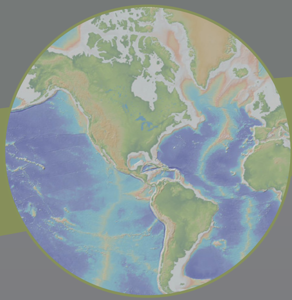
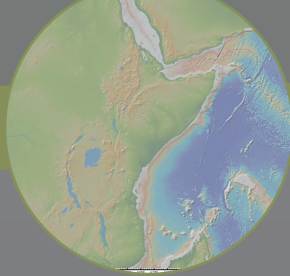
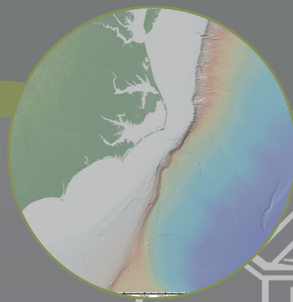

Theoretical & Experimental Institute

for the

Rift Initiation & Evolution initiative

• Abstract Volume •

Hotel Albuquerque • Albuquerque, NM
February 8-10, 2017

Geo**dynamic **P**rocesses at **Ri**fting and **S**ubducting **M**argin**S

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GeoPRISMS is funded by the National Science Foundation

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Cover: Korovin, Konia, Kliuchef volcanoes - Atka Island. Photo courtesy of Game McGimsey and Gene Yogodzinski. Maps created using GeoMapApp.

Presenter		Section		Poster title	Page
Floyd	**Michael**	B	4	*State of the GPS network and velocity solution across the entire East African Rift*	67
Gaherty	**James**	B	3	*Surface-wave imaging of the weakly-extended Malawi Rift from ambient-noise and teleseismic Rayleigh waves from onshore and lake-bottom seismometers*	68
Gans	**Phillip**	B	1	*The progression from magmatic to tectonic extension in a failed continental rift - the Colorado River extensional corridor in the southwestern United States*	69
Gibson	**James**	A	5	*Tectonic and climatic controls on seafloor sedimentary processes from analysis of sonar and 3D conventional seismic data collected during the Galicia 3D seismic experiment*	23
Grapenthin	**Ronni**	A	3	*Post-rifting relaxation after the 2014/15 Holuhraun rifting episode, Iceland*	24
Greene	**John**	A	1	*Refining the formation and early evolution of the Eastern North American Margin (ENAM): New insights from multiscale magnetic anomaly analyses*	25
Greenfield	**Tim**	A	3	*Microseismicity of Corbetti and Bora volcanoes in the Main Ethiopian Rift*	26
Han	**Liang**	A	1	*The effects of rapid sedimentation upon continental breakup: Seismic imaging and thermal modeling of the Salton Trough, Southern California*	27
Harris	**Robert**	B	2	*Heat flow across the Northern Gulf of California: Results of a high resolution survey across the Wagner Basin*	70
Harry	**Dennis**	B	2	*A kinematic model for opening of the Gulf of Mexico*	71
Hayman	**Nicholas**	B	2	*Deformation mechanisms for wide extension and a project concept for the Sao Paulo Plateau*	72
Heilman	**Erin**	A	4	*Role of the Mughese Shear Zone in oblique rifting along the Rukwa-Malawi segment of the East Africa Rift*	28
Huebert	**Juliane**	A	3	*Evidence for off-axis magma pathways in the Central Main Ethiopian Rift as imaged by Magnetotellurics*	29
Hunt	**Jonathan**	A	3	*The influence of structure on CO_2 degassing and past volcanism in the Main Ethiopian Rift*	30
Ilanko	**Tehnuka**	A	3	*Gas geochemistry at the fumarolic ice caves of Erebus volcano, Antarctica*	31
Ilhan	**Ibrahim**	A	4	*Meso–Cenozoic evolution of the Chukchi Borderland: Constraints on the tectonic development of the Amerasia Basin, Arctic Ocean*	32
Ismaiel	**Mohammad**	A	1	*Rift structure and break-up evolution of the Eastern Continental Margin of India: Evidence from high quality seismic reflection profile and drilled well*	33
Jammes	**Suzon**	A	1	*Effect of contrasting structural and compositional inheritances on the development of the North American margin*	34
Karson	**Jeff**	B	1	*Mid-crustal spreading in thick mafic crust of magmatic rifts, volcanic rifted margins and mid-ocean ridges*	73
Kolawole	**Folarin**	A	4	*Active deformation of Malawi Rift's North Basin hinge zone modulated by reactivation of Precambrian Shear zone fabric*	35
Krans	**Susan**	A	3	*Life and Death of a Flood Basalt: A Petro-stratigraphic tour of Flood Basalt Magma Evolution*	36
Lamb	**Lisa**	B	1	*An ideal natural laboratory to examine continental rifting: the sedimentary record of rift initiation and evolution in the Lake Mead Area*	74
Láo-Dávila	**Daniel**	B	4	*Rift border fault segmentation through along-strike deflection: Evidence from Southern Malawi Rift*	75

Presenter		Section		Poster title	Page
Lee	**Hyunwoo**	A	3	*Incipient rifting accompanied by the release of subcontinental lithospheric mantle volatiles in the Magadi and Natron basin, East Africa*	37
Liu	**Yiduo**	A	4	*Geometry and kinematics of the oblique border faults in the Tusas Mountain segment, Rio Grande rift, northern New Mexico*	38
Luckie	**Thomas**	A	3	*Why did we ever break up? Magmatism and extension along the Eastern North American Margin (ENAM) from GeoPRISMS ENAM Community Seismic Experiment refraction data*	39
Lutz	**Brandon**	B	4	*3D modeling of fault systems in Owens Valley, California*	76
Lynner	**Colton**	A	1	*Crustal thinning and a sharp crustal contrast across the eastern North American margin*	40
Mana	**Sara**	A	3	*Tectonomagmatic evolution of the East African Rift System as documented in West Turkana, Kenya*	41
Mark	**Hannah**	A	4	*Seismic cycles on normal faults at divergent plate boundaries from rate-and-state friction models*	42
Marzen	**Rachel**	A	1	*Constraints on crustal structure in the Southeastern United States from the SUGAR 2 refraction seismic refraction experiment*	43
Mesko	**Gary**	A	3	*Character and quantification of plume influence at Rungwe Volcanic Province*	44
Monteleone	**Vanessa**	A	2	*Crustal structure of the Eastern Black Sea Basin: New insights from long-offset seismic data*	45
Morgan	**Juli**	B	1	*Processes occurring during the latest stages of rifting: Evidence from new 3D seismic data of the west Iberia margin*	77
Mostafanejad	**Akram**	A	2	*Imaging Moho within the ancient Reelfoot rift system*	46
Muluneh	**Ameha**	A	4	*Kinematic reconstruction of the Ethiopian Rift since 20 Ma: Implication for deformation and strain accommodation*	47
Myers	**Madison**	A	3	*Ascent rates of rhyolitic magma during the opening stages of explosive caldera-forming eruptions*	48
Nakai	**Jenny**	A	2	*Seismicity of the Rocky Mountains and Rio Grande Rift from the EarthScope Transportable Array and CREST temporary seismic networks, 2008-2010*	49
Naliboff	**John**	A	2	*Modeling 2-D and 3-D continental extension with the open-source, finite element code ASPECT*	50
Nelson	**Wendy**	B	3	*Exploring the link between alkaline lavas and metasomatized mantle in the Western Branch, Uganda*	78
Nyblade	**Andrew**	B	4	*Thick lithosphere, deep crustal earthquakes and no melt: A triple challenge for understanding extension in the western branch of the East African Rift*	79
Oliva	**Sarah Jaye**	A	3	*Deciphering the role of fluids in early stage rifting from full moment tensor inversion of East African earthquakes*	51
Persaud	**Patricia**	A	1	*A bottom-driven mechanism for distributed faulting in the Gulf of California Rift*	52
Rahilly	**Kristen**	A	3	*Comparison of diffuse carbon dioxide measurements at three different geothermal systems*	53
Rotman	**Holly**	A	3	*Activity of West Antarctic Rift System volcanoes in the Western Ross Sea*	54

Constraints on the 3D Basin Architecture of the Weakly Extended Malawi Rift from an Onshore/ Offshore Wide-Angle Refraction Experiment

Accardo N. J., Shillington D. J., Scholz C., McCartney T., Ebinger C. J., Gaherty J. B., Nyblade A. A., Chindandali P. R., Kamihanda G., Ferdinand R. W., Salima J., Mruma A.

Current models of continental rifting increasingly point to the important role of weakening mechanisms like the addition of magmatic products in overcoming the disparity between the magnitude of tectonic forces available for rifting and the forces required to break strong, cold lithosphere. However, many rifts have limited volcanism. To understand the controls on rifting in magma-poor systems, we conduct 3D first arrival time tomography from active-source wide-angle refraction data collected in the Malawi Rift to constrain crustal structure along and across the rift. The Malawi Rift represents a weakly extended rift system located within the southernmost portion of the EARS. The only surface magmatism present occurs within the Rungwe Volcanic Province (RVP) located at the northern termination of the Malawi Rift. We utilize active-source data collected in Lake Malawi as a part of SEGMeNT (Study of Extension and maGmatism in Malawi aNd Tanzania). Over 86,000 unique air gun shots were recorded on an array of 32 offshore “lake” bottom seismometers and 55 onshore seismometers. The resulting ray-coverage encompasses the entire northern section of the Malawi Rift spanning the North and Central basins of Lake Malawi, portions of the surround plateaus, as well as the RVP. First arrivals are picked for all shot-receiver pairs with sufficient signal-to-noise ratio and included in a 3D first-arrival tomography model. Data and preliminary models indicate variations in fault structure and overall sediment thickness between and within rift basins. The North Basin is characterized by a series of synthetic intrabasin faults and sediments thickening to the east along the Livingstone border fault. The Central Basin is characterized by sediments thickening to the west along the Nkhata border fault in the south near Usisya, Malawi and then transitioning to eastward thickening at the northern termination of the Central Basin near the Manda, Tanzania.

Tectonic implication of structural architecture changes along the Red Sea Rift

Aldaajani T., Furlong K.

The Red Sea rift structural architecture changes dramatically along strike from narrow localized spreading in the south to asymmetrical diffuse extension north of 21˚ latitude, separated by the Barakah transform zone. The diffuse extension take place within an area that bounded by the Sarhan Rift, which a Cenozoic failed rift, to the east, the northern Red Sea Rift to the west and Makkah-Madinah-Nafud (MMN) volcanic line to the south and southern east. Our goal is building a finite element model that describes the Red Sea Rift, Sarhan Rift and MMN volcanic line dynamics within one geological context. Consequently, the diffuse extension within the NW Arabian Margin that associated with the Red Sea and Sarhan Rifts initiation will be emphasized. We hypothesize that the NW Arabian margin's lithospheric weakness and structural diversity are influence in changing the extensional mode from narrow to asymmetrical wide rifting. Oppositely, the SW Arabian margin interacts with the far field stresses as a single strong block in which led to localize the extension in the southern Red Sea. Our work may improve the scientific community understanding for how rifts initiate and evolve over time.

Constraints on the Final Stages of Breakup and Early Spreading history of the Eastern North American Margin from New MCS Data of the Community Seismic Experiment

Bécel A. and the Langseth ENAM Community Seismic Experiment Scientific team

In September-October 2014, the East North American Margin Community Seismic Experiment acquired deep penetration multichannel seismic (MCS) reflection across the Mid-Atlantic continental margin offshore North Carolina. This margin formed after the Mesozoic breakup of supercontinent Pangea. One of the goals of this experiment is an improved understanding of events surrounding final stage of breakup including the relationship between the timing of rifting and the occurrence of offshore magmatism and early spreading history of this passive margin that remain poorly understood. Here we present initial results from MCS data along two offshore margin normal profiles, spanning from continental crust ~50 km off the coast to mature oceanic crust and a MCS profile along the enigmatic Blake Spur Magnetic Anomaly (BSMA). Initial images reveal a major change in the basement roughness, including a basement step at the BSMA on both margin normal profiles. Seaward of this anomaly, the basement the basement is very smooth and reflective and clear Moho reflections are observed 2.5-3s twt beneath the basement top. A magmatic pulse would produce a more strongly magnetized upper oceanic crust that could explain the BSMA. Magnetic pulse would also be in agreement with the thicker than normal oceanic crust and smooth basement topography observed in the data.

Drainage development of rifting

Berry M., van Wijk J., Emry E., Axen G.

We study the development of drainage basins in continental rift zones. These drainage systems form as a result of many processes, including tectonics, erodibility, and climate. The drainage systems transport and deposit sediments throughout the rift system, and are therefore important in basin development. We compare the present day drainage system of the Rio Grande rift with drainage patterns produced by forward landscape evolution models. We test sensitivities to parameters such as erodibility, climate, tectonic rift opening rate, etc.

Mantle earthquakes and volcanics near the Red Sea Rift: Harrat Lunayyir, Saudi Arabia

Blanchette A.R., Klemperer S. L., Mooney W.D., Zahran H.M., El-Hadidy S.Y.

Harrat Lunayyir is an active volcanic field located in the western Arabian Shield, outside the margins of the Red Sea rift. Following the 2009 volcano-tectonic crisis a network now exceeding 20 permanent broadband seismographs has been installed in and around Lunayyir. We use common-conversion-point (CCP) stacking of P-wave receiver functions (PRFs) to image the Moho and lithosphere-asthenosphere boundary (LAB). The crust in the Harrat Lunayyir region is ~38 km thick and the entire lithosphere is only ~60 km thick. We locate 68 high frequency volcano-tectonic earthquakes, M < 3, within the mantle lid between 40 and 50 km. The presence of the mantle earthquakes within ~10 km of the LAB implies that the lithosphere is far out of thermal equilibrium and may have been thinned within the last few million years.

