Afar Rift Consortium

Magmatic Rifting & Active Volcanism

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Dedicated to the memory of

Dr Kassim Mohamed Kassim (1970-2011)
and
Dr Mohammed Umer (1959-2011)

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Abstract volume

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Oral Presentations

November 2010 Earthquake Swarm – Western Gulf of Aden

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Session: MOR

In the western Gulf of Aden (west of 450E), a large seismic swarm started in November 2010 with a major shock of magnitude 5.6, and occurred along the westernmost segment of the Aden slow-spreading ridge. This E-W-striking segment with complex tectonic features is considered to be a transition zone between a well defined mid-oceanic spreading ridge to the East and the continental East African and Afar rift systems to the West. Other seismic swarms along the Aden spreading ridge have been previously observed, but both the location and the magnitude of the earthquakes, together with the total swarm duration (> 4 months), confirm that the November 2010 event is significant.

We combined the data recorded by several land seismic stations of regional networks in Djibouti and Yemen,. We analyzed thousands of events, with magnitude ranging from 2.5 to 5.6. Due to the azimuthal coverage of each individual network and to the large distance between its stations, the earthquakes were not very well located using data from a single network. From December 2010 to March 2011, we improved the earthquake localizations by (1) installing a new seismic network along the Yemeni coast including 7 broadband stations (Yocmal project extra part), (2) re-distributing the Actions-Marges Djibouti Profile broadband seismic stations along the Djbouti coasts and (3) merging the data from 1 and 2 with the seismic data recorded by the Yemen and Djibouti permanent networks in one database. We first localized the large earthquakes recorded by at least 7 stations from the four networks. Analysis of this seismic database gives us important information on the geodynamic process of this particular segment of Aden spreading ridge.

We identify three main shallow source zones (< 10 km). The main source zone, where the most seismic energy is released during the swarm, is centered at 120N 420E with earthquakes concentrated along a narrow, 22 km-long, 1090N-trending zone. The second source zone, centered at 12.070N 43.860E with a length of 19 km and trending 300N, concentrated the first earthquakes of the swarm with significant activity in November strongly decreasing afterwards. The third source zone corresponds to a small cluster of events aligned to the east and west of the main source zone, which seems clearly related to the presence of some submarine volcanic cones and major normal faults.

The combination of data from several seismic networks allows the opportunity to precisely study the seismic activity of the major event that has affected the Aden Ridge for the last few decades. Together with available bathymetric and gravimetric data, these results will help to constrain the structure of the transitional zone of the Aden Ridge.

Kinematics of rift propagation throughout the Tadjoura-Ghoubbet connection zone, western Gulf of Aden, Republic of Djibouti.

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Session: AMR

The Tadjoura rift forms the westernmost edge of the westerly-propagating Sheba ridge, between Arabia and Somalia, as it enters into the Afar depression. From structural and remote sensing datasets, the Tadjoura rift is interpreted as an asymmetrical south-facing half-graben, about 40 km-wide, dominated by a large boundary fault zone to the north. It is partially filled up by the 1-3 Ma-old Gulf Basalts which onlapped the older Somali Basalts along its shallower southern flexural margin. The major and trace element analysis of young onshore lavas allows us to distinguish and map four distinct basaltic types. These results, together with radiometric age data, lead us to propose a revised volcano-stratigraphic sketch of the two exposed Tadjoura rift margins, and to discriminate and date several distinct fault networks of this oblique rift. Morphological and statistical analyses of onshore extensional fault populations show marked changes in structural styles along-strike, in a direction parallel to the rift axis. These major fault disturbances are assigned to the arrest of axial fault tip propagation against pre-existing discontinuities in the NS-oriented Arta transverse zone. As the sinistral jump of rifting into the Asal-Ghoubbet rift segment results from structural inheritance, our model contrasts with the en échelon or transform mechanism of propagation that prevailed along the entire length of the Gulf of Aden extensional system.

Seismicity and the Tendaho Dam Safety

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Session: HAZ

The construction of the Tendaho Dam, which is located in the lower Awash River basin, commenced in 2005. Major construction works were completed in 2009, when the dam started to fill. The project targeted developing 60,000 ha of plantation that provides sugarcane for a large-scale factory which is currently being setup with a capacity of 500,000 tons of sugar per annum. Fortuitously, the dam site lies within the area of seismic monitoring of the Afar rifting crisis, and we are able to evaluate seismicity prior to, during, and after dam filling. The time variations in seismicity shed light on potential hazards associated with the construction of the Tendaho Dam. The reservoir loads a tectonically and geothermally active region of Afar, and the dam walls are pinned in hydrothermally altered volcanic strata. Vigorous hot springs and geyser systems occur within a few kms of the dam, on both the heavily faulted Tendaho escarpment, and along the sedimented floor of the Afar depression. Thus, changes in groundwater circulation caused by the dam loading, as well as the local change in stress caused by the weight of the water could result in fractures and eventual failure of the dam. Seismicity data shows a jump in earthquake rates immediately after partial reservoir impoundment in 2009 along with a swarm of activity close to the dam body. The short time interval between dam filling and increased seismicity indicates that the bedrock to the dam is weak and fractured. Focal mechanisms show strike-slip motion with some dip-slip components distinctive among disparities in a varying stress field. The hazards proposed here are only initial insights into understanding the complexity of the Tendaho region, and how the dam fits into this active tectonic framework. Current studies are trying to anticipate and recognize problems before they become an immediate national issue. Future monitoring and analysis could avoid or reduce risk, keeping the Tendaho Dam out of the dam collapse statistics and functioning as the health and life provider it was intended to be. More detailed correlations between water level fluctuations and seismicity await access to dam volume measurements. Whether the observed seismicity in 2009 is because of water mass loading or not, the site is not only close to a triple junction but also located at the axis of the incipient plate boundary between Africa and Arabia. The Peak Ground Acceleration (PGA) for the site used during construction is 0.35g for rock site which is still valid as the reinforced/concrete structures are still intact. However, following the 2010 abnormally heavy rainy season and fast filling of the reservoir to about 400 meters level, leakage of water occurred through the left abutment and at the interface with the dam body that resulted in saturation of the downstream slope of the dam on the left side. Temporary measures, particularly grouting, were taken to curb the problem which showed improvement but they are not a lasting solution which demands all the concerned to be on alert at least until the plantation pays back the invested capital.

Magma evolution during the course of extension along a segment of the West Afar margin (Ethiopia)

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Session: RCM

The main objective of this work is to determine the evolution of magma though the course of rifting in one of the best preserved and clearly defined segment of the southern Red Sea margin. Felsic and basic rocks from marginal grabens (i.e. the western margin of the southern Red Sea system) ranging in age from pre-rift ~ 30 Ma, through syn-rift (onset of rifting) ~ 21 Ma, break-up and thinning between 6 and 3.5-3 Ma to magmatic segmentation ~ 0 Ma were analysed for chemical (major and trace elements) and isotopic (Sr, Nd and Pb) determinations. Preliminary results show that the pre-rift flood basalts, syn-rift lavas (21 Ma) and magmatic segment basaltic fields such as the Dabbahu-Manda Hararo magmatic segment exhibit more or less similar chemical and isotopic signatures. On the other hand, neighbouring other syn-rift lavas from shield volcanoes, stratoid series, Main Ethiopian Rift, Erta'Ale and Manda Inakir active segments which outcrop outside this individual margin segment have isotopic signatures, which are different from the pre-rift lavas and show more or less intense mixing with a lead radiogenic mantle source. Such spatial variations in the isotopic signatures from a segment to another, and the very homogeneous signature of the Dabahu-Manda Harao segment from Oligocene pre-rift CFBs to present day active magmatic segment suggest long-lasting melting of discrete portions of mantle over the plume head (plume material +/- lithosphere). Moreover, the existence of identical and specific mantle source from the pre-rift to the incipient spreading magmatic segments in one of the major segment of the southern Red Sea margin in Afar demonstrate that segmentation of the margins are inherited from the very early stages of continental break-up.

