPRISMS-related Research Nuggets









GeoPRISMS-related Nuggets

Juan de Fuca Plate Ridge to Trench Seismic Experiment -NSF MGG

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Cascadia is a young-lithosphere end member of the global subduction system where relatively little hydration of the down-going Juan de Fuca (JdF) plate is expected due to its young age and presumed warm thermal state. However, numerous observations support the abundant presence of water within the subduction zone, suggesting that the JdF plate is significantly hydrated as it enters the trench. In order to further our understanding of the evolution and hydration of the JdF plate prior to subduction a joint multi-channel seismic (MCS) and wide-angle ocean bottom seismometer (OBS) survey was conducted providing plate-scale images and seismic velocity characterization of the sediments, crust, and shallowest mantle along two ridge-perpendicular transects offshore Oregon and Washington. In addition, an ~400 km long trench-parallel line 10-15 km seaward of the Cascadia deformation front was acquired to characterize variations in plate structure along the margin.

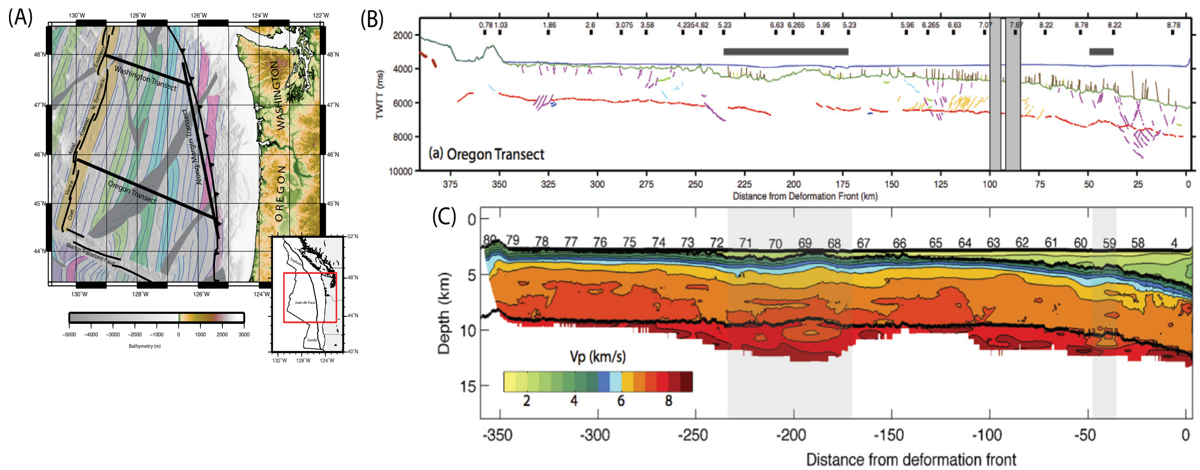

Figure 1. A) Map of seismic experiment, B) interpretation of Oregon plate transect showing faults within the sediment section (brown), crust and uppermost mantle (purple), ridgeward dipping lower crustal reflections (orange), and other sparse events in crust and near Moho (blue) (from Han et al. submitted). C) Seismic Tomography Model for Oregon transect (Horning et al., in prep). Propagator wakes are indicated with black horizontal bars in (B) and gray shading in (C).

Oregon and Washington Transects

Our study provides the first full plate seismic transects documenting evolution of crustal and uppermost mantle structure across an oceanic plate from ridge to trench (Fig. 1, Carbotte et al., 2013 AGU; Han et al., submitted; Han, 2015; Horning et al., in prep.). Within the plate interior MCS images (Fig. 1B) reveal numerous small offset faults within the sediment section beginning 55-70 km from the ridge axis, confirming previous inferences of a broad zone of faulting across the Juan de Fuca plate. Beneath the sediment blanket, sparse dipping reflections from presumed hydrated abyssal hill faults are observed; these faults are confined to the upper crust consistent with the inferred depth extent of abyssal hill faulting at intermediate spreading ridges. The lower crust within the plate interior is mostly acoustically transparent except for a series of distinct low-angle (20-40°) ridgeward dipping reflectors found in same age (6-8 Ma) crust along both transects. These structures are interpreted as ductile shear zones in the lower crust formed due to temporal variations in mantle upwelling associated with plate reorganizations at 8.5 and 5.9 Ma. From tomographic analysis of seismic velocity structure along the plate transects, we infer that the JdF plate acquires a mature structure within 1 Myr after accretion (Fig. 1C). This mature structure is characterized by a hydrated, porous upper crust, and a lower crust and uppermost mantle with seismic velocities consistent with dry gabbro and peridotite, respectively, and the temperatures expected from a cooling plate model.