Magmatically assisted off-rift extension - a study of the Galema range

Chiasera, B., Rooney T.O., Grosfils E., Ramsey M., Zimbleman, J, Yirgu G, Ayalew D., Mohr P.

Within continental rift settings, extensional strain is initially accommodated along the nascent rift margins, subsequently localizing to zones of focused magmatic intrusion. The migration of strain from rift border faults to diking, places an emphasis on constraining the magmatic plumbing system of focused intrusion zones to resolve how extension is accommodated in the rift lithosphere. Existing rifting models concentrate on the relationship between extension and focused magmatism within the rift, but there are interesting cases of contemporaneous magmatic focusing immediately outside the rift margins. We examine the Galema Range, an area of focused magmatic intrusion along the eastern margin of the Ethiopian Rift, which is morphologically similar to areas of focused magmatism within the rift. We find that whole rock thermodynamic modeling and thermobarometric calculations suggest that fractionation (and hence magma stalling depths) within the magmatic plumbing system of the Galema Range is polybaric (~6.5 and ~2.5 kbar). These results, where compared with zones of focused intrusion within the rift, are strikingly similar. Lithospheric extension acting along the Galema Range, and possibly taking advantage of a basement suture, provided precursor to focused magmatism within the rift zone.

Volcanic vs. magma-poor passive margins: insights from numerical modeling experiments

Davis J.K., Lavier L.L.

Numerical modeling experiments have been conducted to controls on the development of end-member volcanic and magma-poor passive margins. Experiments utilized an adapted version of the FLAC algorithm and implemented a parameterization for melt generation from Katz et al. (2003). Volcanic passive margins are characterized by significant volcanic emplacement either preceding or synchronous with continental breakup; in contrast magma-poor margins are characterized by a paucity of igneous activity preceding continental breakup. Therefor we can compare results from numerical modeling experiments, and utilize the timing of significant melt generation relative to continental breakup, to make predictions concerning passive margins morphology. Experiments investigated a range of proposed controls, including extension rate, crustal thickness, crustal Mineral phase, lithospheric geotherm, mantle potential temperature, and mantle depletion, to assess the relative significance of each proposed influencing factor.

Trace element investigation of tephras from the Ledi-Geraru paleontological site in Afar, Ethiopia

DiMaggio, E.N., Arrowsmith, J R., Campisano, C.J., Garello, D.

The history of explosive volcanism in the highly extended Afar region of Ethiopia is recorded in Neogene to Quaternary tephra deposits in stratigraphic sequences exposed along the course of the Awash River and its tributaries. High extension rates and complex extension patterns in the Afar have resulted in faulted or discontinuous strata that require tephra correlation methods for linking rock records. Geochemical fingerprinting of tephras has traditionally been accomplished using major element data collected using electron microprobes. However, recent improvements to the laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) methodology allow minor and trace elements of small (20 μm), discrete, volcanic glass shards to be analyzed that increase the database for correlation and magmatic evolution studies. While discrete grain LA-ICP-MS has been successfully used in tephrochronology studies in places such as Antarctica, Indonesia, and the US, there has been limited application of the method to paleoanthropological sites in eastern Africa. Here we present results of trace and minor element glass analysis measured using LA-ICP-MS of a subset of tephras from the Ledi-Geraru project area in Afar where the earliest fossil of the genus Homo was recently discovered.

Multi-Stage Evolution of the Lithospheric Mantle in the West Antarctic Rift System

Doherty C.L., Class C., Goldstien S.L., Martin A.P., Cooper A.F., Berg J.H., Gamble J.A.

Mantle xenoliths provide an opportunity to investigate the geochemical and dynamic evolution of the lithospheric mantle beneath the West Antarctic Rift System (WARS) and reconstruct a timeline of geologic events that are obscured on the surface. In this study, mantle xenoliths, brought to the surface by recent volcanism (<10 Ma), were collected along a transect from the rift shoulder and into the rift basin, providing a snapshot of the lithospheric mantle following major episodes of rifting. The reoccurrence of Paleoproterozoic stabilization ages across the rift suggest a contiguous subcontinental lithospheric mantle that has been modified and thinned by dynamic extension during the opening of the rift. The WARS lithosphere has also experienced varying degrees of trace element re-enrichment that correspond to carbonatite metasomatism, a generally observed feature of the mantle in continental rifts, and constrains the origin and role of volatiles in WARS. The most highly metasomatized location within the rift produces a well-correlated Sm-Nd isochron indicating that the lithosphere acquired its metasomatic signature ~130 Ma ago, during the late stages of subduction along the paleo-Pacific margin of Gondwana. "HIMU-like" Sr-Nd-Hf isotopic compositions indicate a genetic link between the WARS lithospheric mantle and the petrogenesis of Cenozoic rift-related magmas.

Identifying Triassic rift basins in northwest Africa using gravity enhancements

Dowla N, Bird D., Murphy M.

Bouguer gravity anomalies enhancements aided in identifying three Triassic rift grabens in northwest Africa. Residual Bouguer gravity anomalies enhance shorter wavelengths, produced by crustal structures below sedimentary layers, at the expense of longer wavelengths related to deep crust and upper mantle density variations. Regional gravity anomalies are calculated by upward continuation (2.5 km) of Bouguer anomalies, which are subtracted from the original Bouguer data to create residual fields. The total horizontal gradient of Bouguer anomalies were calculated to enhance linear features, thought to overlie edges of anomaly source bodies, interpreted as graben-bounding faults. The Triassic rift grabens and bounding faults trend NNW-SSE in the south, N-S in the central portion and NNE-SSW in the north. A plate reconstruction for 185 Ma, the time of initial oceanic crust accretion, using the total reconstruction pole of Bird et al., (2008) show these Triassic rift grabens and bounding faults are oriented sub-parallel to Triassic rift basins along the US east coast. Previous studies of US Triassic rift basins show extension occurred in a NW-SE orientation, reactivating NW-SE striking Paleozoic compressional structures as rift bounding normal faults. Triassic rift bounding faults on the African margin are predicted to have undergone similar kinematic reactivation styles.

Lessons learned from the young, fast Woodlark Rift, Papua New Guinea

Eilon Z., Abers G.A., Gaherty J.B., Ge J.

The Woodlark Rift, in Papua New Guinea, is a superb natural laboratory for the study of continental breakup, with oceanic spreading centers propagating into continental crust that has experienced >100km of extension since 3.6 Ma. This rift is distinctive for its rate of opening, its relative youth, low mantle temperatures and sparse Holocene volcanism. Moreover, it hosts the world's youngest ultra-high pressure rocks, exhumed from 3 GPa in 5-8 Ma coeval with rift development. A 2010-2011 temporary seismic experiment provides dense broadband coverage of the highly extended continent adjacent to the mid-oceanic rift tip. We offer a comprehensive geophysical overview of this rift by coupling receiver function, surface wave, and seismicity analyses with finite frequency teleseismic tomography, including a novel technique to jointly recover shear velocity and azimuthal anisotropy. A well developed, low mantle velocity rift axis extends >250 km ahead of the spreading centers, in agreement with a linear trend of volcanism as well as moderately thinned crust and shallow seismicity. Low upper mantle velocities indicate complete lithospheric mantle removal, in contrast with moderate crustal thinning. Strong, spreading-parallel anisotropy implies efficient production of crystallographic fabric within the shallow rift axis, as the mantle "prepares" for seafloor spreading.

Comparative Riftology: Insights into the Evolution of Passive Continental Margins and Continental Rifts from the Failed Midcontinent Rift (MCR)

Elling R., Stein C., Stein S., Kley J., Keller R., Wysession M., Shen W., Rooney T., Moucha R., Frederiksen A., Darbyshire F., Jurdy D.

Continental rifts evolve to seafloor spreading and are preserved in passive margins, or fail and remain as fossil features in continents. Rifts at different stages give insight into the evolutionary paths. Of particular interest is how volcanic passive margins evolve. These are characterized by sequences of volcanic rocks yielding magnetic anomalies landward of and sometimes larger than the oldest spreading anomalies. Seaward-dipping reflectors (SDR) occur in stretched continental crust landward of the oldest oceanic crust, and are underlain by high-velocity lower crustal bodies. How and when these features form remains unclear. Insights are given by the Midcontinent Rift (MCR), formed by 1.1 Ga rifting of Amazonia from Laurentia, that failed once seafloor spreading was established elsewhere. MCR volcanics are much thicker than other continental flood basalts, due to deposition in a narrow rift rather than a broad region, giving a rift's geometry but a LIP's magma volume. The MCR provides a snapshot of the deposition of a thick and highly magnetized volcanic section during rifting. Surface exposures and reflection seismic data near Lake Superior show a rift basin filled by inward dipping flood basalt layers. Had the rift evolved to seafloor spreading, the basin would have split into two sets of volcanics with opposite-facing SDRs, each with a magnetic anomaly. Because the rift formed as a series of alternating half-grabens, structural asymmetries between conjugate margins can naturally occur. Hence the MCR shows that many features form prior to breakup. Because the MCR was massively inverted by regional compression long after it failed and uplifted, its structure is better known than failed rifts that incurred lesser degrees of inversion. It provides an end member for the evolution of actively extending rifts, characterized by upwelling mantle and negative gravity anomalies, to failed and inverted rifts without upwelling mantle and positive gravity anomalies.

Evolution of the Broadly Rifted Zone in southern Ethiopia through gravitational collapse of dynamic topography

Emishaw L., Laó-Dávila D.A., Abdelsalam M.G., Atekwana E.A., Gao S.S.

The Broadly Rifted Zone (BRZ) is a ~315 km wide zone of extension in southern Ethiopia. It is located between the South Main Ethiopian Rift and the Eastern Branch of the East African Rift System (EARS) represented by the Kenya-Turkana Rift. The BRZ is characterized by NE-trending ridges and valleys superimposed on regionally uplifted (~2 km average elevation) terrain. Previous studies proposed that the BRZ is an overlap zone resulted from northward propagation of the Kenya-Turkana Rift and southward propagation of the Southern Main Ethiopian Rift. To understand the relationship between the BRZ's extensional style and its crustal and upper mantle structures, this work first estimated the Moho depths using the two-dimensional (2D) radially-averaged power spectral analysis of the World Gravity Map (WGM 2012) satellite gravity data. Verification of these results was accomplished through lithospheric-scale 2D forward gravity models along E-W profiles. This work found that the Moho topography beneath the BRZ depicts a dome-like shape with a minimum depth of ~27 km in the center of this dome. This work proposes that the Moho doming, crustal arching underlying the BRZ and associated topographic uplift are the result of asthenospheric mantle upwelling beneath the BRZ. This upwelling changed to a NE-directed lateral mantle flow at shallower depth. This is supported by seismic tomography imaging which shows slow S-wave velocity anomaly stretching in a NE-SW direction at lithospheric depth of 0-100 km and 100-175 km from beneath the BRZ to the Afar Depression. At depths between 175-250 km and 250-325 km the slow S-wave velocity anomaly becomes a broad elliptical feature centered beneath the BRZ. This work proposes that the asthenospheric upwelling created gravitationally unstable dynamic topography that triggered extensional gravitational collapse leading to the formation of the BRZ as a wide rift within the narrow rift segments of the EARS.

Upper mantle low-velocity anomalies beneath the East African Rift from long-period ambient noise tomography

Emry E., Shen Y., Nyblade A., Flinders A., Bao X.

The possibility of upper mantle controls on rift initiation and evolution along the East African Rift is a subject of ongoing interest; however sparse and/or uneven instrumentation in the region can hinder a whole-rift interpretation. To better image upper mantle structure beneath the rift and to identify off-rift structure that contributes to active rifting, we utilize a long-period ambient noise, full-wave tomographic approach that is sensitive to Earth structure between seismometers. We utilize records from temporary and permanent broadband seismometers throughout Africa, southern Europe, and the Middle East. We extract empirical Green's functions from ambient seismic noise using a frequency-time normalization method to retrieve coherent signal at 40-340 seconds for 180+ seismometers. We then generate synthetic waveforms using a finite-difference method, measure phase delays, calculate sensitivity kernels, and iteratively invert for upper mantle structure. Results indicate several distinct low-velocity anomalies along the East African Rift, from Afar to the incipient southwestern branch; the anomalies shift with depth within the upper mantle and may connect to the mantle transition zone in places, with the strongest anomaly directly north of the Tanzania Craton. These patterns may indicate separation of buoyant upwellings that are diverted around cratons towards regions of thinner lithosphere.

What role does structural inheritance play in controlling the geometry of rifted basins during multiple phases of extension? A case study from the Northern North Sea.

Fazlikhani H., Fossen H., Bell R.E., Gawthorpe R.L., Rotevatn A., Jackson C.A-L.