Monitoring volcanic activity in Afar using geostationary satellites

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Session: AMR

There have been numerous volcanic eruptions in the Afar-Red Sea region since the onset of the Manda Hararo rifting event in 2005, including effusive basaltic fissures, lava lake overflows and ash rich plumes. Many of these eruptions have occurred in remote areas where eyewitness reports and direct measurements are scarce, so we are reliant on regional seismic networks, InSAR and satellite images to reconstruct events.

Here we present an overview of the past 5 years of volcanism in the region as observed by the multispectral SEVIRI instrument aboard the geostationary Meteosat weather satellites. Geostationary instruments have the advantage of high acquisition rates and constant view geometry making successive observations directly comparable. We attempt to account for the radiant output of the eruptions in terms of simple models of lava emplacement and cooling, and relate events to broader patterns of tectonic and magmatic activity in the region.

Extension by faulting, stretching and magma intrusion in Ethiopia

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Session: AMR

The 2001-2004 EAGLE experiment showed that high seismic velocity, dense, mafic crustal intrusions exist beneath many zones of Quaternary magmatism in the Main Ethiopian rift, and that crustal thinning is minimal. From these observations, a consensus quickly emerged that extension now occurs not by ductile stretching and brittle faulting but by magma intrusion. Striking InSAR images and accompanying seismic data from the 2005 Afar diking episode provided further compelling evidence in support of the magma assisted rifting hypothesis. More difficult to constrain, however, is the extent to which melt intrusion is responsible for extension in the deeper portions of the plate. To this end, seismic anisotropy is a powerful analysis tool. The speeds of horizontally propagating Love (SH) and Rayleigh (SV) waves vary in similar fashions with azimuth for lattice preferred orientation (LPO) and oriented melt pocket (OMP)-type anisotropy, but their relative change is distinctive for each mechanism. This diagnostic is exploited by studying the propagation of surface waves from a suite of azimuths across the MER. Three mechanisms for anisotropy act beneath the MER: periodic thin layering of seismically fast and slow material in the uppermost ~10 km, OMP between ~20–75 km depth, and olivine LPO in the upper mantle beneath. The results are explained best by a model in which low aspect ratio melt inclusions (dykes and veins) are being intruded into an extending plate during late-stage breakup, with little requirement for plate stretching. Evidence from further north in Afar, however, where crustal thickness decreases abruptly into the Danakil Depression, is not so easily explained by the magma assisted rifting hypothesis. Subsidence of the newly forming margin towards and below sea level, and eruption of voluminous basalt flows, is likely the result of late-stage thinning of the heavily intruded, weakened plate just before the onset of seafloor spreading. Faulting, stretching and magma intrusion are thus each important, but at different times during breakup.

Landscape evolution of the Rwenzori Mts and adjacent Albertine Rift, from low-temperature thermochronology

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Session: CLI

In East Africa, the feedback between tectonic uplift, erosional denudation and associated possible climate changes is being studied by a multidisciplinary research group, 'RiftLink'.

The Rwenzori Mts, located SW of Lake Albert, form a striking feature within the Albertine Rift of the East African Rift System. They are built up by a dissected Precambrian metamorphic basement block that has been uplifted to heights of more than 5 km.

Samples taken along and across the Albertine Rift, cover the area around the Rwenzori Mts and the mountain range itself. From thermochronological analysis (AFT, AHe & ZHe) and subsequent thermal modelling a protracted cooling history since Paleozoic times can be revealed.

From cooling ages and derived cooling histories different blocks can be distinguished along the Rwenzori Mts. In the central part a northern and a southern block are separated by a proposed NW-SE trending fault; with the northern block showing much younger apatite fission-track ages (AFT: ~130 ±8 Ma) than the southern block (AFT: from 284.4 ±12.3 Ma to 319.8 ±33.3 Ma). Cooling ages in both blocks do not vary significantly with elevation, despite differences in relief of more than 3 km. Thermal modelling reflects protracted cooling histories, with individual t-T paths demonstrating that the Rwenzori Mts were not exhumed homogeneously as one block. They show decoupled blocks that were relocated separately along distinct fault planes, with the blocks revealing different rates of exhumation during Paleozoic and Mesozoic times.

Since Miocene differentiated erosion and rock uplift movements affected almost the entire Rwenzori Mts, with more pronounced surface uplift along the western flank. AHe cooling ages of ~25 (±0.5) Ma, obtained from this area point to a near surface position of these rocks since Miocene/Oligocene times and very recent (Plio-/Pleistocene) final surface uplift, where erosion could not compensate for.

Thermokinematic modelling, applied to samples from different parts of the working area allow to better constrain the cooling history and landscape evolution of the Rwenzori Mts as well as surrounding Albertine Rift which will be discussed in the frame of this presentation.

Timing and dynamics of dike intrusions in an incipient seafloor-spreading segment in Afar, Ethiopia: seismicity patterns and source mechanisms

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Session: AMR

Oceanic crust is accreted through the emplacement of dikes at spreading ridges, but the role of dike intrusion in plate boundary deformation during continental rupture remains poorly understood. Between 2005 and 2010 the ~70 km-long Dabbahu-Manda Hararo rift segment in Afar, Ethiopia has experienced 14 large volume dike intrusions, 9 of which were recorded on temporary seismic arrays. A comparison of the seismicity characteristics of 7 of the dikes is presented with implications for dike intrusion processes and rift zone magmatic plumbing systems. All of the migrating swarms of earthquakes started from a <5 km-radius zone at the middle of the Dabbahu-Manda Hararo segment, and traveled northward and southward along the rift axis. Small magnitude earthquakes associated with the margins of the propagating dike tips are followed by the largest magnitude, primarily low-frequency earthquakes with peak frequencies ≤2 Hz. The seismic moment distributions show >80% of the energy is released during the propagation phase, with minimal seismic energy release after the dike propagation ceases. Northward propagating dikes had faster average velocities than those that propagated southward, suggesting preconditioning by the 2005 mega-dike, or ongoing heating from a sub-crustal magma source north of the mid-segment. Given the possibility of complex source mechanisms, we also solved for five different source models for the largest earthquakes (ML >3.5) generated during the intrusion of two of the large volume dikes. Comparison of the fits to the waveforms for the different models shows that the earthquakes have significant non-double couple components. The best double-couple mechanisms, which are mainly normal faulting with small strike-slip components, have slip planes nearly perpendicular to the geodetically determined plate opening direction. Most of these earthquakes are low-frequency earthquakes, and they occurred during the propagation phase of the dikes. The space-time distribution of the source mechanisms with respect to the migrating patterns of seismicity during dike emplacement, the shallow source depths estimated, and the non-double couple nature of the mechanisms suggest these earthquakes are generated mainly by normal faulting above the dikes with some component of tensile opening under the influence of dike related fluids. Total slips of 0.8 m and 1.3 m are estimated using the source parameters for the November 2007 and October 2008

dikes, respectively. These values are comparable to geodetic total slip estimates. Similarity of the slip estimates from seismic and geodetic data, and the larger cumulative seismic versus geodetic moment deficits indicates that most of the plate opening by dike intrusion is accommodated aseismically. Additional insights from comparison of seismicity rate changes and Coulomb stress changes, and crustal tomography studies in progress will also be presented. The results so far show during dike intrusions surface faulting above dikes and graben formation are the main processes that control the development of rift zone geomorphology and topography. Our results help understand the creation and maintenance of rift valley topography.