Near the deformation front (DF), plate bending due to sediment loading and subduction inferred from basement topography begins ~150 and 80 km from the DF with more bending observed along the Oregon transect. Bright fault plane reflections are observed on the Oregon transect that extend through the crust and 6-7 km into the mantle beginning ~40 km from the DF (Fig. 1B), similar to those previously imaged offshore Nicaragua by Ranero et al. (2003) and attributed to hydrated fault zones due to subduction bend faulting. On the Washington transect, bend faults are confined to the sediment section and upper crust and more limited plate hydration in this outer trench slope region is inferred.

Starting at a distance of ~140 km from the Cascadia deformation front, we observe systematic changes in Vp structure of the plate as a function of distance from the DF (Fig. 1C). Variations in upper crustal velocities are interpreted as resulting from the competing effects of increased faulting and porosity due to plate bending, and mineral precipitation associated with hydrothermal circulation. Within the lower crust, plate bend faulting results in seismic velocities progressively decreasing towards the DF, due to increased porosity and hydration of the lower crust. Within 110-20 km west of the DF, relatively low mantle velocities are consistent with limited alteration of the mantle, but no mantle hydration is detected within 20 km of the deformation front. The largest lower crustal and mantle hydration anomalies are found at the location of the propagator wakes centered at ~200 and 45 km (Fig. 1C). Thus, paleosegment boundaries are zones of enhanced hydration that may locally affect subduction zone processes.

Strike transect 44.3°N-47.8°N:
Along our ~400 km long seismic transect parallel to the DF we observed a transition in crustal structure at ~45.8°N including a change from horizontal to southward dipping basement, more abundant crustal reflectivity, and lower crustal velocities to the south (Han, 2015; Canales et al., 2014). These results are attributed to an increase in bend-fault related plate hydration south of ~ 46°N. We speculate that the greater extents of crustal hydration of the incoming Juan de Fuca plate in this region, inferred from our plate transects and the deformation front strike line may contribute to the creeping of the megathrust beneath central Oregon.

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Horning, G, Canales, J.P., Carbotte, S.M., Han, S., Carton, H., Nedimovic, M.R. A 2-D Tomographic Model of the Juan de Fuca Plate from Accretion at Axial Seamount to Subduction at the Cascadia Margin from an Active Source OBS survey, in prep for submission July 2015, J. Geophys. Res.

Rising sensitivity of tremor and slow slip to tidal stress reveals fault weakening and low friction

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Episodic Tremor and Slip (ETS) is a recently-discovered phenomenon in which weak seismic signals called tremor accompany slowly-migrating slip on a plate boundary interface in slow earthquakes with moment magnitudes up to ~M7.5 and durations of weeks to years. Slow slip and tremor migrate in tandem along the deep portions of subduction zones at speeds averaging 8 km/day in Episodic Tremor and Slip events. Northern Cascadia hosts such events with magnitudes of 6.5 to 6.8 every 12 to 15 months.

Solid Earth and ocean tides raised by the Sun and Moon generate stresses that influence slow slip and tremor. This research showed that tidal influence increases over several days as slow slip occurs at a spot, implying weakening of the fault. Tidal stress perturbations were computed every 12 km and 10 minutes for six large ETS that featured slip over the same portion of the plate boundary in northern Cascadia. The migration front of each ETS was determined and used to classify tremor into early, intermediate, and late activity at each location. Analysis of tidal stresses at the times and locations of 33,000 tremors reveals that tremor rates are exponential functions of stress, with the dependence increasing over several days after passage of the front as slip accumulates at a spot. Tidal sensitivity is then defined as the factor that multiplies Coulomb stress in the exponent. This progressively-increasing tidal sensitivity contrasts with insensitivity of tremor early during slip. These results constrain the timing and degree of fault weakening during an ETS event.