In multiphase rift systems pre-existing crustal structures, which typically lie within crystalline basement, may influence the nucleation, growth and linkage of overlying normal faults. However, our understanding of the physical and kinematic linkage between basement and cover structures is limited, since deep structures are commonly poorly imaged in seismic reflection data. The North Sea Rift is an ideal natural laboratory to study the role of structural inheritance on the geometry of rifts, having undergone multiple phases of contractional (Ordovician-Devonian) and extensional (Devonian, Permian-Triassic and Middle Jurassic-Early Cretaceous) deformation. In this study we constrain the influence of pre-existing crustal structures on the evolution of Permian-Triassic and Middle Jurassic-to-Early Cretaceous normal fault systems. To achieve this we utilize 2D and 3D seismic reflection and borehole data from the Northern North Sea, covering the eastern margin of North Viking Graben. We show that pre-existing basement structures control the first-order rift geometry, including the location and the strike of the main Permian-Triassic bounding faults and intrabasement highs. In detail, however, the link is more complex, with some Permian-Triassic rift-related normal faults seemingly unrelated in terms of location or strike to intrabasement structures. Similar complexity is observed between Permian-Triassic and Middle Jurassic-to-Early Cretaceous rift related.

Magnetotelluric imaging of lithospheric modification due to late Cenozoic extension in the Rio Grande Rift, New Mexico, USA

Feucht D.W., Sheehan A.F., Bedrosian P.A.

We present crustal and upper mantle electrical resistivity models from two-dimensional (2D) anisotropic inversions of broadband and long period magnetotelluric (MT) data collected in the Rio Grande Rift in New Mexico, USA. Previous geophysical studies including seismic tomography and geodetic observations suggest that the Rio Grande Rift is a broad tectonic feature in the upper mantle responsible for minimal crustal modification with the exception of modest thinning and a narrow zone of brittle faulting near the rift axis. The data used in this study consist of over 75 broadband MT soundings (period range from 100 Hz to 10,000 s) collected by the University of Colorado Boulder and the United States Geological Survey during the summers of 2012 and 2013. We also present additional data from the large but underutilized MT data set of the Summer of Applied Geophysical Experience (SAGE), which consists of over 100 wideband (100 Hz to 1000 s) MT soundings collected in and around the Española Basin in north-central New Mexico over the past 25 years. We compare our 2D anisotropic models to 2D isotropic models in an attempt to identify artifacts that result from improper modeling of higher dimensionality MT data. A key feature that we identify in the resistivity models presented here is a broad (~200 km wide) zone of enhanced conductivity (<15 Ωm) in the mid- to lower-crust that is imaged beneath profiles crossing the rift in both northern New Mexico (latitude of Taos) and southern New Mexico (latitude of El Paso, TX). This anomaly extends well beyond the geologically and structurally defined surface expression of the rift. We interpret this lower crustal conductor as a combination of melt and fluid accumulation that is a direct result of the broad thermal anomaly in the upper mantle and evidence of recent tectonic activity in the rift.

Tectonic and climatic controls on seafloor sedimentary processes from analysis of sonar and 3D conventional seismic data collected during the Galicia 3D seismic experiment

Gibson J., Shillington D., Sawyer D., Morgan J., Ranero C., Reston T.

Due to a very low sedimentation rate, the deep Galicia Basin provides a unique opportunity to gain insight into the control by recent tectonic and/or climatic processes on deep-sea sediment delivery. In order to study the sediment delivery system we use morphological and geophysical attributes drawn from multi-beam (MB) sonar bathymetry/backscatter data supplemented with the 3D multi-channel seismic (MCS) seafloor surface collected using R/V Marcus G. Langseth during the Galicia 3D seismic experiment (2013). We observe a submarine canyon that is controlled by rift-block geometry and connected to the Galicia Bank. Relatively low reflectivity is associated with the canyon, but a large (~125 km^2) tongue-shaped area of high reflectively is seen in the deep abyssal plain seaward of the canyon mouth. This suggests that processes such as flow stripping are taking place resulting in relatively coarse grain deposition in the basin. This interpretation is further supported by the presence of variable wavelength (400m-5km) sediment waves and discrete linear bands of high reflectivity. Spectral analysis of the sediment waves reveals short-wavelength overprinting of relatively long-wavelength features suggesting a relatively recent shift in the flow regime. The spectrums also provide quantitative measurement of the wavelength, amplitude, and phase of the reflectivity relative to the bathymetry from which we make estimations as to grain size and flow velocity. The large tongue shaped high reflectivity feature extending ~30 km into the basin is analyzed in respect to geometry and variable reflectivity. The results of the above analyses along with interpretation of seafloor spectral decomposition provide insight into recent sediment delivery. From the combined analysis/interpretation we make estimations as to the most recent source process i.e. turbidity current vs debris flow in the framework of tectonic and/or climatic controls.

Post-Rifting Relaxation After the 2014/15 Holuhraun Rifting Episode, Iceland

Grapenthin R., Ofeigsson B., Hreinsdottir S., Bennett R.

On August 16, 2014 an intense seismic swarm started below the eastern part of Bárðarbunga Caldera, Iceland. A regional dike propagated ~40 km from its subglacial host magma reservoir and approached to within ~10 km of Askja volcano. A fissure eruption in Holuhraun lasted from 31 Aug. 2014 through 27 Feb. 2015 and produced a lava flow of 1.4 km^3 over 84 km^2. An NSF RAPID award partially supported the installation of 8 continuous GPS (cGPS) stations to capture the early post-rifting response and enable monitoring at Askja Volcano. Here, we show initial results of the post-rifting deformation and impact of the surface load of the new lava flow on GPS time series and provide preliminary models for the source processes.

Refining the Formation and Early Evolution of the Eastern North American Margin (ENAM): New Insights from Multiscale Magnetic Anomaly Analyses

Greene J.A., Tominaga M., Miller N.C., Karl M.R.

We examine multiscale magnetic anomaly data from the Eastern North American Margin (ENAM) to investigate the late rifting and early seafloor spreading history of the margin. We integrate sea surface, USGS aeromagnetic, and EMAG2 satellite magnetic anomaly data with recent seismic reflection and satellite gravity data. Based on our evaluation of magnetic anomaly character, we: (1) refine anomaly correlations throughout the ENAM; (2) assign updated ages and chron numbers to identified M0-M25 anomalies and estimate seafloor spreading rates along the margin; (3) propose the possible existence of pre-M25 anomalies; (4) identify five correlatable anomalies between the East Coast and Blake Spur Magnetic Anomalies, which possibly document the late rifting to earliest seafloor spreading regimes; (5) distinguish three regions within the Jurassic Quiet Zone seafloor that have notable differences in magnetic anomaly coherency, lineation angle, and spreading rate, suggesting that each region experienced rifting and the transition to seafloor spreading in a different manner; and (6) observe an anomalously high amplitude magnetic anomaly zone near the Hudson Fan, which may be related to a short-lived propagating rift segment that accommodated the spreading angle change between the rifting at the East Coast Magnetic Anomaly and the M25 Mid-Atlantic Ridge.

Microseismicity of Corbetti and Bora volcanoes in the Main Ethiopian Rift

Greenfield T., Keir D., Ayele A., Lavayssiere A., Kendall J-M.

Corbetti and Bora are central volcanoes in the Main Ethiopian Rift. Both volcanoes consist of a caldera ~15 km across formed between 200 and 300 thousand years ago which has been infilled with resurgent volcanism that continues to the present day. Using InSAR, Corbetti and Bora are observed to be currently deforming. This is assumed to be due to the present-day injection of magma into shallow magma chambers. Microgravity surveys performed around Corbetti backup this interpretation but the depth and potential hazard of these hypothetical bodies is currently undetermined. The active rift zone in Ethiopia is densely populated, therefore assessing the hazard at these dangerous volcanoes is very important.

Since February 2016, a seismic network consisting of 30 instruments has been monitoring the activity around both of these volcanoes. We use the first 8 months of data to automatically detect and locate the microseismicity recorded by this network. The arrival time picks are manually refined to improve locations and generate focal mechanisms. We show that Corbetti is seismically quiet with little seismicity within the caldera itself. The bulk of the seismicity is instead focused beneath the city of Hawassa to the south of the volcano. This is likely to be due to small amounts of motion on N-S trending normal faults.

Bora is significantly more seismically active with 700 earthquakes detected and located on the SE corner of the caldera. These earthquakes are very shallow and are likely to be due to activity within an active geothermal region.

The effects of rapid sedimentation upon continental breakup: seismic imaging and thermal modeling of the Salton Trough, Southern California

Han L., Hole J.A., Lowell R.P., Stock J.M., Fuis G.S.

The Salton Seismic Imaging Project (SSIP) illuminated crustal and upper mantle structure of the Salton Trough, the northern-most rift segment of the Gulf of California plate boundary. The crust is 17-18 km thick and homogeneous for ~100 km in the plate motion direction. New crust is being created by distributed rift magmatism, Colorado River sedimentation, and metamorphism of the sediment. A ~5 km thick preexisting crustal layer may still exist.

New meta-sedimentary rocks host shallow seismicity in the active rift. While the lower crust stretches by ductile flow and magmatism is not localized. The preexisting continent has essentially broken apart, but seafloor spreading has not initiated. This is because rapid sedimentation and magmatism create new crust to maintain the crustal thickness, which delays crustal breakup and the initiation of seafloor spreading. The thick metasediment will eventually become part of passive continental margins in the future, which could be misinterpreted as stretched preexisting continental crust. Since high heat flow and river deltas are expected during the late stages of continental breakup, metasediment may be an important and under-recognized component of global passive continental margins and rifting models.

Role of the Mughese Shear Zone in oblique rifting along the Rukwa-Malawi segment of the East Africa Rift

Heilman E., Kolawole F., Atekwana E.A., Abdelsalam M.G.

Numerous studies have investigated the role of Precambrian structures in strain localization along the rectilinear NW-SE trending border fault system of the Rukwa-Malawi segment of the East African Rift System. The Mbozi-Rungwe domain has also been considered as the major zone of strain accommodation for relative extension between the Rukwa Rift and Malawi Rift's North Basin. However, little is known about the structural interaction between the hinge zones of the two rifts. Analyses of high-resolution aeromagnetic data covering this area reveal a >500 km-long prominent NW-SE trending magnetic lineament representing the Ufipa Fault and its continuation along the entire southern boundary of the Mughese Shear Zone (MSZ). This magnetic lineament offsets another distinct N-S trending ~90 km-long and 300-500 m-wide magnetic lineament orientated orthogonally to it. We interpret this N-S trending lineament as a mafic dike emplaced within the MSZ during the Lower Mesozoic Karoo rifting episode which was later displaced right-laterally by strike-slip movement along the Ufipa Fault during Late Pleistocene-Holocene NW-SE-directed extension. Our results suggest that segments of the Precambrian fabric of the MSZ were initially reactivated as brittle discontinuities which later partly accommodated relative slip between the Rukwa Rift and Malawi Rift's North Basin.

Evidence for off-axis magma pathways in the Central Main Ethiopian Rift as imaged by Magnetotellurics

Huebert J., Whaler K., Fisseha, S.

Using newly recorded (2016) broadband and long-period magnetotelluric (MT) data along a 110 km long transect crossing the whole width of the Main Ethiopian rift, we present a regional 2-D model of electrical resistivity of the crust with a number of distinct anomalies. The derived model endorses a previous study that drew the surprising conclusion that there was no highly conductive region associated with a magma chamber directly under the central-rift-volcano Aluto. Instead the existence of a strong conductor under the Silti-Debre Zeyit Fault Zone 40 km to the north-west is confirmed. It is associated with the Butajira volcanic field, which hosts a number of scoria/ cinder cones at the boundary between the NW plateau and the rift. Conductive anomalies with this amplitude (<10 Ωm) are very likely to be associated with partial melt and/or fluids in dikes or faults. The Butajira area was previously classified as a failed volcanic segment with a high number of volcanic vents but low seismicity. With the evidence presented by MT new light can be shed onto potential magma pathways in the crust, as this offset between a central rift volcano and a potential deeper magmatic source is enigmatic.

The influence of structure on CO_2 degassing and past volcanism in the Main Ethiopian Rift

Hunt J.A., Mather T.A., Pyle D.M.

Volcanism in the Main Ethiopian Rift takes a variety of forms and represents a largely unquantified risk for the country's growing population. Distributed volcanic fields, active during the Quaternary, are aligned along bands of normal faults. Recent extension is focussed along these bands, significantly accommodated by magmatism. Large, peralkaline volcanoes are distributed along the axis of the rift - some show present unrest (e.g. Aluto, Corbetti - deformation, hydrothermal activity) whilst others are likely extinct.

Diffuse CO_2 surveys have been used to investigate areas of high flux in an attempt to quantify net emissions and characterise the pattern of degassing along the rift. Previous work suggests a huge contribution from rifts - we find that degassing is concentrated in localised areas and only specific faults, probably determined by magma storage. We therefore expect a lower (but significant) net flux from the rift, and warn of the ongoing risk from regional and distributed volcanism.

Digital elevation models of several peralkaline volcanoes have been generated. These are being used to characterise past volcanic events and assess the importance of pre-existing structures to vent location and eruption style. Results will have implications for hazard management and our understanding of rift-related volcanism.

Gas geochemistry at the fumarolic ice caves of Erebus volcano, Antarctica

Ilanko T., Fischer T., Kyle P., Curtis A., Oppenheimer C., Sano Y.

Volcanic degassing is the result of a number of processes. These include volatile exsolution at various depths, and the modification of the gas phase by redox reactions and hydrothermal systems.

At Erebus volcano, overlying the Terror Rift, high CO_2 fluxes through the summit lava lake suggest, in addition to shallow magmatic degassing, a much deeper source of CO_2-rich fluid. With crustal thicknesses of approx. 20 km in the region, this CO_2 has been proposed to originate in the mantle (e.g. Oppenheimer et al. 2011). Flank degassing through Erebus' fumarolic ice caves lacks the shallower magmatic component from the lava lake and presents an opportunity to understand pathways for deeply sourced gases. Gas emissions were measured by direct sampling at these caves, as well as by ground-based remote sensing.