Pulses of deformation reveal frequently recurring shallow magmatic activity beneath the Main Ethiopian Rift

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Session: HAZ

The Main Ethiopian Rift (MER) has experienced significant volcanism, and the mantle beneath is characterized by high temperatures and partial melt. Despite its magma-rich geological record, only one eruption has been historically recorded, and no dedicated monitoring networks exist. Consequently, the present-day shallow magmatic processes in the region remain poorly documented, and the associated hazards may be underestimated. We use satellite-based interferometric synthetic aperture radar observations to demonstrate that significant deformation has occurred at four volcanic edifices in the MER (Alutu, Corbetti, Bora, and Haledebi) from 1993 to 2010. This raises the number of volcanoes known to be deforming in East Africa beyond 12, comparable to many subduction arcs despite the smaller number of recorded eruptions. The largest displacements are at Alutu volcano, the site of a geothermal plant, which showed two pulses of rapid inflation (10–15 cm) in 2004 and 2008 separated by gradual subsidence. Our observations indicate a shallow (<10 km), frequently replenished zone of magma storage associated with volcanic edifices and add to the growing body of observations that indicate shallow magmatic processes operating on a decadal timescale are ubiquitous throughout the East African Rift. In the absence of detailed historical records of volcanic activity, satellite-based observations of monitoring parameters, such as deformation, could play an important role in assessing volcanic hazard.

Initiation of dike intrusion episodes on spreading centers; Krafla (Iceland), Dabahu (Afar, Ethiopia) and 9°N on the East Pacific Rise

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Session: MOR

Geologic, seismic and geodetic constraints on dike intrusions and volcanic eruptions on spreading centers come from two well studied magmatic episodes: the sequence of 20 events that occurred from 1975-1984 on the Krafla segment in Iceland and the 14 events that began in 2005 and may be ongoing on the Dabbahu segment of the Southern Red Sea in the Afar of Ethiopia. Measurements along the fast-spreading 9°N segment of the EPR indicate major differences in the recurrence time and spatial extent of magmatic events compared to these slow-spreading, subareal segments. These observations bear on several important questions about magmatic processes on spreading centers, including: (1) What controls the time interval between dike intrusion episodes and between dike events? (2) How does the depth and size of a magma chamber affect magma intrusion and extrusion? (3) What controls the distance of dike propagation? (4) What controls the number of intrusive and extrusive events in an episode? After discussing several of these questions I will focus on a conceptual model relating to the first of them.

Unlike volcanoes with shallow magma chamber that sit atop thick lithosphere the magma sills at the EPR overlie hot, partially molten crust. Thus, it is unlikely that such magma chambers could be overpressures enough to force dike formation. If magma chambers at slower-spreading ridges also overlie hot, weak crust then this suggests a way to estimate the time between dike intrusion events. To initiate a dike at a plate-spreading center, fault activity may be needed to break through the ductile "buffer zone" above the magma chamber, bringing magma in contact with stressed brittle rock. An episode of one or more dikes would relieve extensional stresses near the spreading axis. In that case the repeat time for dike episodes equals the time to re-stress the axial lithosphere to the point of fault failure. Then the time to re-stress axial lithosphere and trigger new dikes depends linearly on the depth to the axial magma chamber and inversely on the spreading rate. For reasonable elastic and fault failure parameters the model is consistent with observed time intervals (assuming that the region of axial lithospheric stress relief during a dike episode is a about ten kilometers wide). Observations of increased earthquake activity above axial magma chambers for years before a dike intrusion episode are consistent with this mechanism of dike initiation.

Magmatic processes at Mid-Ocean Ridges: insights from a recently erupting segment of the East Pacific Rise

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Session: MOR

Magmatic processes of crustal formation at Mid-Ocean Ridges (MOR) begin at depth with mantle upwelling and pressure-release melting in response to plate separation above. Mantle melts rise to the surface and freeze through a variety of processes to form a basaltic crust that is internally stratified (to varying degrees) of extrusive basalts, sheeted dikes, and layered and massive gabbroic rocks. At fast and intermediate spreading ridges and along magma-rich portions of the slow ridges, magma reservoirs have been detected within the crust. These reservoirs are the source bodies for the dike and lava sections and contribute, at least in part, to the formation of the underlying intrusive section. This presentation will provide an overview on magmatic processes at MOR with a particular focus on a recently erupting segment of the fast spreading East Pacific Rise 9°50'N, where 2 volcanic eruptions have occurred over a 13 year time period. Recent 3D multi-channel seismic imaging reveals the detailed structure of the crustal magma body that lies 1.6 km beneath this erupting region. The axial magma body is segmented on a fine scale with complex regions of overlap and offset melt zones. Lens segments coincide with compositionally uniform lavas on the seafloor above, indicating they are chemically isolated and that magma delivery to the seafloor is primarily via vertical intrusion. The magma lens undulates in depth on a fine scale and this topography may play an important role in the focusing of historic dike intrusion events in the same location along the ridge axis. These and other implications for magmatic processes at mid-ocean ridge volcanic systems will be discussed.

Remote detection and monitoring of volcanic eruptions in the East African Rift

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Session: HAZ

During the ongoing Afar rifting episode that began in 2005, satellite observations of sulfur dioxide (SO_2) emissions have played a key role in eruption detection and monitoring. Detection of SO_2 emissions by the Ozone Monitoring Instrument (OMI) on NASA's Aura satellite has often been the first indication of an eruptive event, typically followed by thermal infrared (IR) manifestations of active lava effusion. Since 2005, SO_2 emissions associated with eruptions in Afar have ranged from low or undetectable (e.g., Dabbahu and Manda Hararo) to among the largest volcanic SO_2 emissions measured since the 1990s (2011 Nabro eruption), reflecting the variability in eruption style and magnitude. The 2011 Nabro eruption, its first in recorded history, released an estimated ~2 Tg or more of SO_2 and resulted in aviation impacts and a significant stratospheric aerosol perturbation that has been detected worldwide by ground-based lidar instruments. Here we summarize the OMI SO_2 measurements for recent eruptions in Afar, in conjunction with high temporal resolution SO_2 data from the Spinning Enhanced Visible and IR Imager (SEVIRI) on the geostationary Meteosat Second Generation (MSG) satellite, which provide constraints on eruption plume dynamics. In addition, we also present comparisons between SO_2 measurements and volcanogenic infrasound recorded by arrays in Djibouti and Kenya. Infrasound data records can provide the most detailed eruption chronologies available for remote eruptions, including eruption onsets, durations, and fluctuations in intensity. We focus in particular on the 2011 Nabro eruption, which produced near continuous SO_2 emissions and infrasound until mid-July. As seen in numerous other studies, sustained low frequency infrasound from Nabro was coincident with high-altitude emissions. However, the eruption also produced hundreds of enigmatic short-duration, impulsive explosion signals, in addition to the sustained infrasonic jetting signals more typical of subplinian-plinian eruptions. Analysis of this rich infrasound record, and comparisons between relative infrasound energy and SO_2 emissions to investigate the relationship between degassing and infrasound, should provide new insight into possible eruption source mechanisms. At the time of writing, the November 2011 effusive eruption of Nyamulagira (DR Congo) is also producing detectable infrasound coincident with high SO_2 emissions, and will serve as another case study. These examples demonstrate the utility of using regional infrasound arrays to characterize volcanic eruptions in

remote and poorly monitored regions such as the East African Rift. Our ultimate goal is to develop an autonomous eruption detection and monitoring system for East Africa based on infrasound detection of volcanic emissions, near real-time satellite retrievals of SO_2 and ash and trajectory modelling.