The relative importance of shear and normal stress on the inferred fault interface is evaluated using the friction coefficient. The inclusion of mean stress in the formulation of pore pressure allows inference of intrinsic, rather than merely effective, friction. Correlation of tremor and tidal stress is maximized for very low values of intrinsic friction of 0 to 0.1. The analysis constrains the average macroscopic friction over the study region. These observations provide constraints that models of tremor and slow slip must satisfy.

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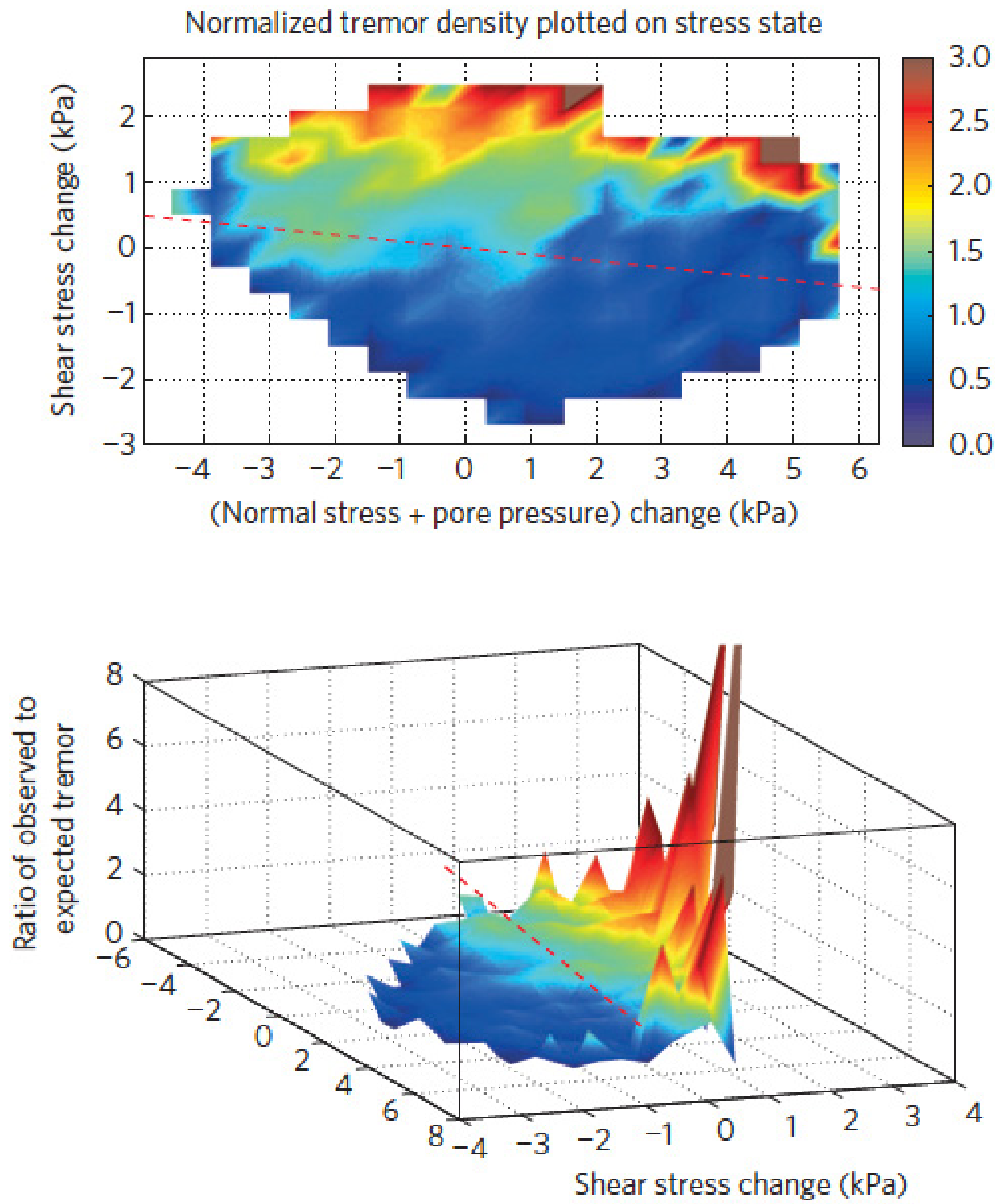

Figure 1. Sensitivity of tremor to shear versus normal stress changes. a) Ratio of observed-to-expected tremors (3 to 10 days after slip front) plotted in effective-normal-stress versus shear-stress space. Effective normal stress is normal stress plus pore pressure with Skempton coefficient 0.5. Expected number of tremors is based on the time that the fault occupies that stress state. Stress bins do not overlap. Positive normal stress is tensile. Dashed red line has slope -0.1, indicating very shallow slope of Coulomb sliding line, i.e., low intrinsic friction. 3-D perspective view shows exponential character.