Analyses show elevated carbon dioxide, water, and methane levels in the caves, and carbon isotope ratios ranging from air- to mantle-like compositions. These are likely due to deeply sourced gases mixing with surface air, though a few samples have heavier isotope ratios potentially indicating hydrothermal interactions. Direct samples from some vents contain very low oxygen and may represent a relatively pristine gas sourced from depth.

Meso–Cenozoic evolution of the Chukchi Borderland: Constraints on the tectonic development of the Amerasia Basin, Arctic Ocean

Ilhan I., Coakley B.J.

Any model for the tectonic development of the Amerasia Basin requires structures to accommodate the continental Chukchi Borderland in a plate-tectonic framework. We have interpreted 2D multi-channel seismic reflection data and tied these data to the late 80's Crackerjack and Popcorn exploration wells in order to: (1) develop a tectono-stratigraphic framework for the Chukchi Shelf and Borderland, and (2) indirectly test existing models for the development of the Amerasia Basin. Based on sequence stratigraphic principles, we have mapped four regional unconformities and used these to subdivide the basement and basin fill into five sequences. These sequences are: (1) pre-Brookian deformed strata (Mesozoic–Paleozoic); (2) pre-Brookian syn-rift#1 and dipping reflectors; (3) post-rift#1, inferred lower Brookian orogenic sediments (Barremian–pre-Cenozoic); (4) syn-rift#2 (inferred upper Cretaceous–Paleocene); and (5) post-rift#2, upper Brookian progradational wedge (Cenozoic). The angular relationship between the inferred Jurassic basal unconformity and the underlying syn-rift#1 sequence along the north striking normal faults of the Chukchi Plateau is inconsistent with clockwise rotation of the Chukchi Borderland away from the East Siberia. This falsifies one popular model for the Chukchi Borderland and its role in the development of the Amerasia Basin. In addition, the stratal relationship between the dipping reflectors and the overlying Brookian sediments along the inferred lower Cretaceous unconformity and the continuity of the orogenic sediments across the southern Chukchi Borderland substantially constrain other models proposed for tectonic development of the Amerasia Basin, Arctic Ocean.

Rift Structure and Break-up Evolution of the Eastern Continental Margin of India: Evidence from High Quality Seismic Reflection profile and Drilled Well

Ismaiel M., Krishna K.S., Srinivas K., Mishra J., Saha D.

The Eastern Continental Margin of India (ECMI) and adjacent ocean basins lie beneath enormous thick pre- and post-continental collision sediments, and this led to hamper our understanding of rift evolution and tectonic development of both the eastern Indian and Bangladesh margins. Seismic data interpretation and 3-D gravity inversion on ECMI and adjacent deep-water region have produced basement configuration, crust thickness and Moho topography that provide prospect to decipher the modes of rift evolution and location of Continent-Ocean Boundary (COB) along the margins. The basement, particularly in shelf and slope region of the peninsular India, is traversed by nearly coast perpendicular grabens, and their seaward continuity is observed up to 150 km. The geometry of rifted crustal blocks and crustal thickness variations along the margin elucidate three different modes of continental breakup along the ECMI, viz., 1) sheared rift on southern segment of the ECMI (off Southern Granulite Terrain), 2) hyper-extended rift on central segment (off Dharwar craton), and 3) hypo-extended rift on northern segment (off Bastar craton).

Effect of contrasting structural and compositional inheritances on the development of the North American Margin

Jammes S.

If progress has been achieved in the understanding of rifting processes, fundamentals questions remain on the role played by structural inheritances in the localization and development of rift structures. Here we focus on the eastern North-American margin. In this area the continental crust is the result of series of accretionary-collisional orogens during the Proterozoic and Paleozoic, juxtaposing terranes with different compositional and structural inheritances. It is consequently probable that the northward propagation of the Atlantic Ocean in the Mesozoic has been constrained by these different lithospheric fabrics. To study this question we compare the architecture of the Newfoundland and Labrador sea margins that developed on different terranes (respectively Appalachian and Greenville). 2D thermo-mechanical models are used to study the control of inheritances on localization and architecture of the margins. Structural and compositional inheritances are integrated in our models by using a bimineralic composition in which the distribution of the heterogeneities is constrained by geological and geophysical observation (wavelength and orientation in seismic profiles). Finally, our results are compared to the Orphan basin that constitutes the junction between the two rift systems. Its architecture and development is consequently the result of the competition between two systems subject to different crustal inheritances.

Active deformation of Malawi Rift's North Basin hinge zone modulated by reactivation of Precambrian Shear zone fabric

Kolawole F. , Atekwana E.A., Laó-Dávila D.A., Abdelsalam M.G., Ivey T., Chindandali P.R., Salima J., Kalindikafe L.

We integrated temporal high resolution aeromagnetic data, recent earthquake data and near-surface electrical resistivity tomography to address the long-standing question on the role of pre-existing Precambrian structures in modulating strain accommodation and subsequent ruptures leading to seismic events within the East African Rift System (EARS). We used aeromagnetic and electrical resistivity data to elucidate the relationship between earthquake surface rupture locations and rift-related blind faults within the hinge zone of Malawi Rift's North Basin half graben. Through the application of tilt and directional derivative filters, we identified and constrained the trend of the Precambrian metamorphic fabrics at rift flanks and beneath the basin sedimentary cover, and correlated them to the buried faults. Also, we used depth-to-magnetic-source modelling techniques to investigate the three-dimensional attitude of the faults. Our results reveal an unprecedented detail of the basement structure dominated by high frequency WNW-NW -trending magnetic fabric, and lower frequency NNW-trending magnetic lineaments super-imposed on the high frequency magnetic fabric. The high frequency lineaments are associated with sub-aerial exposures of the Precambrian Mughese Shear Zone, and the lower frequency lineaments represent structures in the areas overlain by rift sediments. Mapped surface ruptures associated with the 2009 Mw6.0 Karonga earthquake swarm align with one of the NNW-trending lower frequency magnetic lineaments - a 37 km-long structure oriented 148°-162°/40°SW and characterized by along-strike segmentation, and geoelectrical disruption associated with ground rupture and liquefaction. Fault geometries, regional kinematics and spatial distribution of seismicity suggest that seismogenic rift-related faults coincide with basement shear zone fabric along the hinge zone of Malawi Rift's North Basin half graben. Our results also suggest that the structural development of half graben hinge zones are not entirely controlled by crustal flexure, but can be actively modulated by underlying pre-existing basement fabric.

Life and death of a flood basalt: A petro-stratigraphic tour of flood basalt magma evolution

Krans S.R., Rooney T.O., Kappelman J.W., Ayalew D., Yirgu G.

Continental flood basalt provinces (CFBPs), which preserve the magmatic record of an impinging mantle plume head, offer a spatial and temporal insight into melt generation processes in Large Igneous Provinces (LIPs). In particular, detailed stratigraphic and petrographic interpretations are an invaluable asset to placing the geochemical evolution of CFBPs in context. Despite the utility of CFBPs as a probe of melting processes in LIPs, poor preservation has restricted our understanding of the magmatic evolution within these voluminous eruptions. The NW Ethiopian plateau offers a remarkably complete stratigraphic section from flood basalt initiation to termination, and is thus an important target for study of CFBPs more broadly. The NW Ethiopian flood basalt province has been spatially subdivided into three geochemical domains: High- Ti (HT1 and HT2) closest to the proposed center of the Afar plume, and the Low-Ti (LT) further for the plume center. This study presents the first flow-by-flow stratigraphy of the LT domain and utilizes petrographic observations to examine magma variation between flood basalt initiation, main phase volcanism, and flood basalt termination. We observe distinct and consistent variations in the magmatic evolution of the Ethiopian LT flood basalt, illustrating a shallowing of the magmatic plumbing system over time.

Incipient rifting accompanied by the release of subcontinental lithospheric mantle volatiles in the Magadi and Natron basin, East Africa

Lee H., Fischer T.P., Muirhead J.D., Ebinger C.J., Kattenhorn S.A., Sharp Z.D., Kianji G., Takahata N., Sano Y.

We present updated water chemistry as well as new gas chemistry and isotopes of the MNB thermal springs. The spring waters are produced by water-rock interactions between trachyte lavas and meteoric water, supported by equilibrated temperatures (122 to 153°C). Dissolved gases are mixed by deep (mantle-derived) and shallow (air/ASW) sources according to the N_2-He-Ar systematics, and deep sources are in equilibrium at about 100 - 150°C. N_2 is mostly atmospheric with minor mantle-derived contribution. CO_2 is contributed by both mantle and limestone. Helium is derived from both mantle and crust. However, SCLM can be the mantle end-member for N_2, CO_2, and He in the MNB, with the contribution of continental crust. The higher 4He flux values in the MNB relative to the mean continental flux suggest that fracturing induced by magmatism release radiogenic He to the fluids. Fluxes of mantle-derived volatiles (^3He, N_2, and CO_2) are 0.27%, 1.44%, and 0.24% compared to global fluxes. Our results demonstrate the MNB thermal springs discharge volatiles from SCLM which significantly interacted with continental crust, that characterizes volatiles of the early stage continental rifting in the EAR.

Geometry and kinematics of the oblique border faults in the Tusas Mountain segment, Rio Grande rift, northern New Mexico

Liu Y.A., Murphy M.A.

The Rio Grande rift regionally strikes N-S and facilitates E-W extension. However, its border faults in the Tusas Mt segment, northern New Mexico are NW- and NE-striking, following Precambrian structures. Classic models of oblique extension predict oblique displacement along the Tusas Mt border faults. However, our field investigation on fault slip directions finds that most oblique normal faults in Tusas accommodate predominantly pure extension, while some highly-oblique faults preserve almost pure strike-slip component. Basement rocks in northern New Mexico underwent a series of tectonic events during Proterozoic, Paleozoic, and Cretaceous-Eocene. Subsequently, these crustal/lithospheric weaknesses exert a strong influence on the structure and kinematics of the Rio Grande rift, by guiding the border faults in oblique directions and deflecting local stress fields adjacent to the normal faults. Such observation of slip re-orientation is comparable with the active West Branch of the East African rift system, and is demonstrated by analog experiments conducted on centrifuges. This study demonstrates that varying slip directions may be generated in one phase of extension, and multi-phase extension may not be necessary if oblique extension is influenced by pre-existing mechanical anisotropy.

Why did we ever break up? Magmatism and extension along the Eastern North American Margin (ENAM) from GeoPRISMS ENAM Community Seismic Experiment refraction data

Luckie T.W., Worthington L.L., Magnani M.B.

Understanding the distribution of magmatism during rift initiation and evolution preserved in continental margins helps explore the connection between extension and magmatism throughout the continental breakup cycle. We use onshore-offshore active source seismic data collected in 2014-2015 from the GeoPRISMS ENAM Community Seismic Experiment along the mid-Atlantic coast in eastern North Carolina to determine crustal velocity structure of extended continental crust. Two margin-dip profiles were acquired using five onshore explosive-source shots on the northern profile and six on the southern profile, and recorded using 720 Reftek-125 seismometers deployed at 250 m intervals. Additionally, offshore airgun shots were recorded using 80 seismometers deployed onshore during offshore data acquisition. This experimental setup yields crustal refraction, Moho reflection and refraction, and intracrustal reflection arrivals. Preliminary 2-D velocity models of each onshore profile reveal a crustal thickness between 35-40 km and a high velocity (>7.0 km/s) layer at the base of the crust. This feature may represent magmatic underplating that has only previously been observed offshore along the margin, and could be related to syn-rift magmatism along the ENAM or to the Central Atlantic Magmatic Province (CAMP).

Crustal thinning and a sharp crustal contrast across the eastern North American margin

Lynner C., Porritt R.W.

Passive tectonic margins, like the eastern North American margin (ENAM), represent the confluence of oceanic and continental tectonic regimes where no active deformation is occurring. The present-day ENAM was formed due to rifting associated with the breakup of the Pangaea supercontinent ~200 Ma. In order to properly study the formation and evolution of the ENAM, we need to understand the formation and evolution of the both sides of the margin. Combining seismic data from the recent ENAM community seismic experiment (CSE) and the eastern EarthScope seismic stations gives us a dense margin crossing seismic dataset. Using Rayleigh wave phase velocities from ambient noise, we invert for shear velocity across the ENAM. Very slow shear velocities (<2.2 km/s) are seen in the oceanic sediments and crust. Deeper, the oceanic lithosphere is characterized by fast shear velocities (~4.8 km/s). Crossing the margin, we see a sharp transition in crustal thickness. Immediately adjacent to the oceanic-continental crustal boundary, a thinning in ocean crustal thickness that coincides with the East Coast Magnetic Anomaly (ECMA) is observed, possibly preserved from the initial rifting of the margin ~200 Ma.

Tectonomagmatic evolution of the East African Rift System as documented in West Turkana, Kenya

Mana S. , Cai Y., Beck C.C., Goldstein S.L.