Volcanic hazards of rift environments

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Session: HAZ

Subaerial rifting environments are rare but all have frequent volcanic activity. The process of rifting generates basaltic magma, which means that most of the associated volcanism is basaltic, and primarily effusive. Basaltic eruptions typically produce small cinder cones at vent regions and extensive lava flow fields. Although lava flows rarely cause fatalities, they can cause extensive loss of property, particularly when they emerge from long fissure vents, and protracted eruptions can cause problems because of acid gas emissions. From a hazards perspective, however, the larger concern is the potential for phreatomagmatic activity when ascending magma encounters either groundwater or surface water (lakes or the ocean). For example, evidence for phreatomagmatic activity can be seen in the tuff cones of the Ardoukoba Rift in Djibouti and neighboring regions of the Red Sea, Arabia, East Africa; phreatomagmatism is also a common component of volcanism in other regions of active rifting, such as Iceland and Baja California. Interaction between magma and water can generate highly explosive eruptions and abundant fine-grained material that form widespread ash deposits. Importantly, this means that most of the available magma is erupted explosively rather than effusively. Effusive eruptions may also transition to explosive activity when lava flows enter standing water or when the rifts feeding lava flows propagate into subaqueous environments. Rift environments are also locations of bimodal volcanic activity, that is, associated basaltic and silicic volcanism. Silicic magma forms when mafic magma stalls in the shallow crust, and erupts either explosively, to generate ash falls and flows, or effusively, to produce lava flows and domes. For example, a silicic explosive eruption from Dubbi volcano in 1861 deposited ash more than 300 km from the volcano, destroyed two villages and caused more than 100 fatalities. Similarly, a 2005 silicic eruption of Dubbahu volcano produced ash and a small pumice cone, and forced the evacuation of >6000 people from nearby villages. Perhaps the most notorious recent silicic eruption from a rifting environment is that of Eyjafjallajokull, Iceland, in 2010. Although exacerbated by phreatomagmatic interactions with glacial water, the silicic composition of the Eyjafjallajokull magma clearly enhanced the disruption caused by this eruption. In fact, bimodal volcanic activity is common in Iceland, as evidenced by historic silicic and mafic eruptions from volcanoes such as Katla and Hekla. The potential for bimodal volcanism poses particular challenges for volcano monitoring and prediction, because the nature of eruptive activity is so dependent on magma composition (which can be difficult to ascertain prior to an eruptive event). Also challenging is evaluating the potential for eruptions both along newly formed rifts (rather than known stratovolcanoes) and through surface water (particularly in surface depressions and coastal regions).

Dallol Volcano and Danakil Depression, Ethiopia

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Session: AMR

Dallol volcano is located in Danakil Depression in the northern part of the Afar triangle on the NNW trending active Erta Ale axial segment which hosts a number of active volcanoes including the perennial lava lake of Erta Ale. The salt crusted depression which lies below sea-level (ca. -120 m a.s.l.) was linked to the Gulf of Zula on the Red Sea by the narrow extensional Alid graben to the north which is floored by fissural basalts and the active Alid and Jallua rhyolitic volcanoes. An evaporite succession over 1000m thick deposited between 200 and 25 Ka attests to a number of marine ingressions into the depression and has left behind a number of brine lakes (Barberi et al., 1972). The elliptical Dallol volcano which rises gently to sixty meters from the salt plain (-48m a.s.l.) has a longer diameter of 5km and a summit crater (ca. 100m diameter) which was a site of a phreatic eruption in 1929 (GVN, 2008). Artisanal rock salt mining, seasonal ecotourism and the sub-surface resources of potassium salts are currently driving economic activities in the area and have resulted in a permanent settlement at Ahmedela town near Dallol. Geothermal reservoirs which reside below the evaporite succession and evidently get recharge from precipitation on the northwestern plateau hold promise to a renewable energy supply in the area (Varet 2010).

The vicinity of Dallol volcano is characterized by frequent earth quakes of magnitude 4.5-5.5 Richter scale obvious from cracks healed with later salt deposits and a number of phreatic eruptions. Dallol crater has a number of active and fossil hot-springs, geysers and fumaroles which have formed a colourful mosaic of salt deposition and acid pools inside the crater. Eruptions caused by subsurface boiling of thermal brine (~300g/kg solute) without thermal input from a volcanic system is questionable due to collegative properties of solutes. Thus Dallol is an ideal site to study the complex interactions between volcano-tectonic and hydro-geochemical phenomena. XRD analyses of samples from hydrothermal deposits from within the crater show that most samples have major constituents of halite, sulfur, calcite, sodalite and hematite with minor silica. Impurities of metallic oxides and replacement in the NaCl structure by elements such as potassium or florine has given halite a brown, yellow or bluish color at many sites. Residents of Ahmdela town observed unusual dark colored smoke from Dallol crater in the first week of January, 2011 an event that was not strong enough to be recorded by global volcano monitoring satellites. Observations on remnant dark-grey ash and sulfur deposits at the sites suggest a degassing of a near surface volcanic vent. Previous phreatic eruptions at Dallol and the surrounding salt plain that have left behind bubbling acid brine pools are best explained by a number of active maar craters obscured by thick evaporite succession and frequent marine invasions of the salt plain during the Holocene. The geodynamic setting of Dallol volcano suggests that besides earthquakes phreatic and probably phreato-magmatic eruptions are the prevailing geo-hazards.

Climatic and tectonic interactions in the East African rift system: The view from the Lake Malawi basin

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Session: CLI

Climate and tectonic processes are commonly assumed to interact in shaping landscapes, lakescapes, and the sedimentary records of basins. However, there is surprisingly little hard data on how that interaction actually occurs in continental rifts, and especially in how feedbacks may occur between the two types of process. At the largest scales, modeling experiments suggest that the long term aridification of East Africa during the late Neogene may have been at least in part driven by the effects of orography (uplift and major volcanic edifices) on moisture balance within the region. However, at the scale of individual rift segments, climate-tectonics feedbacks are poorly understood. Lake Malawi, in the western branch of the African rift, provides a useful testbed for examining these potential effects. Climate, and vegetation, within the Malawi rift is strongly controlled by the effects of the seasonal migration of the Intertropical Convergence Zone, which (at least recently) reaches its southern edge just south of the basin and determines the seasonal polarity of winds. Satellite-based observations of vegetative greenness and moisture suggest that south facing topographic highs along the rift axis, associated with half-graben escarpments and the Rungwe volcanic pile at the north end of the basin, intercept moisture carried by southeasterly winds during the lake's dry season, creating anomalous precipitation highs and dense tropical forests in these areas. Striking precipitation variability along individual half-graben rift segments may also lead to differences in erosion rates, thereby creating a potential feedback loop to local tectonism. Drill cores from the Lake Malawi Drilling Project, extending back over 1.2Ma, provide a means of exploring these interconnections in time, especially when coupled with a better understanding of the basin's geomorphology. They demonstrate extreme fluctuations in precipitation, lake level and vegetation, which profoundly affected incision and sedimentation rates on the rift floor. Given our knowledge of the African climate system, a model of rift basin/orography/microclimate/sedimentation feedbacks can be generalized to other portions of the EARS lying in different climate settings and for different time periods.