Diffuse degassing of deeply-derived carbon dioxide along fault systems of the East African Rift

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NSF award numbers: 1113066, 1113355, 1113677

Deep carbon sourced from the Earth's mantle or subducted lithosphere is mainly released from active volcanoes as carbon dioxide (CO_2). However, one of the most poorly constrained sources of naturally emitted CO_2 is 'tectonic degassing', occurring along fault zones in the absence of active volcanism[1]. A recent field survey in the Natron-Magadi basin in South Kenya and North Tanzania provided new evidence for the mass transport of CO_2 through fault systems in the East African Rift. We measured diffuse soil CO_2 flux using an accumulation chamber, and found a strong association between the locations of fault scarps and CO_2 flux maxima[2]. In some places, these faults feed sets of hydrothermal springs with geochemical signatures (e.g., N_2-He-Ar relative abundances) indicative of mantle- or crust-derived volatile components[3].

Carbon isotope data reveal that the diffuse CO_2 has a likely mantle source. Seismic studies along the Eastern rift provide evidence for volumetrically significant accumulations of magma at depth[4], which we highlight as the likeliest source of the mantle-derived CO_2 measured at the surface. We conclude that massive CO_2 transfer from the mantle to the atmosphere occurs along extensional faults that may penetrate to lower crustal levels, as indicated by deep (15-30 km), normal fault earthquakes. These results suggest that the East African Rift is a significant contributor to Earth's global CO_2 budget. Furthermore, CO_2-rich fluids circulating through fault zones in these basins may facilitate lithospheric weakening and strain localization to the point of continental rupture.

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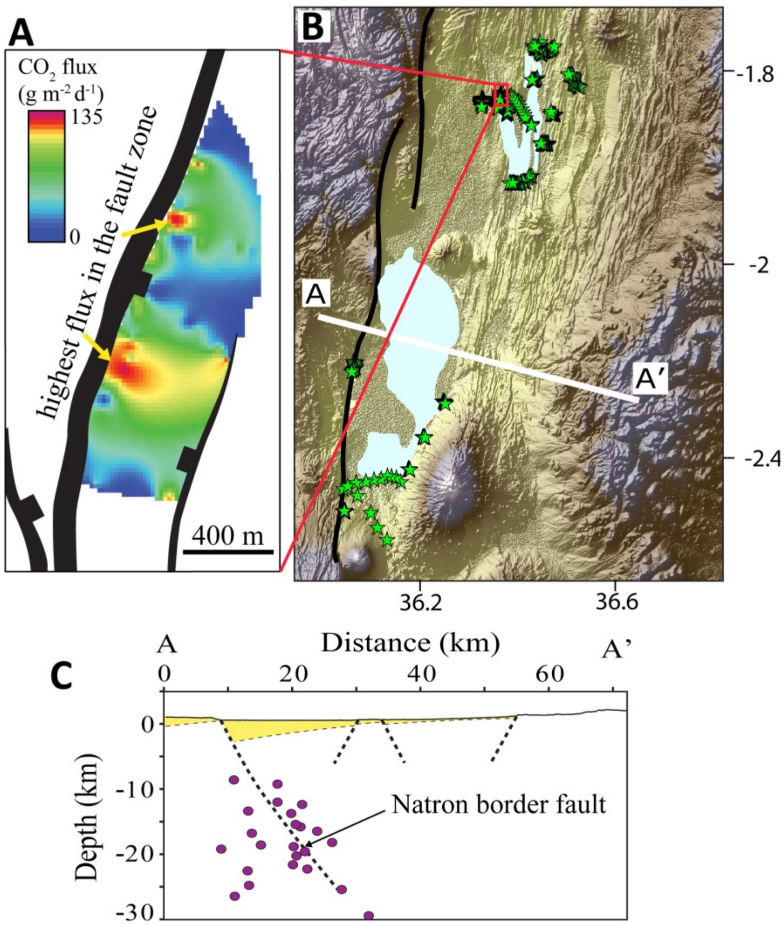