We present preliminary results for igneous rocks from West Turkana (Kenya). These were collected with the aim to better constrain the tectonomagmatic development of the Turkana Basin within the East Africa Rift System (EARS) and span a wide area ranging from the Lokitaung Gorge to Lothagam. We intend to combine new high-precision $^{40}Ar/^{39}Ar$ dating analyses with whole rock geochemistry and radiogenic isotope data. The Turkana Basin is a unique intra-domal region, where we see evidence that both magmatism and extension occur during the earliest phases of rifting. The onset of magmatism during the Late Eocene in the Turkana Basin shares the distinction of being the earliest magmatism in the EARS, together with the Amaro and Gamo tholeiitic basalts in southern Ethiopia. Magmatism continued in the Turkana Basin until modern times providing the opportunity to track the evolution of the mantle throughout the history of the basin. Previous geochemical studies in the Turkana Basin have identified sub-lithospheric mantle sources as well as a plume component but no data exist from West Turkana. The improved temporal evolution will have several applications: (a) achieve a better understanding of the role that magmatism had on rift inception and the breakage of the continental plate; (b) constrain basin development through time; (c) constrain plume dynamics and plume lithosphere interaction in west Turkana region.

Seismic cycles on normal faults at divergent plate boundaries from rate-and-state friction models

Mark H., Behn M., Liu Y., Olive J-A.

We use rate-and-state friction models to study the effects of fault geometry and thermal structure on the seismic coupling (defined as the fraction of fault slip that is accommodated seismically) of normal faults at divergent plate boundaries. In general, we find that the seismic coupling coefficient scales with W/h*, the ratio of the width of the seismogenic zone on the fault surface (W) to the critical earthquake nucleation size (h*), where W is controlled by seismogenic layer thickness and fault dip. This scaling relationship can explain, to first order, the variations in seismic coupling observed at divergent plate boundaries. At mid-ocean ridges, seismic coupling is observed to vary with both spreading rate and ridge segment morphology. Seismic coupling is very low at the fast-spreading East Pacific Rise (50%). Our models and available observations of seismic moment release suggest that seismic coupling on normal faults in a range of extensional settings is primarily controlled by W/h*.

Constraints on crustal structure in the Southeastern United States from the SUGAR 2 refraction seismic refraction experiment

Marzen R.E., Shillington D.J., Lizarralde D., Harder S.

The Southeastern United States is an ideal location to study the interactions between continental collision, magmatism, and continental rifting. Continental collision during the Alleghenian Orogeny (~290 Ma) formed the supercontinent Pangea. Extension leading to the breakup of Pangea began ~230 Ma, forming the South Georgia Basin and other rift basins. The Central Atlantic Magmatic Province (CAMP) magmatism was emplaced at ~200 Ma, and continental separation occurred afterwards.
We present preliminary velocity models for the ~400-km-long refraction seismic line from the SUwanee Suture and GA Rift basin experiment (SUGAR) Line 2. This line is central to CAMP magmatism, and crosses the South Georgia rift basin and two hypothesized locations for an ancient suture zone. Fifteen shots spaced at ~20-40 km were recorded by 1981 Texans spaced at ~250 m. We observe refractions from the basin, crust, and upper mantle on multiple shot gathers at a variety of shot-receiver offsets, as well as wide-angle reflections from the base of the sediments, within the crust and the Moho. Prominent mid crustal reflections may arise from the top of elevated lower crustal velocities and possible lower crustal layering. We compare our 2D inversion results to other geological and geophysical data from the region.

Character and quantification of plume influence at Rungwe Volcanic Province

Mesko G.T., Class C., Maqway M.D., Boniface N., Manya S., Hemming S.R., Shillington D.J.

The scarcity of magmatism in the western branch of the East African Rift (EAR) suggests that magmatic intrusion is not a prerequisite to continental rifting. To better understand magma's role in early continental extension, we have analyzed primitive magmas from Rungwe Volcanic Province, an isolated volcanic province in the southern EAR, to characterize the mantle source in chemistry and Sr-Nd-Pb-Hf isotopes. Ar-Ar dates of samples capture any evolution of the mantle source throughout the ~19 Ma volcanic history. Our independently calibrated thermobarometer suggests a sub-lithospheric melt source with no apparent thermal anomaly characteristic of a plume. The majority of erupted lavas possess major and trace element characteristics consistent with low fraction melt generated from carbonatite enriched garnet peridotite. One group of recently erupted lavas originate deeper than others, and lack the chemical and isotopic signatures of possible carbonatite metasomatized lithosphere. Seismic imaging of plume-like, point source melts like Rungwe suggest significant removal or perturbation of the underlying continental lithosphere. The volatile contributions of lithosphere enhance melt volumes without a pronounced thermal anomaly in the asthenosphere.

Crustal Structure of the Eastern Black Sea Basin: new insights from long-offset seismic data

Monteleone V., Minshull T.A., Moreno H.M.

The Eastern Black Sea is a deep water basin which was formed by the clockwise rotation of the Mid Black Sea Ridge away from Eurasia in Cretaceous-Palaeocene time. The basin is filled by a thick (up to 10 km) sedimentary sequence and appears to be underlain in part by oceanic crust. However, the distribution of oceanic and thinned continental crust remains poorly known, and the structures accommodating the stretching are still poorly imaged. The stretching appears to increase to the west, so the basin forms a natural laboratory to study processes of crustal stretching and breakup and subsequent sediment deposition and compaction. Long-offset reflection seismic profiles acquired in 2011-2012 using 10.2 km streamer and a large airgun source, provide new information on the deep structure of this area. The seismic dataset has been used to map the key horizons, such as the top of the acoustic basement and the Moho and to examine crustal reflectivity patterns as an indicator of crustal type. These data, integrated with constraints from previous seismic studies and potential field data will be used to unravel the nature and thickness of the crust and the mechanism of extension within the basin.

Imaging Moho within the ancient Reelfoot rift system

Mostafanejad A., Langston C.A.

We imaged the lithospheric discontinuities and lateral and vertical variations of the Moho boundary in the northern Mississippi Embayment (ME) within the ancient remnants of the intraplate Reelfoot rift system via downward continuation of the transfer functions. The ME is a synformal structure parallel to the Mississippi river, filled with succession of unconsolidated sediments that covers the New Madrid Seismic Zone (NMSZ). NMSZ is associated with the Reelfoot Rift system and consists of three major fault segments with mixed seismicity of thrust, strike-slip and normal faulting. Radial and vertical transfer functions were calculated for 154 broadband stations inside and outside the MS. To reduce the effect of high amplitude reverberations and scattering noise caused by sediments in the receiver functions, we created a stack of vertical components of displacement from stations outside the embayment on the bedrock and deconvolved it form the 86 radial components inside and outside the embayment. We have been able to successfully trace Moho boundary with high resolution in the study area using distinctive negative amplitudes at a depth of about 50 km.

Kinematic reconstruction of the Ethiopian Rift since 20 Ma: Implication for deformation and strain accommodation

Muluneh A.A., Cuffaro M.

We present the kinematic reconstruction of the Ethiopian Rift (ER) since the onset of rifting in the region. The south and central ER are fully closed by the reconstruction poles since 20 and 15 Ma, respectively. Considering the pre-rift extension, there is an overlap of about 30 km in the northern ER. Combing published GPS velocity vectors, earthquake focal mechanism and fault slip data, we investigate the along strike variation in kinematics and deformation pattern.

Ascent Rates of Rhyolitic Magma During the Opening Stages of Explosive Caldera-Forming Eruptions

Myers M.L., Wallace P.J., Wilson C.J.N., Watkins J., Liu Y., Morgan D.

We investigate the timescales of rhyolitic magma ascent for three supereruptions that show contrasting eruptive behavior at eruption onset, including: (1) the Bishop Tuff, Long Valley (650 km^3, 0.77 Ma), (2) the Oruanui eruption, Taupo NZ (530 km^3, 25.4 ka), and (3) the Huckleberry Ridge Tuff (2,500 km^3, 2.1 Ma). We present best-fit modeled ascent rates for H_2O and CO_2 profiles for REs from Huckleberry Ridge (n=10), Bishop (n=14), and Oruanui (n=5), measured using Fourier Transform Infrared Spectroscopy, with a spatial resolution of 20 μm (providing 4-15 points per RE). Using a code refined to include an error minimization function, best-fit profiles for the Bishop REs give ascent rates of 0.6-30 m/s. These Bishop ascent rates overlap with those of the Huckleberry (0.3-5.5 m/s), but extend to higher values. Although initially there seems to be little correlation between ascent rate and initial eruptive behavior, there is an increase in the number of faster ascent rates and deeper starting depths with higher stratigraphic height. Overall, there is significant overlap between the three datasets, with an average ascent rate of 4±7 m/s. Our calculated ascent rates fall towards the lower end of ascent rates previously estimated (5-40 m/s).

Seismicity of the Rocky Mountains and Rio Grande Rift from the EarthScope Transportable Array and CREST temporary seismic networks, 2008-2010

Nakai J.S., Sheehan A.F., Bilek S.L.

We developed a catalog of small magnitude (ML -0.1 to 4.7) seismicity across Colorado and New Mexico from the EarthScope USArray Transportable Array and CREST (Colorado Rocky Mountains Experiment and Seismic Transects) seismic networks from 2008-2010 to characterize active deformation in the Rio Grande Rift. We recorded over 900 earthquakes in the Rio Grande Rift region, not including induced earthquakes and mine blasts, and find that the rift is actively deforming both broadly and in distinct regions. Neogene faults in the northern rift in northern Colorado are seismically active in the North Park basin and northwestern Colorado. The central rift from the San Luis Basin (southern Colorado) to south of the Socorro Magma Body is the most seismically active portion of the rift, and seismicity delineates the deformation boundary of the Colorado Plateau transition zone, which is spatially correlated with volcanic vents, dikes, and faults within the western Jemez Lineament. The eastern Jemez Lineament is nearly aseismic and surrounded by a halo of seismicity culminating in boundaries defined by large recent earthquakes MW 5.5 and 3.9 in Amarillo, Texas and eastern Colorado. The southern rift is characterized by diffuse seismicity and continuing rift seismicity into Texas and Mexico, continuing south of the New Mexico-Mexico border. This study provides an updated seismic catalog built with uniformity in seismograph coverage and low epicentral uncertainties (~2 km) that allows for regional evaluation of seismicity. During this time period, clusters of seismicity and moderate magnitude earthquakes characterize deformation in a low-strain rate extensional environment.

Modeling 2-D and 3-D continental extension with the open-source, finite element code ASPECT

Naliboff J.

The CIG-supported, finite element code ASPECT is designed to model mantle convection using state of the art techniques for adaptive mesh refinement, parallel scaling and non-linear solvers. Here, I will present work that has helped adapt ASPECT to model long-term lithospheric deformation. Preliminary results will illustrate application of these adaptations to both 2-D and 3-D thermal-mechanical models of continental extension. As ASPECT is an open-source and community-driven code, input files for all the presented simulations will be publicly available for download and suggestions for future improvements are encouraged.

Deciphering the role of fluids in early stage rifting from full moment tensor inversion of East African earthquakes

Oliva S.J., Ebinger C.J., Roecker S.W., Keir D.B., Shillington D.J., Chindandali P.

The East African Rift splits around the Archaean Tanzania craton into the magmatic Eastern branch and the mostly amagmatic Western branch, which continues south of the craton. Temporary seismic networks recently deployed in three rift sectors allow for comparison and insights into the early stages of rifting, including areas with lower crustal earthquakes. We analyze earthquakes with ML > 3.5 in the area. We present source mechanisms as well as better-constrained source depth estimates from moment tensor inversion using Dreger and Ford TDMT algorithm (Dreger, 2003; Minson & Dreger, 2008). Data and synthetic waveforms are bandpass filtered between 0.02 to 0.10 Hz, or a narrower frequency band within this range, depending on lake noise, which can interfere strongly on the lower end of this frequency range. Results suggest local stress reorientations as well as significant dilatation components on some events within magmatic rift sectors. The implications of these results for crustal rheology and magmatic modification will be discussed in light of the growing complementary data sets from the three projects to inform our understanding of early rifting as a whole.

A bottom-driven mechanism for distributed faulting in the Gulf of California Rift

Persaud P., Tan E., Contreras J., Lavier L.

Observations in the continent-ocean transition of the Gulf of California (GOC) show multiple oblique-slip faults distributed in a 200x70 km^2 area. In contrast, north and south of this broad pull-apart structure, major transform faults accommodate plate motion. We propose that the mechanism for distributed faulting results from the boundary conditions present in the GOC, where basal shear is distributed between the southernmost fault of the San Andreas system and the Ballenas Transform fault. We hypothesize that in oblique-extensional settings whether deformation is partitioned in a few dip-slip and strike-slip faults, or in numerous oblique-slip faults may depend on (1) bottom-driven, distributed extension and shear deformation of the lower crust/upper mantle, and (2) the rift obliquity. We explore the effects of bottom-driven shear on the deformation of an elastic-plastic layer with the help of pseudo-three dimensional numerical models that include side forces. Strain localization results when the basal shear abruptly increases in a step-function manner while oblique-slip on numerous faults dominates when basal shear is distributed. We further explore how the faulting style varies with obliquity and demonstrate that the delocalized faulting is reproduced in models with an obliquity of 0.7 and distributed basal shear boundary conditions, consistent with GOC observations.

Comparison of diffuse carbon dioxide measurements at three different geothermal systems

Rahilly K.E., Fischer T.P.