Multiple Dyke Injection Events in Afar: Numerical Modelling of the Heat Flow Equation.

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Session: AMR

The mechanism of magma transport through cold lithosphere and crust, and the distance over which magma travels, controls the presence and type of resultant surface volcanism as well as the rate of crustal extension and spreading. As a result, in the Afar province in the north east of Ethiopia, the East African rift is slowly parting via the process of dyke injection and normal faulting to form a new ocean. The region is an ideal setting to study the processes of multiple dyke injection, and how these can lead to the splitting of the crust.

In this study, numerical modelling through the finite difference method has been applied to the geological setting of an actively spreading rift, with solutions for the one- and two-dimensional heat flow equations computed according to the explicit method. The initial temperature profile is set up by the crustal geotherm and a symmetry condition implemented at the centre of the intrusion in order to effectively double the computational domain. A constant temperature boundary condition for the other edges of the domain is assumed. It is also assumed that the physical and chemical properties of the crust can be simplified to be homogeneous over the intruded depth, so that the thermal diffusivity of the crust can be treated as being independent of depth and temperature. Dykes of a basaltic composition are intruded sequentially at a constant rate. Each one is instantaneously intruded into the crust at a constant temperature, and the model computes how heat is dissipated over time throughout the crust. The resultant temperature profile is used to calculate a profile of melt fraction and from this the distribution and quantities of melt within the crust are predicted.

The model is used to investigate how the size and frequency of dyke intrusions affect two important geophysical observables within the East African rift system: the distribution of melt and the presence of aseismic zones. Changes in the initial conditions such as altered geothermal gradient or intrusion frequency and therefore the spreading rate of the crust, can also affect the development of the temperature distributions and the resultant melt fractions. The results can be compared with previous geophysical studies conducted in the region to provide constraints on the amount of melt present in the crust and to determine whether the crust is experiencing brittle extension or ductile spreading. This thermal modelling of the crust beneath Afar develops our understanding of the nature and frequency of magma intrusions in the East African rift system, and the conditions for the creation and evolution of the magmas that are seen at the surface.

Research on the Tectonic and Magmatic Development of the Ethiopian Rift System and its Contributions to Geothermal Resources Exploration and Development

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Sustained, systematic geologic work started in Ethiopia only in 1968 with the establishment of the Geological Survey. The earliest several years were taken up by that institution climbing a steep learning curve. As was the case with the rest of the country, the pre-existing knowledge on the geologic development and resources of the Ethiopian Rift System (ERS) was both scanty and of poor quality. The earliest geothermal resource exploration effort involved only the inventory and characterization of the hydrothermal features which were the obvious expressions of the subsurface resources. However during the late 1960s and early 1970s, access into most parts of the ERS was poor, geologic information was lacking, even topographic maps of any scale did not exit. Thus the it was deduced from hydrothermal fluid water chemistry that geothermal resources existed in the subsurface in certain definite areas but they were never explained in terms of the tectonic controls which gave rise to them and determined their characteristics. This changed with the initiation of international research interest and the explanation of the ERS in terms of Plate Tectonics theory and crust mantle interactions. This has contributed to the reliable prediction of the distribution of the most prospective high enthalpy geothermal prospect areas, some of them blind geothermal systems with little or no surface expression, and the conceptual evaluation of their gross prospectivities. The detailed surface exploration of a number of areas and the drilling exploration of two geothermal systems have provided reliable models which can be applied to grossly apply to other less explored prospect areas based on analogies in tectonic setting, magmatic character and hydrologic setting which are largely learned from research output. The ERS has of the order of 50 geothermal prospect areas which are capable of being exploited using conventional and newly emerging technologies.

Mantle magma chamber imaged magnetotellurically beneath an active magmatic segment in Afar, Ethiopia

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Session: AMR

Though the existence of shallow magma chambers below volcanoes and mid-ocean ridges is well established, there have been no reports of extensive magma reservoirs within the mantle. Indeed the buoyancy of magma relative to the mantle is considered to forbid the presence of magma bodies there. However, a magnetotelluric (MT) survey along a 50 km transect across the Dabbahu magmatic spreading segment in Afar demonstrates the presence of a large magma body well within the mantle. The MT survey reveals the existence of a region of very high electrical conductivity that extends for 30 km across the strike of the segment, and reaches down to about 40 km depth, 20 km into the mantle, for which the only plausible interpretation is a substantial magma chamber. Interpretation integrates information from other techniques that have been employed alongside MT, including seismology, GPS, LiDAR, InSAR, structural mapping, and petrology. The conductivity structure suggests melt fractions within the mantle of up to 20%, and a magma volume of at least 3000 km^3, enough to supply dykes at the current rate of activity for 5000 years, or to build the full thickness of the crust at the current far-field spreading rate for 150000 years. The conductivity structure will be compared with that from a profile across a currently inactive segment, and from sites close to the Dabbahu volcano. Our data provide indications of a very substantial magma chamber beneath the Dabbahu volcano.

Two Decades of InSAR Observations in the Kivu Basin, Western Branch of East African Rift

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Session: AMR

The Kivu Basin is a ~100 km long segment of the Western Branch of East African Rift, bordered respectively to the North and the South by the Virunga Volcanic Province (VVP) and the South Kivu Volcanic Province (SKVP).

Volcanism in the SKVP is considered as extinct but seismicity remains an important threat to the population as cruelly reminded by the 2008 earthquakes sequence that killed about 40 people in the Bukavu and Cyangugu region.

In contrast, the VVP experience low seismicity but hosts two of the most active volcanoes of Africa: Nyamulagira and Nyiragongo. The first erupted about 30 times over the last century while the second hosts in its crater what is currently the largest (semi-) permanent lava lake on Earth (~200 m wide). In January 2002, such as previously in 1977, the Nyiragongo lava lake was drained through a network of fractures that opened from the volcano up to the nearby city of Goma located 15 km to the South. Fast lava flows destroyed 10 % of the city, killed nearly 150 persons, made 100.000 people homeless and created a humanitarian crisis whose socio-economic impact is still visible today.

However, due to the complex local situation affecting the eastern Democratic Republic of Congo, remote sensing remains nowadays the most sustainable tool to monitor and study that segment of the East African Rift. Here we make use of the hundreds of SAR images acquired over the Kivu Basin since the early 90s by European, Japanese, German and Canadian satellites.

Conventional InSAR processing allowed studying various eruptions and earthquakes. Assessing source characteristics and mechanisms by inverting the observed deformations provided fundamental data to draw hypothesis about the tectonic context and the rift opening modes. The estimated dikes overpressure associated to the last Nyiragongo eruption suggests that the rift opening in the Virunga Volcanic Province is now driven by magma.

In the younger -though extinct- South Kivu Volcanic Province, the agreement between the geodetic and seismic moment estimated for the Bukavu-Cyangugu earthquake favours a mode of rift opening in which crustal extension is accommodated seismically.

The abundance of data allowed also creating time series of EW and vertical ground deformation using a novel technique that integrates multiple InSAR data sets acquired by various sensors, with different and varying acquisition parameters, temporal and spatial sampling and resolution and polarization. These times series suggest the first identification of pre-eruptive deformation in the Virunga.

Finally, the archives -and the still on-going systematic acquisition of SAR images- allow reconstructing the history of the Nyiragongo active lava lake level rise.

More detailed information about the results presented here will be available in accompanying posters by co-authors.