A: Contoured CO_2 flux map (25 m grids) in a faulted graben in the Natron-Magadi basin (courtesy of Cynthia Werner). CO_2 flux data collected during our preliminary 2014 field season. Black lines represent faults. B: DEM map of the Natron-Magadi basin study area. Black lines represent active border faults. Green stars show the location of diffuse CO_2 flux measurements. Light blue polygons represent lake water. C: Cross-section through the Natron basin from A-A' shown in (b). Purple circles represent earthquake foci within 2 km of the cross-section. Seismicity data were collected from 2013 to 2014 on the CRAFTI broadband seismic network. Yellow fill represents basin sediments, and dashed lines show the inferred projection of faults.

Why do Mafic Arc Magmas Contain ~ 4 wt% Water on Average?

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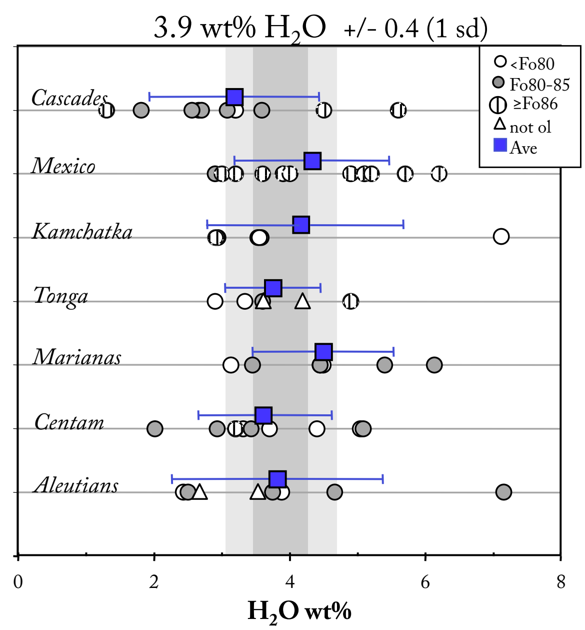
Over the last fifteen years there has been an explosion in data on the volatile contents of magmas parental to arc volcanoes. This has occurred due to the intense study of melt inclusions, trapped primarily within olivine, as aliquots of magma that have escaped degassing during eruption. The surprising first-order result is the narrow range in H_2O concentrations of the least degassed melt inclusions when averaged by volcano. Nearly all arc volcanoes are sourced with mafic magmas that contain 2-6 wt% H_2O. Moreover, the average for each arc varies even less, from 3.2 to 4.5, with an average for all seven arcs of 3.8 +/- 0.5 wt% H_2O. The narrow range and common average value for H_2O is in stark contrast to that for most other subduction tracers, such as Nb or Ba, which vary by orders of magnitude. A modulating process must be at work, either in the crust or mantle. One possibility is that melt inclusions reflects vapor saturation at the last storage depth prior to eruption, and water contents are diffusively reset in the crust. Another possibility is that the melting process in the mantle modulates water content in the melt such that magmas rise out of the mantle with ~4 wt% H_2O. This could occur through a feedback between the water content of the source and the degree of melting that maintains nearly constant water contents in the melt for a restricted range in mantle temperature. Crust and mantle controls may dominate in different regions and may be distinguished from coupled trace element or CO_2 variations.

Plank, T., Kelley, K.A., †Zimmer, M.M., Hauri, E.H. and Wallace, P.J. (2013) Why do mafic arc magmas contain ~4 wt% water on average? Earth and Planetary Science Letters, Frontiers Article, v. 364: 168-179.

Connection to GeoPRISMS: This work grew out of talks and discussions presented at the first GeoPrisms meeting in San Antonio, TX in 2010 (when established as the successor to the MARGINS program) and the Subduction Cycles and Deformation Implementation meeting in Bastrop, TX in 2011.



Water concentration in melt inclusions from volcanic arcs showing the remarkably narrow range in the average for each arc around ~4 wt% H_2O (from Plank et al., 2013). Each point plotted is the maximum water concentration measured in mafic melt inclusions from a single volcano or cinder cone. Most inclusions are hosted in olivine; symbols reflect forsterite (Fo) content and non-olivine hosts (clinopyroxene and plagioclase). Blue boxes are averages of volcanoes within each arc (error bars are one standard deviation). Grey vertical bar reflects average of all arcs (dark grey is one s.d; light grey is two).