Valles Caldera is a 13-mile wide, circular resurgent caldera within north-central New Mexico. Carbon dioxide degassing at Valles Caldera represents end-member hydrothermal and magmatic gases discharged at hot spot volcanoes such as Yellowstone and Kilauea. Repeat measurements of diffuse carbon dioxide emissions will be taken at multiple locations within the Valles caldera using an accumulation chamber in order to examine temporal and spatial variations. Isotopic measurements of collected gas samples will be used to examine the sources of emitted carbon dioxide.
We propose to compare CO_2 flux and sources within Valles Caldera, located at the intersection between the Jemez lineament and the Rio Grande Rift, with measurements at two different tectonic settings. We will be measuring diffuse carbon dioxide emissions using the accumulation chamber at the Yellowstone caldera, located above a migrating intracontinental hotspot. We will also make measurements over the Utah FORGE (Frontier Observatory for Research in Geothermal Energy) hot dry rock geothermal system, located at the boundary of the Colorado Plateau and the Basin and Range. These measurements will be used to analyze the effects of volcanic and tectonic settings on diffuse carbon dioxide emissions.

Activity of West Antarctic Rift System volcanoes in the Western Ross Sea

Rotman H., Kyle P.

The West Antarctic Rift System (WARS) is a major Cenozoic area of extended and thinned crust extending over 3,000 km beneath the Ross Sea, Ross Ice Shelf and the West Antarctic Ice Sheet. Rift related volcanoes occur on the rift shoulders in the western Ross Sea and in Marie Byrd Land. Most of the volcanoes are polygenetic and have alkalic undersaturated compositions. The active Erebus volcano is the best known because of its persistent anorthoclase phonolite lava lake but in the west Ross Sea other young and potentially active volcanoes include Mounts Morning, Rittmann, and Melbourne, as well as The Pleiades and small basanite vents in the Royal Society Range and north Victoria Land. Ice cores and englacial tephra deposits suggest Mt. Melbourne erupted in the last few 100 years and multiple times over the last 15,000 years. Magmatism is related to lithospheric extension and decompressive melting of rising mantle. We present an over-view of the youngest volcanism and a catalog of eruptions of Erebus.

Evolution of the Upper Lithosphere in the ENAM Area from Wide-Angle Seismic Data

Shuck B., Van Avendonk H.

Offshore North Carolina lies the geologic record of the rifting episode between North America and Africa that initiated at approximately 200 Ma. In this study we analyze 2-D and 3-D marine wide-angle seismic data from the ENAM experiment with the goal of understanding the relationship between melt migration and extension in the lithosphere during continental breakup. The East Coast Magnetic Anomaly (ECMA) lies near the eastern U.S. continental shelf and it is often considered to be associated with breakup between North America and West Africa. However, a puzzling feature of the ENAM site is the Blake Spur Magnetic Anomaly (BSMA) which lies 200 km eastward of the ECMA. We would expect the BSMA to have a mirror counterpart on the African plate if rifting was symmetric in nature, but we do not observe one. This leads us to formulate two alternative hypotheses: 1) Oceanic crust exists between the ECMA and BSMA, or 2) The ECMA and BSMA together form a wide volcanic margin. We construct seismic velocity models along ENAM lines parallel and perpendicular to the margin to determine structural fabrics in the mantle, which give insight into how the ECMA and BSMA are related to structure of the lithosphere.

Crustal reheating and mantle upwelling during continental break-up triggered by lithospheric deformation

Smye A.J., Lavier L., Stockli D., Zack T.

Oceanic basins are formed where continents are broken apart. At magma-poor continental margins, this has long been explained by uniform thinning of the lithosphere accompanied by passive upwelling of hot asthenosphere. Non-uniform, depth-dependent thinning has been proposed as an alternative to explain the anomalously shallow environment of deposition along many continental margins. Depth-dependent thinning models predict that the lower crust and sub-continental lithospheric mantle undergo a phase of increased heat flow during thinning of the lithospheric mantle. However, this early syn-rift heating is yet to be clearly documented at magma-poor continental margins. Here, we show that the lower crust of the Alpine Tethyan margin experienced reheating during the break-up phase of continental rifting, consistent with the depth-dependent thinning hypothesis. U-Pb dating and diffusion modeling of trace elements in rutile from lower crustal rocks in the Ivrea Zone, Southern Alps, shows that conductive heating of the lower crust occurred during the transition from plate stretching to thinning and was followed by advective heating associated with emplacement of asthenospheric melts. Combined with dynamic models of the rifting process, we use these data to show that coupling of deformation between the crust and lithospheric mantle establishes isostatic disequilibrium that

Examining crustal deformation and magma-tectonic interactions in a young continental rift zone

Stephens K.J., Wauthier C., Oliva S.J., Weinstein A., Ebinger C.

Seismic and volcanic hazards pose a huge threat to communities living in the East African Rift System (EARS). In order to quantify these hazards, we need to understand the interactions of magmatic and fluid pathways with tectonic structures formed in rift basins. In this study, we examined Interferometric Synthetic Aperture Radar (InSAR) data spanning 2013-2014 obtained through the COSMO-SkyMed constellation (ASI). Preliminary examination of the dataset suggests deformation related to two M4 earthquakes occurring in June 2013. Recent research [e.g., Wauthier et al., 2016] has shown that joint analysis of geodetic and seismic datasets helps to constrain deformation source models. Future work will involve performing joint analysis of InSAR data and seismic data obtained through the NSF-funded CRAFTI project in order to examine the geometry of fluids and magmatic pathways, as well as their interaction with rift-related faults in the Natron basin area.

Sustained Deformation at the Tendaho Geothermal Prospect, Ethiopia

Temtime T., Biggs J., Lewi E.

In complex tectonic settings, numerous natural and anthropogenic processes can cause surface deformation. We focus on the Tendaho graben, in Central Afar, Ethiopia which is tectonically and volcanically active with normal faults,eruptive fissures, hydrothermal vents and central volcanoes and contains towns and recently built infrastructure such as the Tendaho Dam. We use InSAR to study surface deformation in Tendaho graben. The InSAR data was collected by the Envisat satellite in 2004-2010. The cumulative displacement is compared to data from a continuous GPS station projected in to the satellite's Line-of-site (LOS). We observe a 20 km diameter of circular area of deformation located NE of the town of Semera, in the area of a geothermal prospect site. The displacement rate is 5cm/yr of range increase along the satellite LOS, corresponding to subsidence. The time-series from both InSAR and GPS shows ongoing deformation, starting, at the end of 2008. We use a Bayesian inverstion to find the best fitting source and compare this to locations of seismicity. pattern of deformation is consistent with either magmatic or geothermal processes. Understanding this sporadic deformation is vital for unveiling the tectonic of the region and for assessing the seismic and volcanic hazard to development and identifying resources.

Arid Continental Rift Systems: Exploration of the Rio Grande Rift Basin Complex

Welcome L.T., Wood L.J.

Despite arid continental rifts having been extensively previously studied, many questions remain about their origin, evolution; fill architecture and fluid migration histories. The Rio Grande rift (RGR) of New Mexico and Colorado, U.S. is a Tertiary age rift that provides an excellent analog for studying arid, continental rifts worldwide. The Rio Grande Rift's extensive development, friendly location and data density make it an ideal location for study. Such analogs provide important insights into rifts. Rifts host up to 31% of the world's giant hydrocarbon fields (Mann et al., 2003), several giant copper and other mineral deposits (Neoproterozoic rifts of southern Africa), and are important regional aquifer systems throughout the world.

The intention of this research is to examine the central-northernmost basins (Albuquerque, Espanola and San Luis basins) of the RGR and their associated sub-basins. Paying special attention to the basins' initiation and climax stages. The main objectives are to incorporate previous and newly acquired data: (1) to examine the spatial evolution and temporal history of the basins, (2) to produce a modern, comprehensive study detailing the stratigraphic and sedimentologic architecture fill of the specific basins. It is this research's overall goal that the RGR would be used to further enhance our understanding of arid continental rift basin evolution.

Evolution of the Broadly Rifted Zone in southern Ethiopia through gravitational collapse and extension of dynamic topography

Emishaw L., Laó-Dávila D.A., Abdelsalam M.G., Atekwana E.A., Gao S.S.

The Broadly Rifted Zone (BRZ) is a ~315 km wide zone of extension in southern Ethiopia. It is located between the South Main Ethiopian Rift and the Eastern Branch of the East African Rift System (EARS) represented by the Kenya-Turkana Rift. The BRZ is characterized by NE-trending ridges and valleys superimposed on regionally uplifted (~2 km average elevation) terrain. Previous studies proposed that the BRZ is an overlap zone resulted from northward propagation of the Kenya-Turkana Rift and southward propagation of the Southern Main Ethiopian Rift. To understand the relationship between the BRZ's extensional style and its crustal and upper mantle structures, this work first estimated the Moho depth using the two-dimensional (2D) radially-averaged power spectral analysis of the satellite World Gravity Map (WGM 2012) model. Verification of these results was accomplished through lithospheric-scale 2D forward gravity models along E-W profiles. This work found that the Moho topography beneath the BRZ depicts a dome-like shape with a minimum depth of ~27 km in the center of the dome. This work proposes that the Moho doming, crustal arching underlying the BRZ and associated topographic uplift are the result of asthenospheric mantle upwelling beneath the BRZ. This upwelling changed to a NE-directed lateral mantle flow at shallower depth. This is supported by seismic tomography imaging which shows slow S-wave velocity anomaly at lithospheric depth of 75 km to 150 km stretching in a NE-SW direction from beneath the BRZ to the Afar Depression. This work proposes that the asthenospheric upwelling created gravitationally unstable dynamic topography that triggered extensional gravitational collapse leading to the formation of the BRZ as a wide rift within the narrow rift segments of the EARS.

Passive seismic investigations of the amagmatic southern and southwestern segments of the East African Rift System

Reed C.A., Yu Y., Liu K.H., Gao S.S., Atekwana E.A., Mickus K., Massinque B., Mdala H., Chindandali P., Moidaki D., Mutamina D.

In order to investigate the origin and structure of the incipient southwestern and young southern segments of the East African Rift System (EARS), 50 PASSCAL broadband seismic stations were installed for the SAFARI (Seismic Arrays For African Rift Initiation) experiment from 2012 to 2014 across the Malawi (MRZ), Luangwa (LRZ), and Okavango (ORZ) rift zones. The studies summarized herein represent the first local teleseismic studies to examine crustal and mantle seismic structure using a dense array among any of the three rift zones [Gao et al., 2013 (Eos); Yu et al., 2015a (GRL); Yu et al., 2015b (EPSL); Yu et al., 2015c (G-cubed); Yu et al., 2017 (Geosphere); Reed et al., 2016 (JGR)].

Shear wave splitting (SWS) analyses of the ORZ reveal APM-parallel fast orientations similar to those observed in the vicinity of the LRZ and central-southern MRZ. Receiver function (RF) analyses of the mantle transition zone (MTZ) beneath all three rift zones reveal an essentially ubiquitous unperturbed transition zone with a mean thickness on par with the global average. Apparently uplifted MTZ discontinuities beneath the Kalahari Craton and the central MRZ-northern Mozambique region respectively imply the presence of anomalously thick lithosphere characterized by higher-than-normal seismic velocities. The primary results obtained from these SWS and MTZ analyses concordantly suggest that, as the dual consequence of the absence of evidence for a lower-mantle thermal upwelling traversing the MTZ or upper mantle as well as the lack of spatially-variable SWS measurements beneath the study areas, the rift zones are developing within an environment governed by a stress regime indicative of intra-plate rotational kinematics related to relative movement of cratonic blocks, and that the potential plume influence commonly acknowledged for geophysical phenomena beneath the Eastern Branch of the EARS does not exist within the MTZ or upper mantle beneath southern Africa.

H-k stacking of receiver functions recorded within the ORZ reveals a 4-5 km uplift of the Moho situated directly beneath the rift basin concordant with a low-density upper mantle modeled using gravity data, which is interpreted as potential decompression melting. High ratios of the P-to-S wave velocities (Vp/Vs) beneath the border faults of both the ORZ and the MRZ are indicative of fluids percolating along major faults within the crust. Crustal thicknesses on the order of 40-50 km adjacent to the rift zones are related to Precambrian East African orogenesis and the subsequent mobile belts within which the rift basins formed, while marginally smaller thicknesses were observed beneath the MRZ that indicate the absence of significant Cenozoic crustal thinning.

Finally, a P-wave tomographic investigation for Botswana reveals high-velocity anomalies beneath the Kalahari Craton, supporting previous MTZ-based interpretations, as well as a localized reduction in seismic velocity on the scale of 1% in the upper asthenosphere beneath the ORZ, which supports the hypothesis for the lithospheric accommodation of extensional stresses in the southernmost EARS.

Surface uplift history and geodynamics of the Socorro Magma Body (SMB), central Rio Grande Rift

Axen G.J., van Wijk J., Yao S., Sion B.

The SMB is a N-S elongate ~elliptical sill, ~19 km deep with volume of ~400 km^3. ~Circular surface uplift over the north 2/3 has average maximum rate of ~2.5 mm/yr (~1911 to now). Earthquake swarms above the SMB may reflect episodic, decadal-scale inflation or release of related stress, modulated(?) by volatiles or groundwater flow. 2D numerical models yield uplift patterns and evolution. Preliminary results are: 1. Without magma injection the SMB should solidify in â‰¤500 yrs. 2. Magma pressure increase rate controls surface uplift rate. 3. The inflation-driven uplift profile is pseudo-conical with a narrow flat top, similar to the observed profile. Width of geodetically measurable uplift (>~0.5-1 mm/yr) is similar to the SMB width. 4. Thermal expansion of host rocks drives uplift when heating begins, at ~constant rates similar to measured rates, then drops to near zero soon after heating ends. 5. Expansion-driven uplift is ~plateau-shaped, wider than the SMB, and unlike the observed profile. The northern SMB probably is actively inflating but expansion-driven uplift is subdued over the whole SMB. River terraces record surface doming between ~10 and ~50 ka, suggesting that magma source-region and/or plumbing-system processes operate on a 10 ka timescale.