Seismic and geodetic evaluation of earthquake and volcanic hazards in East Africa

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Session: HAZ

The rift valleys of eastern and central Africa exhibit profound along-strike differences in the volume and composition of magmatic products, the timing of rift initiation, the pre-rift plate structure, and rift morphology. Rift sectors in the Eastern rift (Tanzania-Ethiopia), southern Red Sea, Gulf of Aden, and parts of the Western rift are marked by active volcanoes and fissures, and volcanoes show elongation parallel to plate opening direction. Likewise, the rock record demonstrates the increasing significance of explosive volcanic eruptions. The growing evidence of frequent and sometimes volumetrically large magma intrusions, combined with the historic-Recent record of damaging earthquakes, motivates our systematic comparison of seismic and geodetic moment release along the length of the southernmost Red Sea and East African rift systems. The spatial pattern of moment release shows that significant deformation occurs outside the fault-bounded rift valleys and across the uplifted plateaus, extending from South Sudan through Botswana, and across the largely unfaulted but uplifted Tanzania craton. Since 1979, at least twenty-two dike intrusions with or without fissural eruptions in East Africa have been detected, attesting to the importance of magma intrusion in plate boundary deformation. Although several studies have concluded that magma intrusion inhibits the buildup of large elastic strains, leading to frequent, low-magnitude earthquakes, no systematic comparison of magmatic and amagmatic sectors has yet been undertaken. Comparison of seismic moment release and effective elastic thickness shows that seismic moment release is greatest where the rift transects strong cratonic lithosphere lacking surface volcanism, as in the Western and Southwestern rift arms. The relatively high strength of cratonic lithosphere promotes transmission of seismic energy, and ground shaking from regional and teleseismic earthquakes poses a strong hazard throughout the stable interiors of Africa. Seismic moment release is comparatively low in rift sectors with volcanoes located within the central rift valley, suggesting that magma intrusion accommodates an increasingly larger role of plate boundary deformation as rifting progresses to rupture. A case study area is the Afar depression, including the Tendaho damsite where seismicity was rapidly induced by water loading. The broadly distributed deformation zone may indicate metasomatic modification and bottom-up weakening of thick, cold cratonic lithosphere above the African superplume. Our results motivate a re-evaluation of seismic and volcanic hazards throughout eastern and southeastern Africa, and highlight the need for widely distributed GPS networks.

Magma Plumbing during the Krafla Rifting Episode of 1974-1989

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Session: AMR

The Krafla rifting episode was a sequence of magmatic and tectonic events along the North America – Eurasia plate boundary in N-Iceland, beginning in 1974 with increased seismicity within the Krafla caldera and lasting until 1989 when inflation of the caldera stopped. The activity was confined to the Krafla volcanic system and adjacent transform zone. The volcanic system consists of a central volcano with associated rift zones that extend for about 100 km along the plate boundary, perpendicular to the plate separation vector. A localized crustal magma chamber has been identified at about 3 km depth within the caldera, both by seismic methods and geodetic location of an inflation-deflation source. The chamber sits on top of a 30 km wide intrusive dome extending from the base of the crust at 19 km depth. Magma ascended from depth and accumulated in the magma chamber during most of the episode. The inflation periods were punctuated by sudden deflation events lasting from several hours to 3 months. The walls of the chamber were then breeched and magma was injected into the adjacent rift zones leading to rifting there. A total of about 20 discrete rifting events were identified, each one affecting only a portion of the plate boundary. The course of events was similar in all events, beginning with subsidence and spasmodic tremor in the caldera, followed by earthquakes that migrated away from the caldera into the rift zone. Subsidence within the Krafla caldera was concurrent with rifting. Large-scale extension with surface faulting correlated with regions of intensive seismicity. The rift zone earthquakes stopped at the same time as the deflation of the caldera. Re-inflation of the caldera began immediately following each deflation and rifting event. The rate of re-inflation was highest in the beginning, but gradually diminished with time. This indicates that the pressure difference driving the magma flow to the inflating magma chamber from the reservoir feeding it is highest in the beginning, then diminishes as the counter-pressure increased. The sequence of rifting events can be subdivided into 5 sub-sequences where each event propagated a shorter distance from the caldera than the previous event in the sub-sequence. Sub-sequences 1 and 3 consisted of events within the northern rift zone, whereas sub-sequences 2 and 4 occurred in the southern rift zone. The last sub-sequence consisted mostly of fissure eruptions, from the center of the caldera about 10 km into the northern rift zone. A conceptual model to explain these observations assumes that the course of events is driven by the increasing magma pressure in the Krafla magma chamber and its interaction with the tectonic stress field along the divergent plate boundary. Rifting is induced by dikes that are injected into the crust when the chamber pressure exceeds a limit set by the stress field in the surrounding crust. Each new dike increases the compressive stress so this limit gets higher with each event. Our model implies that all dikes during the Krafla episode were fed laterally from the magma chamber.

Age and petrogenesis of young basalt lavas from the Dabbahu-Mando Hararo Rift segment

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Session: AMR

New geochemical and geochronological data from basaltic lavas in the DMH segment provide important constraints on magmatic processes at this transitional rift zone. Ar-Ar ages for lavas from the NE flank of the rift zone constrain the formation of the current axial graben to less than ~30 ka and give a (maximum) time-averaged slip rate for the eastern graben bounding fault of ~1.3 mm yr^{-1}. Ages for lavas across the rift flank of ~30-200 ka show a largely consistent age-versus-distance profile from the rift axis, indicating that a focused axial melt supply has persisted here for least 200 ka, and that during this time the DMH segment has been accommodating essentially all Afro-Arabian extension. Assuming purely magmatic extension, this would imply a rifting phase similar to the 2005-2010 event occurring every 500-700 years. Ages of basalts erupted on the western margin of the rift, at the Badi and Dabbayra volcanoes, range from ~450 – 25 ka and show no clear temporal-spatial pattern, implying a distinct melt supply system, feeding contemporaneous eruptions along this volcanic-tectonic lineation.

Geochemical data for basaltic and silicic lavas show that all samples are isotopically closely similar. However, there are clear differences in both major element trends and trace element concentrations between lavas erupted within the rift, and those erupted off-axis along the Badi-Dabbayra lineation. The major and trace element geochemistry of the basaltic lavas is consistent with melting of fertile mantle with elevated potential temperature at depths near the garnet-spinel transition. Inferred melt fractions from trace element melting models vary from ~4-6%, with rift zone lavas consistently requiring a slightly higher degree of partial melting for lavas erupted at the rift axis. This implies that axial lavas are derived from a longer melting column and suggests that a focused upwelling is present beneath the rift segment.

Major element differentiation trends for basaltic lavas for each location are also distinct. Rift axis lavas can be modelled with a two stage crystallization history, with initial melt storage at ~45 km in the upper mantle which supplied fractionated liquids to a shallow magma chamber ~10 km below the rift axis. In contrast, evolutionary trends from the off-axis magmas imply single-stage fractionation in a storage region near the base of the crust at a depth of ~25 km. These results are broadly consistent with the available geophysical constraints on melt storage.