Rifting in Eastern Africa: Geodetic Data Deciphers Spreading Forces

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Written by Linda Rowan - 7 October 2014

Summary

The driving forces of the East African Rift System that are shredding the eastern part of Africa have been debated for decades. Using geodetic data from GPS stations and other seismic data the authors model plate motions that they use to decipher the forces sustaining present-day rifting. The models show that density variations within the lithosphere, causing gravitational potential energy (GPE) gradients, are enough to explain current rifting. Other forces and/or weakening processes, such as those from mantle upwelling, are needed to initiate rifting that began millions of years ago.

Observations

Eastern Africa is being torn apart along a classic continental rift system called the East African Rift System. The rift runs north to south through east Africa for about 5,000 kilometers and stretches from the eastern border of Congo to easternmost Madagascar. The principal tectonic action is the Nubian plate separating from the Somalian plate. Beneath the rift, seismic tomography has imaged a superplume of hot and viscous upwelling mantle that is thought to create at least four major domes of high topography. These domes generate regions of high gravitational potential energy (GPE) along the length of the lithosphere of the rifting zone. There is a longstanding debate over whether the major force due to the GPE gradients or from mantle upwelling acting below the lithosphere is the main driving force of present rifting.

Results

Geodetic data monitoring the millimeter-scale plate motions comes from permanent GPS stations that are part of Africa Array and temporary GPS stations deployed by scientists for short times over several decades. UNAVCO supported most of these GPS sites. Seismic data used to image crustal and mantle structure is the other crucial component that informs the modeling. The model that best fits the data shows that only forces from GPE gradients are necessary to sustain current rifting and that buoyancy forces from mantle upwelling would lead to faster rifting than is observed. Thus results from this work help to resolve the debate over which major force drives present-day rifting in East Africa.

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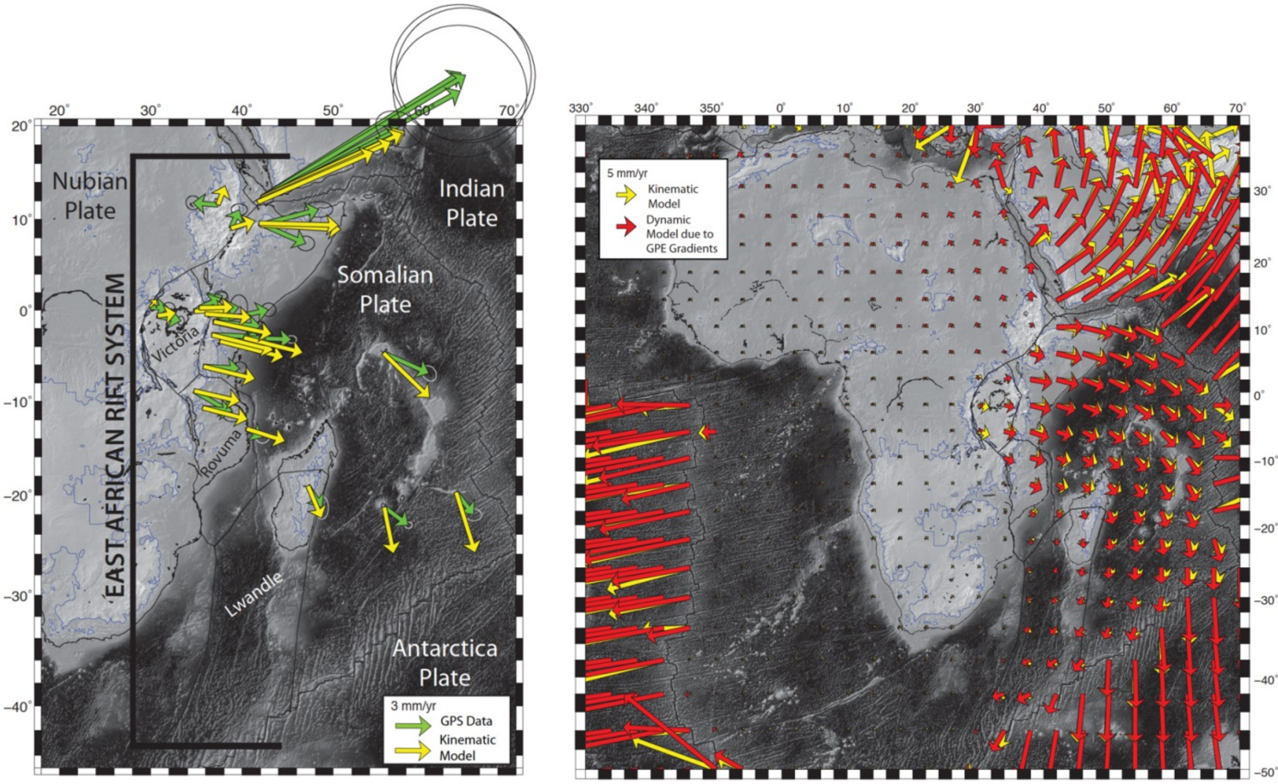
Keywords