Rheologic feedbacks between crystal preferred orientation and mantle flow driven by plate spreading

Blackman D., Castelnau O., Boyce D., Dawson P., Laske G.

Linked micro-macro scale numerical experiments explore the rheologic effects of crystal preferred orientation (CPO) and the magnitude of feedback on the pattern of upper mantle flow beneath slowly-spreading plates. The CPO and associated anisotropic rheology are coupled with a regional flow model via a local viscosity tensor, which quantifies the stress:strain-rate response of a textured polycrystal. The olivine polycrystals have anisotropic viscosity for a significant portion of the model and this alters the flow, particularly near the base of the lithosphere. For background asthenosphere viscosity of ~1020 Pa s and a rigid lithosphere, the modification of the corner flow pattern is not drastic but the change could affect melting. Stronger fabric is predicted below the flanks for fully coupled, power law polycrystals than was determined using prior linear, intermediate coupling models. SKS splitting is predicted to be modestly different between intermediate and fully coupled cases for plates less than 20 Myr old. Surface waves, however, are predicted to have twice the magnitude of Rayleigh wave azimuthal anisotropy. For the TEI, we aim to complete runs using a less conservative background viscosity (~$5x10^{18}$ Pa s) to assess feedbacks with near-axis small scale convection that has been predicted by prior models.

Crustal structure across the Okavango continental rift zone, Botswana: Results from the PRIDE-SEISORZ active-source seismic profile

Canales J.P., Moffat L., Lizarralde D., Laletsang K., Harder S., Kaip G., Modisi M.P.

SEISORZ is the active-source seismic component of PRIDE, a project that aims to understand the processes of continental rift initiation. In November 2014 we conducted a crustal-scale, 450-km-long seismic refraction/wide-angle reflection profile across the Okavango Rift Zone (ORZ) in NW Botswana consisting of 19 sources and 900 receivers. The profile crosses several tectonic domains: the Congo craton, the Damara metamorphic belt and the Ghanzi-Chobe fold belt, and the Kalahari craton. The record sections display clear crustal refraction (Pg) and wide-angle Moho reflection (PmP) phases, and a mantle refraction arrival (Pn), with the Pg-PmP-Pn triplication appearing at 175 km offset. There are distinct changes in the traveltime and amplitude of these phases along the transect and on either side of the rift axis, that correlate with sharp transitions across tectonic terrains and show evidence for shallow faulting. Current results include: (1) the presence of a sedimentary half-graben structure at the rift axis; (2) slower upper crust and thicker, faster lower crust to the southeast of the ORZ than to the northwest; and (3) 4-6 km thinner crust beneath the ORZ than in the surrounding domains (fold belts and Congo and Kalahari cratons) where the crust is crust 45 km thick.

Isostatically driven asthenosphere flow and the transition form rifting to seafloor spreading

Conder J.

The transition from continental rifting to mature seafloor spreading is a key moment in rift evolution. This transition is central to the creation of new plates and the self-sustained nature of plate tectonics. However, the reasons why rifts like the Mid-Continent rift in North America fail while the Laurasian and Gondwanan rifts progressed to become the Mid-Atlantic ridge are not well understood. Recent work shows that for rifting in the presence of an ocean to reach isostatic equilibrium, there must be an outward flow in the asthenosphere away from the rift. This flow is driven in the relative spreading direction and imparts a systematically positive drag - mantle push - component on the overlying lithosphere, enhancing rifting. This flow may be especially important as a plate-driving enhancement is in early plate development. The number of failed rifts across the planet suggest that a certain level of impetus must be reached before spreading becomes a self-sustaining process. As this flow only develops once inundation of the rift from the ocean occurs, this may be a tipping point in the transition from rifting to seafloor spreading, making plate tectonics easier to self-sustain.

Active deformation and magmatism during early stage rifting of Archaean lithosphere in the Eastern rift, Africa

Weinstein A., Oliva S.J., Ebinger C.J., Roecker S., Tiberi C., Witkin C.E., Aman M., Hadfield R., Gautier S., Muzuka A., Mulibo G., Kianji G., Msabi M., Ferdinand-Wambura R., Albaric J., Lambert C., Rodzianko A.

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State of the GPS network and velocity solution across the entire East African Rift

Floyd M.A., King R.W., and the GeoPRISMS EARS GPS Working Group

We present the latest GPS velocity solution for the entire East African Rift, processed by the Geodesy and Geodynamics Group at MIT. The network consists of both continuously operating and survey-mode GPS sites, and is processed completely to the beginning of 2016. This will be updated periodically as new surveys are performed and continuous GPS data becomes available. The geodetic velocity solution provides constraints on the large-scale kinematics of surface motions as well as more local effects both within and outside of the rift structures.

Surface-wave imaging of the weakly-extended Malawi Rift from ambient-noise and teleseismic Rayleigh waves from onshore and lake-bottom seismometers

Gaherty J.B., Accardo N.J., Shillington D.J., Ebinger C.J., Nyblade A.A., Mbogoni G.J., Chindandali P.R.N., Ferdinand R.W., Mulibo G.D., Kamihanda G., Keir D., Scholz C., Selway K., O'Donnell J.P., Tepp G., Gallacher R., Mtelela K., Salima J., Mruma A.

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The progression from magmatic to tectonic extension in a failed continental rift - the Colorado River extensional corridor in the southwestern United States

Gans P.

The lower Colorado River extensional corridor represents a spectacular example of a failed continental rift, analogous to the Asal Rift in NE Africa. Structural and stratigraphic relations within this ~100 km wide corridor of large magnitude indicate that extension and voluminous mafic to silicic volcanism are intimately related, but that the inception of magmatism consistently preceded the inception of tectonic extension by up to a few million years. Both extension and magmatism generally migrated northwards within the corridor at a rate of 3 cm/yr from the latitude of Parker, AZ at 21 Ma to the latitude of Las Vegas at 14 Ma. The orientations, ages, and cumulative width of extensive dike swarms preserved in tilted crustal sections within the corridor suggest that these dikes represent feeders for the voluminous volcanic successions that immediately pre-date the inception of large scale extensional faulting and block rotation. These relations indicate that the earliest phases of extension were accommodated mainly by diking, but gave way abruptly to tectonic extension either due to an increase in strain rate or reduction in magma supply.

Heat flow across the northern Gulf of California: Results of a high resolution survey across the Wagner Basin

Harris R.N., Negrete-Aranda R., Neumann F., Contreras J., González-Fernandez A., Sclater J.

To better understand the thermal regime of the northern Gulf of California we systematically measured heat-flow across the Wagner Basin - a tectonically active basin that lies at the southern terminus of the Cerro Prieto fault. The Wagner Basin is bounded by the Cerro Prieto fault on the east and on the west by a series of faults that link to the Consag Basin to the south. Seismic reflection profiles show sediment in excess of 5 s two-way travel time implying a sediment thickness > 5 km. The heat flow profile is 40 km long, has a nominal measurement spacing of ~ 1 km, and is collocated with a seismic reflection profile. We have estimated corrections for environment perturbations due to sedimentation and changes in bottom water temperature. The mean and standard deviation of heat flow across the western, central, and eastern parts of the basin are 262 ± 189, 108 ± 35, 1077 ±579 mW m-2, respectively. Corrections for sedimentation would increase heat flow across the central part of basin by 40 to 60%. We interpret the relatively high heat flow and large variability on the western and eastern flanks in terms fluid discharge,

A KINEMATIC MODEL FOR OPENING OF THE GULF OF MEXICO

Harry D.L., Jha S.

Lineated magnetic anomalies interpreted to be seafloor spreading isochrons are identified in the central and eastern Gulf of Mexico. The southernmost of these anomalies coincides with a strong positive vertical gravity gradient interpreted to mark the location of the extinct spreading ridge in the Gulf. Magnetic models show that the magnetic lineations correlate with geomagnetic time scale chrons M22n (150 Ma), M33n (161 Ma), M39n (165 Ma), and Toar-Aal N (174 Ma). M22n lies astride the fossil ridge and defines the age at which seafloor spreading ended. M33n lies between the ridge and the Florida shelf. M39n lies close to the shelf edge in the eastern Gulf. Taor-Aal N is the oldest recognized seafloor spreading anomaly and is present only in the central Gulf, laying near the ocean-continent transition (OCT). The magnetic anomalies define an Euler pole located at 22°N, 82°W. Counterclockwise rotation of Yucatan caused continental extension to propagate from the western into the eastern Gulf between ~215-174 Ma. Seafloor spreading began ~174 Ma and was asymmetric, with all extension occurring north of the spreading ridge. Symmetric seafloor spreading was established by 161 Ma and continued until 150 Ma.

Deformation mechanisms for wide extension and a project concept for the Sao Paulo Plateau

Hayman N., Lima, Lavier, Svartman Dias

A recently completed integrated geologic-observation and computational modeling effort shows that extensional provinces become wide (>100% extension) as a result of weakening of the mantle and lower crust. Deformation mechanisms responsible for this weakening appear to be hydrous retrograde fabric development, in most places reactivating and/or transposing earlier orogenic fabrics. In turn, seismic data illustrate that such deformation results in anastomosing patterns of reflectivity, the shear zones that accommodated depth-depending stretching and thinning. It is puzzling though, that regions of mantle exhumation appear to require a relatively strong lower-crust and upper mantle, and regions without mantle exhumation never achieve breakup without abundant magmatism. Perspectives from the South China Sea, the Alps and Pyrenees, and the western US Basin and Range, are helping to unravel the contrasts between strength, strain localization, and the role of hydrous metamorphic and melting reactions. A possible place to continue this work through academic seismic data acquisition and drilling is the central Brazilian margin where the Sao Paulo Plateau forms a basement high at the edge of a ~400-km wide part of the margin, yet is adjacent to one

Mid-crustal spreading in thick mafic crust of magmatic rifts, volcanic rifted margins and mid-ocean ridges

Karson J.

Mafic crust generated by spreading in a range of environments ranging from magmatic rifts to volcanic rifted margins to mid-ocean ridges show similar structures that indicate that mid-crustal flow is an important process during the early stages of crustal accretion but at different scales. Thick oceanic crust of the Greenland-Iceland-Faroe Ridge provides an especially dramatic example of the evolution of hot mafic crust. A high magma budget near the Iceland hotspot generates thick (~40 km) mafic crust in a plate boundary zone about 50 km wide. The upper crust (~10 km thick) is constructed by the subaxial subsidence and thickening of lavas fed by dense dike swarms over a hot, weak lower crust to produce structures analogous to seaward-dipping reflectors of volcanic rifted margins. Segmented rift zones propagate away from the hotspot creating migrating transform fault zones, microplate-like crustal blocks and rift-parallel strike-slip faults. These structures are decoupled from the underlying lower crustal gabbroic rocks that thin by along-axis flow that reduces the overall crustal thickness and smooths-out local crustal thickness variations. Spreading on mid-ocean ridges with high magma budgets have much thinner crust (10-5 km) generated at a much narrower (few km) plate boundary zone. Subaxial subsidence accommodates the thickening of the upper crust of inward-dipping lavas and outward-dipping dikes about 1-2 km thick over a hot weak lower crust. Along-axis (high-temperature ductile and magmatic) flow of lower crustal material may help account for the relatively uniform seismic thickness of oceanic crust worldwide. Spreading along even slow-spreading mid-ocean ridges near hotspots (e.g., the Reykjanes Ridge) probably have similar features that are transitional between these extremes. In all of these settings, upper crustal and lower crustal structures are decoupled near the plate boundary but eventually welded together as the crust ages and cools. Similar processes are likely to occur along volcanic rifted margins as seafloor spreading begins and in magma-rich continental rifts.as

An ideal natural laboratory to examine continental rifting: the sedimentary record of rift initiation and evolution in the Lake Mead Area

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The Lake Mead area, situated in the Central Basin and Range, is an ideal natural laboratory to examine continental rifting. The widespread Oligocene – Miocene Rainbow Gardens and Horse Spring Formations provide a detailed record of faulting, basin formation, sedimentary fill and paleogeography from ~25 to 12 Ma, prior to and during the main phase of extension from ~17 to ~8 Ma. Consisting of a variable mix of carbonates, siliciclastics, tuffs, and evaporites that formed in small basins of varying size, the deposits have been subsequently beautifully exposed by down-cutting of Colorado River tributaries, likely due to establishment of the Colorado River in the area at 5-6 Ma. The stratigraphy is highly variable in terms of lateral and vertical facies, making it hard to map across faults, but this complexity is actually advantageous: separate basins and subbasins have their own unique characteristics that can be used to unravel deformation. We probed 216 tuff samples for geochemical fingerprinting and dated 22 samples using $^{40}Ar/^{39}Ar$ geochronology. We measured over 70 detailed sections and, in the highly variable areas, walked out beds to document lateral changes. We mapped at 1:5,000 and 1:10,000 scales, conducted paleocurrent analyses and examined over 80 sandstone thin sections for provenance analysis. Finally, we ran 715 lacustrine carbonate samples for stable O and C isotope analyses to better understand the depositional environment of the lakes as well as paleoclimate changes. With this huge integrated dataset, we created a detailed chronostratigraphic framework and defined a number of sedimentary basins and subbasins. These basins are used to understand and reconstruct the episodes of faulting that created and dismembered them.