Magmatic differentiation at Dabbahu Volcano, Afar

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Session: AMR

Dabbahu is a composite volcano at the north end of the active Manda-Hararo segment of the Afar Rift, Ethiopia. Dabbahu has erupted magmas ranging in composition from mildly alkaline basalt through trachyandesite to peralkaline rhyolites (comendites and pantellerites). Effusive eruptions predominate. On the basis of a new geological map, 93 new whole rock major and trace element data, mineral analyses from 65 samples, and 9 new ^{40}Ar / ^{39}Ar dates we show that Dabbahu has been active for a little over 60,000 yrs, but a hiatus occurred between the eruption of comendite (29 ka) and pantellerite (~8 ka) lavas. Continuous variations in whole rock chemistry, mineral compositions, e.g. Fo88-0 olivine, and calculated eruption temperatures support earlier findings (Barberi et al., 1974) that the different magma types are related through protracted (~90%) fractional crystallisation from a basaltic parent. Geochemical modelling indicates recently erupted basalts from the Manda-Hararo axial rift constitute plausible parent compositions. Field evidence indicates that magmas were not erupted in fractionation sequence and some mixing occurred between more and less evolved compositions. The sub-volcanic plumbing system must be configured in such a way that cogenetic magmas of different composition can be stored separately prior to eruption, rather than in a single large sub-volcanic reservoir. We propose that differentiation from basalt to rhyolite occurs in dykes or sills at relatively shallow depths (5-10 km) beneath the volcano, although some prior differentiation of mantle-derived basalts is likely to have occurred at greater depths. Fractionation occurred under relatively reducing conditions (~FMQ) with ~0.4 wt% H2O in the parental basalt. Radiogenic isotope data rule out significant crustal contamination during differentiation.

Barberi, F., Ferrara, R., Santacroce, R., Treuil, M., and Varet, J., 1974, A transitional basalt - pantellerite sequence of fractional crystallisation, the Boina centre, (Afar Rift, Ethiopia): Journal of Petrology, v. 16, p. 22-56.

Origin of Mafic- Peralkaline Silicic Plume Volcanism in the Dabbahu-Manda-Hararo Rift, Afar Depression

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The youngest plume province worldwide occurs at the seismically and volcanically active East African - Red Sea - Gulf of Aden (Afar) triple junction, where one or more upwellings has impinged the thick cratonic lithosphere since ~45 Ma. A spectacular example of magmatism in the Afar depression is seen in the present to < 2 Ma old bimodal fissured mafic and peralkaline silicic eruptions in the ~60 km-long Dabbahu-Manda Hararo (DMH) Rift. In this study we report major, trace elements, and Nd-Sr-Pb isotopes in recent basaltic and silicic rocks originating from the center of the DMH rift segment, exposed along the rift axis and flanks of this segment. The rare earth element (REE) patterns of the silicic rocks and basalts are different in two significant ways: (1) the silicic rocks show a prominent positive Ce-anomaly that is extremely rare in volcanic rocks; and (2) this positive Ce-anomaly is accompanied by a strong negative Eu-anomaly. These anomalies are absent in the basaltic rocks. The positive Ce-anomaly is probably due to interaction in a magma chamber, similar in composition to the basalts, with deep saline aquifer or brines that typically show positive Ce-anomaly. The REE patterns of the two lava groups are interpreted to be due to fractional crystallization primarily of plagioclase with attendant olivine and pyroxene fractionation in a magma chamber similar in REE composition as the basalts that erupted in the DMH segments. We model the REE content and patterns of the silicic rocks primarily due to ~20% fractional crystallization of plagioclase in the DMH basalts. The Nd-Pb isotopic composition of the basalts and rhyolites of the DMH are similar to the Ethiopian plume as defined by the ~30 Ma old Ethiopian flood basalts. Based on their high 3He/4He ratios (R/RA ~30) and Nd-Sr-Pb isotopic data, the source of the Ethiopian plume is generally believed to be in the lower mantle. Therefore, the similarity of the Nd-Pb and Pb-Pb isotopic variations between the Ethiopian plume and the DMH lavas indicates that these lavas were sourced from the lower mantle, and this source zone showed little variation over the past 30 Ma. Some of the silicic lavas fall distinctly outside the plume field toward more radiogenic 87Sr/86Sr at relatively restricted Nd and Pb isotopic compositions. This excursion in Sr-isotopic ratios of the silicic lavas, in concert with their positive Ce-anomaly, is interpreted to be due to mixing of the Afar plume-derived basaltic magma with fluids from saline aquifers. We conclude that the bimodal lavas are consanguineous, the silicic lavas being generated by fractional crystallization of plagioclase, olivine and pyroxene in a lower mantle plume-derived basaltic magma-chamber, accompanied by the interaction with saline aquifers. This mode of generation of bimodal volcanism from parental primitive basalts without contribution from pre-existing continental crust may have important implication for the origin of early continental crust in the Hadean/Archean Earth. In addition, our

geochemical data from <2 My lavas in the DMH rift show little or no evidence for crust-derived or mantle lithosphere-derived products.

A NEW EPITHERMAL GOLD DISCOVERY: MEGENTA, TENDAHO, AFAR DEPRESSION

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Session: RES

The term epithermal derives from the genetic classification scheme for hydrothermal ore deposits proposed by Lindgren. On the basis of stratigraphic relationships in volcanic sequences, and by analogy with mineral and metal occurrences and mineral textures in active hydrothermal systems, Lindgren inferred that epithermal deposits formed at <200°C and <100 atmospheres (~100 bars). In a comprehensive analysis of the tectonomagmatic controls and styles of epithermal gold mineralization in the northern Great Basin of the western United States two contrasting environments are distinguished: first , high sulphidation and base metal bearing low sulphidation hosted by calc-alkaline andesitic and dacitic volcanic rocks as part of a conventional arc assemblage: second, base metal deficient low sulphidation deposits associated with a bi-modal basalt-rhyolite suite generated during rifting. Bimodal volcanic suites and low sulphidation gold deposits characterise several extensional arcs: the Palaeocene are in the central Andes of northern Chile hosts the rhyolite dome related El Penon veins; the middle to late Jurassic arc in Patagonia of southern Argentina hosts Cerro Vanguardia vein systems. Most of the low sulphidation gold deposits (Ivanhoe, Sleeper, Mule Canyon, Midas) in the northern Great Basin of the western United States were generated over a 2 m.y. interval of the Miocene within and near the northern Nevada rift, a product of back-arc extension related by some investigators to the Yellowstone mantle plume. The Afar Depression lies within the Afro-Arabian Rift System. This rift system extends from Syria in the north and passes through Jordan valley, Dead Sea, Red Sea, Afar Depression and the East African Rift and terminates in southern Africa. The Main Ethiopian Rift, the southern Red Sea and the western Gulf of Aden lie within the Afar Depression forming a rift-rift-rift triple junction between the Nubian, Somalian and Arabian Plates. The volcanism within the Afar Depression is strongly bimodal. Stratex initiated a programme in January 2008 to prove the concept of gold potential of the African Rift valley. In March 2009 work commenced in the Lakes District of the Main Ethiopian Rift based on data from geothermal reports. In October 2009 Stratex visited the Tendaho graben to investigate in and around known hot springs. This resulted in the definition of the Megenta hot spring gold occurrence. Detailed rock channel sampling returned highest grades of 16.7 g/t Au with anomalous gold values >0.1 g/t Au encountered over much of the prospect thus confirming the system as gold bearing. Drilling has confirmed the features of alteration and mineralisation at Megenta are typical of a low sulphidation epithermal vein system with grades up to 19.5 g/t Au over 0.7 metres in veins. In addition the drilling has given new insights into the development of the Tendaho Graben.