East African Rift System, tectonic plate motion, mantle convection, gravitational potential energy, superplume


Nubian Plate
Indian Plate
Somalian Plate
EAST AFRICAN RIFT SYSTEM
Victoria
Rovuma
Lwandle
Antarctica Plate
3 mm/yr
GPS Data
Kinematic Model
5 mm/yr
Kinematic Model
Dynamic Model due to GPE Gradients

Crustal recycling by subduction erosion in the central Mexican Volcanic Belt

EAR 12-20481 - Starting date: 15 July 2012

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Recycling of upper plate crust in subduction zones, or 'subduction erosion', is a major mechanism of crustal destruction at convergent margins. In the central Mexican Volcanic Belt (MVB), we compared Sr-Nd-Pb-Hf and trace element data of crustal input material to Sr-Nd-Pb-Hf-He-O isotope chemistry of a well-characterized series of olivine-phyric, high-Mg# basalts to dacites (Straub et al., 2015). Remarkably, Hf-Nd isotope and Nd/Hf trace element systematics identify granodiorite eroded from the fore-arc, and not the trench sediment, as principal crustal component recycled from slab. Mass balance and physical parameters imply that the granodiorite may buoyantly rise as bulk 'slab diapirs' into the mantle melt region. Such granodiorite diapirs then dominate arc chemistry together Pb- and Sr-rich fluids from MORB-type altered oceanic crust (AOC) and minor deep slab melts. Overall, the central MVB magmas inherit their striking geochemical diversity principally from the slab which emphasizes the importance of continental crust recycling in arc crust formation relative to its new formation in modern subduction zones.

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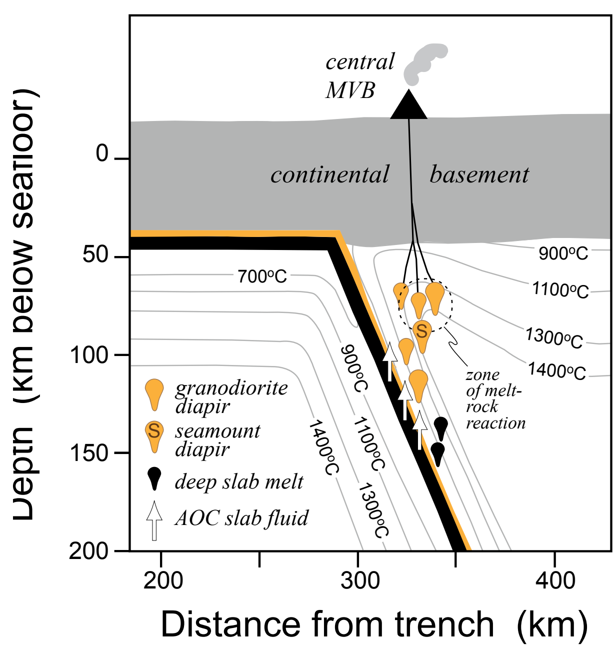

Figure 1. Cartoon of central Mexico subduction setting showing buoyantly rising slab diapirs of 'light' granodiorite (ochre color, mingling with AOC fluids and minor deeper slab melts). In hot core of the mantle wedge the slab diapirs react with peridotite to form pyroxenites segregation that finally give rise to arc volcanism (Straub et al., 2015). Thermal subduction model is based on Manea and Manea (2011)..