In the last four decades, several key papers from the Lake Mead area have put forth important theories of extensional processes (e.g. Anderson, 1971; Wernicke and Axen, 1988), including the idea of simple detachment faulting followed by major extensional breakup of the hanging wall (Spencer et al., 2001) versus the sequential development of a rolling hinge or domino-style faulting or a hybrid of these two (e.g., Brady et al., 2000). Our work suggests that the chronostratigraphy and stratigraphic relationships of this area do not support a model of continuous progressive deformation of the hanging wall through time and space but instead suggest cycles of deformation where a single large basin is broken up by faults into smaller subbasins over a short time interval, less than 100 ky. The deposits record two such cycles. Transtension plays a significant role in this deformation (Umhoefer et al., 2010) as well as pre-existing structures. Finally, we are creating a step-by-step tectonic reconstruction of the entire area from 24 Ma to present.

Rift border fault segmentation through along-strike deflection: Evidence from southern Malawi Rift

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We used Shuttle Radar Topography Mission Digital Elevation Model and aeromagnetic data to examine along strike border fault segmentation in the southern Cenozoic Malawi Rift. This segment of the rift traverses Mesozoic igneous ring complexes and Precambrian crystalline rocks with well-developed foliation. We focused on the interaction of the southeastern border fault of the rift with these inherited upper crustal heterogeneities. This part of the border fault is characterized by an outer NNE-trending discontinuous well-developed escarpment and an inner "zig-zag" less-developed escarpment. At 35°21'E and 15°8'S, the inner border fault interacts with nested igneous ring complexes and deflects along strike departing from parallelism with the preexisting Precambrian structure. At 35°17'E and 15°14'S, the outer border fault follows Precambrian foliation then reactivates a steep margin of a ring complex before it terminates abruptly before reaching the nested ring complexes where it encountered NW-trending Precambrian structures. The border faults were well-developed when they reactivated Precambrian foliation that facilitated strain localization, and they were deflected or terminated when they encountered the ring complexes that presented an anisotropic rheology. Our rift border fault segmentation model can be used to describe rift evolution elsewhere and demonstrates how anisotropy can govern border fault propagation and segmentation.

3D modeling of fault systems in Owens Valley, California

Lutz B., Phillips F., Axen G.

Three dimensional analysis of relocated hypocenter data in northern Owens Valley reveals a complex subsurface fault system that can be projected to major range bounding structures in the White Mountains and Sierra Nevada. Clusters of hypocenters representing distinct fault planes were used to generate mesh surfaces inclined to the point data. In the White Mountains, normal faults of various orientations merge into a single, northwest trending, moderately dipping listric fault. This master fault can be extended to the surface where it aligns with surface outcrops of the range bounding White Mountains fault zone.
Fault systems in the Sierra Nevada and around long Valley Caldera ruptured deeper in the crust. These data also reveal coalescence of chaotic shallow faults into a master listric fault at depth.
The robust fault plane models will serve as vital inputs to kinematic models of faulting in oblique and transcurrent deformation fields.

Processes occurring during the latest stages of rifting: Evidence from new 3D seismic data of the west Iberia margin

Jordan B., Sawyer D., Morgan J., Shillington D., Reston T., Ranero C.

A recently acquired 3D seismic dataset over the West Iberia margin demonstrates the complex 3D architecture of hyperextended continental crust and exhumed continental mantle at the distal edge of the margin. Faulted continental crustal blocks show higher degrees of extension in the north than the south. Similarly, pre-tectonic sediments are cut by more small scale normal faults in the north. I hypothesize that extension within the frontal basin was constrained by basement topography, specifically a small mantle ridge identified at the southern extent of the basin that may have obstructed the extension of the continental crustal blocks and overlying sediments. Several thrust faults also cut the pre-tectonic sediments and are interpreted to be the result of gravity-driven sliding during late-stage extension. After large-scale extension of continental crustal blocks, further extensional creep caused small-scale normal faulting of the pre-tectonic sediment in the north.

Exploring the link between alkaline lavas and metasomatized mantle in the Western Branch, Uganda

Nelson W., Furman T., Pitcavage E.

Tectonic processes influence the subcontinental lithospheric mantle's (SCLM) thermal, physical and mineralogical properties. Metasomatism by silicate melts and hydrous/carbonated fluids can create lithologies (i.e. pyroxenites) that are denser, more fusible, and less viscous than adjacent peridotite. This may lead to lithospheric instability, erosion, topographic uplift and even continental rifting. We explore the link between metasomatized SCLM and mafic volcanism in the Ugandan portion of the Western Branch of the East African Rift System using Re-Os isotopes from both alkaline mafic lavas and pyroxenite mantle xenoliths. The lavas record age-corrected $^{187}Os/^{188}Os$ that range from 0.1421 to 0.2105. The data confirm that many of the lavas were derived from a metasomatized mantle source. Mantle xenoliths also record a wide range of ^{187}Os abundances. One peridotite xenolith has a mildly radiogenic signature ($^{187}Os/^{188}Os$ = 0.1342) whereas the pyroxenites span a wide range of $^{187}Os/^{188}Os$ ratios (0.1270-0.5052). Based on these data, some of the SCLM was sampled by mantle xenoliths but, as a whole, the SCLM is more heterogeneous than the lavas suggest. The widespread, metasomatized SCLM readily contributed to melting, which occurred prior to and during Western Rift extension, suggesting that the metasomatized SCLM played a vital role in rift development.

Thick lithosphere, deep crustal earthquakes and no melt: A triple challenge for understanding extension in the western branch of the East African Rift

Nyblade A., O'Donnell J.P., Selway K., Brazier R., Tahir N., Durrheim R.

Geodynamic models predict that rifting of thick, ancient continental lithosphere should not occur unless it is weakened by heating and magmatic intrusion. Therefore, the processes occurring along sections of the western branch of the East African Rift, where ~150 km thick, Palaeoproterozoic lithosphere is rifting with no surface expression of magmatism, are a significant challenge to understand. In an attempt to understand the apparently amagmatic extension we probed the regional uppermost mantle for signatures of thermal alteration using compressional (Vp) and shear (Vs) wave speeds derived from Pn and Sn tomography. Pervasive thermal alteration of the uppermost mantle and possibly the presence of melt can be inferred beneath the Rungwe volcanic centre, but no signatures on a similar scale were discerned beneath amagmatic portions of the western rift branch encompassing the southern half of the Lake Tanganyika rift and much of the Rukwa rift. In this region, Vp and Vs wave speeds indicate little, if any, heating of the uppermost mantle and no studies have reported diking. Yield strength envelopes confirm that currently modelled stresses are insufficient to produce the observed deformation along these portions of the rift system.

Wave speed structure of the Eastern North American Margin

Savage B., Covellone B.M., Shen Y.

The eastern North American margin (ENAM) is the result of nearly a billion years of continental collision and rifting. To the west of this margin lies thick continental lithosphere of the North American craton, and to the east is oceanic lithosphere in the Atlantic. The substantial changes in lithosphere thickness at this boundary are thought to drive asthenosphere upwelling along the edge of the continent. Through iterative, full-waveform, ambient noise tomography, we observe a heterogeneous low wave speed margin along the continent in the upper mantle. Multiple low wave speed features imaged within the margin are consistent with asthenospeheric upwelling due to edge-driven convection. Also within the margin are high wave speed anomalies that maybe the remnants of eclogitic delamination of the Appalachian crustal root, which contribute to convection at the margin. Edge driven, small-scale convection keeps the margin weak and thus controls the large scale plate tectonic patterns and the crustal deformation. The imaged mantle wave speed anomalies, interpreted as edge-driven convection, correlate with and may increase the likelihood of damaging earthquakes in the eastern portion of North America.

Imaging active intra-basin faults in the Northern Basin of Lake Malawi from seismic reflection data

Shillington D., Accardo N., Chindandali P., Scholz C., Ebinger C., Onyango E., Peterson K., Gaherty J., Nyblade A., McCartney T., Oliva S., Kamihanda G., Ferdinand R., Salima J., Mruma A.

Many questions remain about the development and evolution of fault systems in weakly extended rifts, including the relative roles of border faults and intra-basin faults, and segmentation at various scales. The northern Lake Malawi (Nyasa) rift in the East African Rift System is an early stage rift exhibiting pronounced tectonic segmentation, which is defined by ~100-km-long border faults. The basins also contain a series of intrabasinal faults and associated synrift sediments. The occurrence of the 2009 Karonga Earthquake Sequence on one of these intrabasinal faults indicates that some of them are active. Here we present new multichannel seismic reflection data from the Northern Basin of the Malawi Rift collected in 2015 as a part of the SEGMeNT (Study of Extension and maGmatism in Malawi aNd Tanzania) project. This rift basin is bound on its east side by the west-dipping Livingstone border fault. Over 650 km of seismic reflection profiles were acquired in the Northern Basin using a 500 to 1540 cu in air gun array and a 1200- to 1500-m seismic streamer. Dip lines image a series of north-south oriented west-dipping intra-basin faults and basement reflections up to 5 s twtt near the border fault. Cumulative offsets on intra-basin faults decrease to the west. The largest intra-basin fault has a vertical displacement of >2 s two-way travel time, indicating that it has accommodated significant total extension. Some of these intra-basin faults offset the lake bottom and the youngest sediments by up to 50 s twtt (~37 m), demonstrating they are still active. The two largest intra-basin faults exhibit the largest offsets of young sediments and also correspond to the area of highest seismicity based on analysis of seismic data from the 89-station SEGMeNT onshore/offshore network (Peterson et al, AGU, 2016). Fault patterns in MCS profiles vary along the basin, suggesting a smaller scale of segmentation of faults within the basin; these variations in fault patterns appear to correlate with variations in the distribution of aftershocks from the 2009 and 2014 Karonga earthquakes and in background seismicity beneath the lake.

The middle to late Miocene evolution of the central to southern (USA + Mexico) Basin and Range in relation to continental rupture of the Gulf of California

Umhoefer P.

The Basin and Range (BR) includes a continuous belt from the Gulf of California extensional province through Southwestern USA to the Walker Lane. This includes the extensional to transtensional belt that lies east of the main Pacific - North America plate boundary. Much of the younger BR is the result of the W to NW motion of Baja California and Sierra Nevada microplates away from North America. These microplates are parts of the Cretaceous batholith; the eastern edge of the batholiths define the western edge of the BR. The transtensional faulting of the southern Gulf of California and Walker Lane belts are remarkably similar with normal faults along the batholith linked to mixed normal and strike-slip faults. This late to middle Miocene transtensional belt has domains of strain partitioning and no partitioning, the controls of which are unknown, but inherited structures may play a role. The southern part of the transtensional belt evolved to continental rupture to form the Gulf of California, while the northern Walker Lane became a secondary part of the modern plate boundary at those latitudes. The relation between these "failed rupture" to rupture provinces must be better known in order

How to form a micro-continent

van Wijk J., Axen G.

We present a new model that explains the formation of micro-continents. Micro-continents are fragments of continental crust, separated from the main continent by oceanic lithosphere. In our model, continental breakup is followed by seafloor spreading, which, during its initial phase, may be magma-limited or -starved. During phases of magma-starved seafloor spreading, the spreading ridge strengthens, which may induce a ridge jump. When the new spreading ridge jumps into adjacent continental lithosphere a sliver of the continent may break off, forming a micro-continent. When the spreading ridge jumps into oceanic lithosphere, an asymmetric ocean basin forms.

Spatial and temporal variability of tectonic uplift rates on the Southeastern Ethiopian Plateau, East African Rift System

Xue L., Abdelsalam M.

We used Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) to extract geomorphic proxies (normalized steepness, stream length gradient, shape factor, and valley height ratio) for the Southwestern Ethiopian Plateau. We also imaged the Moho beneath the plateau using two-dimensional power radially-average power spectral analysis of World Gravity Model (WGM 2012) satellite gravity data. Our aim is to examine the uplift history of the plateau that might be associated with the uprising of the Afar mantle plume and opening of the East African Rift System. This plateau which is bounded by the Afar Depression in the north and the Main Ethiopian Rift in the east exposes Cenozoic volcanic rocks at the top underlain by Mesozoic sedimentary rocks which in turn underlain by Precambrian crystalline rocks. Studies in the Northwestern Ethiopian Plateau resulted in two contrasting models for explaining the uplift history of the region. Thermogeochronology studies suggest a continuous and steady uplift rate since ~30 Ma possibly driven by the ascending Afar mantle plume. Interpretation of incision of drainage systems in the plateau suggests three stage and accelerated uplift. Our work found two areas with high rate of tectonic uplift located around the Mendebo and the Ahmar mountains. These regions show two distinct phases of uplift of the Southeastern Ethiopian Plateau.

Extremely rifted continental crust in the pre-Taiwan collision zone of the South China Sea

Yan P., Wang Y., Zhong G., Wang J.

To account for the reason for continental subduction in Taiwan arc-continental collision, it was supposed that the slab in the SW Taiwan be oceanic so as to be pulling the hind continental slab into the Manila trench. However, new deep seismic imaging shows evidently that the crust over the large span of SW Taiwan is continental, hyper to extremely extended, which challenges the fundamental of previous Arc-Continental model (Huang et al., 2006). The continental lithosphere, evolved to the final rifting stage with only lower crust and exhumed mantle remained, might be denser and readiably subductable when converging with oceanic plate.