Seismically imaging the upper mantle beneath the northern East-Africa rift system

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Session: MLI

Plume related volcanism in Ethiopia has long been cited to have instigated continental breakup in northeast Africa. However, to date seismic images of the mantle beneath the region have not produced conclusive evidence of a plume-like structure. Previous seismic studies using regional deployments of sensors in East-Africa show that low seismic velocities underlie Africa, but their resolution is limited to the top 200-300km of the Earth. Thus, the connection between the low velocities in the uppermost mantle and those imaged in global studies in the lower mantle is unclear.

The recent Afar Consortium experiment included the deployment of 41 seismic stations for up to 5 years. These data, when combined with permanent stations and legacy and new temporary deployments in Ethiopia, Eritrea, Djibouti and Yemen allow us to image the mantle in high resolution to the base of the transition zone.

Relative travel-time tomography shows focused low velocity anomalies in the top 50-100km, likely associated with melt. These predominantly lie underneath the current rift axis, and regions of recent volcanism (e.g., Dabbahu, Nabro). Pn tomography also shows focused anomalies in the uppermost mantle (40-50 km), and Sp receiver functions show an increase in velocity at 75 km depth, likely showing the base of the melting column.

Below ~150km relative travel-time tomography shows evidence for a broader SW-NE oriented sheet like anomaly. There exists little evidence for a narrow plume like upwelling. This seems consistent with seismic anisotropy results that show a dominant NW-SE fast direction in the asthenosphere, overprinted by a more shallow melt/fossil anisotropic signature.

In the transition zone, the seismic velocity anomalies become more focused with two sharp-sided low velocity regions. One lies beneath Afar, the other beneath the western plateau in Ethiopia. These features suggest that smaller plumes may be rising from some larger feature in the lower mantle. This interpretation is supported by numerical and analogue experiments that suggest the 660km phase change and viscosity jump may impede flow from the lower to upper mantle creating a thermal boundary layer at the base of the transition zone. This allows smaller, secondary upwellings to initiate and rise to the surface.

The absence of any radial pattern of anisotropy suggests that the flow field in the upper mantle is dominated by lateral flow from the 'African superswell', rather than these smaller upwellings in the transition zone. This flow is likely driven along gradients in the lithosphere from thicker lithosphere beneath Kenya/Tanzania into Afar where lithosphere has been largely destroyed. However, the constraint on the depth of the melting column beneath Afar necessitates that the superswell has a weak thermal signature.

Melt distribution between the crust and mantle beneath the Dabbahu-Manda Hararo rift segment, Afar, from 3D magnetotelluric imaging

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Session: AMR

The Dabbahu-Manda Hararo rift segment, in Afar (Ethiopia) has been active since 2005 with volcanic eruptions and seismic tremor associated with a 60 km long dike intrusion in September 2005 followed by several subsequent dyke intrusions. Seismicity, geodetic, and seismological studies suggest a magmatic source beneath the Ado'Ale volcanic complex (AVC), located in the mid-segment, and possibly a second magmatic source to the North, beneath the Dabbahu volcanic complex. In order to constrain the location, depth, and geometry of the magmatic sources, magnetotelluric (MT) data were collected from 17 sites along a profile across the rift segment, at a latitude between the Dabbahu volcano and AVC. Two-dimensional (2D) inversion of the Dabbahu profile data provides the first evidence of a large magma chamber at mantle depths. However, three-dimensional (3D) imaging is required to better define the geometry of the magma chamber(s) and to understand its interaction with the tectono-magmatic activity in the upper crust along the rift segment. In order to better constrain the distribution of magma bodies, 6 new MT sites were collected between the AVC and the closest accessible location near Dabbahu. The whole data set was used to provide a 3D image of the resistivity structure beneath the northern part of the rift segment. Given the spatial resolution of the MT data, we can only interpret the uppermost resistivity distribution in the vicinity of the MT sites while data can constrain the whole of the modelled space at depths from a few km to well into the mantle. The results show a complex distribution of electrically conductive structures in the crust at depths between 5 and 8 km. The larger crustal conductors are located beneath the Dabbahu volcano and beneath the western flank of the rift segment, in the area of the AVC, where magmatic sources were suggested by other geophysical results. Deeper, from 8 km depth, the model show a homogeneous large conductor, more than 20 km wide, extending all along the rift segment axis and reaching mantle depths. The 3D inversion of the MT data set confirms the 2D results, providing evidence of a magma reservoir within the mantle but also provides the unique image of how the crustal reservoirs are connected to the main magmatic source along the rift segment. Additionally, 20 MT sites were collected at the currently inactive southern end of the Dabbahu-Manda Hararo segment. The MT site distribution allows application of the same 3D interpretation approach. The 3D image of the crustal-mantle structure in an inactive context, compared to the northern part of the rift segment, clearly show differences, with a generally more resistive crustal structure. The comparison of the two 3D models allows us to confirm our interpretation of the crustal and mantle conductors in terms of melt content.

Relation of geothermal activity to volcanism in extensional settings, and the resulting characteristics of associated epithermal ore systems

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Session: RES

Magmatism related to extensional tectonics, with a focus here on the Taupo Volcanic Zone of New Zealand, strongly affects the chemical characteristics of the intrusion-centered geothermal systems that are hosted in the resultant rift setting. In turn, the characteristics of ore deposits that form in the shallow, epithermal portion of these geothermal systems are distinctly different from those deposits formed in volcanic arcs.

Extensional structures exert first-order control on vertical permeability, although secondary structures typically influence fluid flow in geothermal systems, and these may subsequently host ore veins. Volcanic units are the principal host rocks at shallow depths, although the roots of geothermal systems commonly extend into basement; permeable horizons such as tuffs can act as aquifers for the geothermal reservoir, and units that fracture in a brittle fashion, such as dome rocks, provide shallow channel ways. The fluids in such geothermal systems are dilute, <1 wt% NaCl equivalent, in part due to meteoric water being the major component. However, there are several lines of evidence for magmatic components, likely related to a mafic source, particularly in the gases such as CO_2 and H_2S; reactive magmatic components such as SO_2 and HCl are neutralized at several km depth. The fluids at ~1 km depth are ~300°C with a pH ~5.5 due to the contained H_2CO_3, and are in redox equilibrium with the wall rock; this makes these system much more reduced than the more saline and reactive fluids in volcanic arcs, where causative intrusions are much shallower.

As a result of the near-neutral pH and reduced, H2S-dominant fluids of low salinity, the principal metals that are transported are gold and silver, in contrast to chloride-complexed base metals in geothermal systems of volcanic arcs. Boiling is thus the most effective mechanism to precipitate the H_2S-complexed metals, particularly where throttles result in rapid depressurization at shallow depths of a few 100s m; this also leads to supersaturation of amorphous silica, causing colloidal silica gels to form prior to the fluids discharging at the surface, where they form silica sinters. Thus, where deep fluids are focused near the surface, boiling results in gas loss and an increase in pH (causing a shift from illite to adularia plus calcite stability), deposition of colloform silica bands, and – if there are metals transported due to high H_2S contents – deposition of gold and silver in a ratio of ~1:1 within colloform-banded quartz veins.

The fissure swarms of the Northern Volcanic Rift Zone, Iceland

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Session: AMR

The Mid-Atlantic divergent plate boundary is mostly situated below sea level. However, the interplay between the divergent plate boundary and a hotspot formed Iceland. The island possesses the only on-land part of the Mid-Atlantic plate boundary. In southern Iceland, the plate boundary is split between the Western and the Eastern Volcanic Zones. The Northern Volcanic Rift Zone is, however, the only rift zone in Northern Iceland, making it an ideal area to study the behaviour of divergent plate boundaries. We have mapped Holocene fractures and eruptive fissures within the Northern Volcanic Rift Zone from aerial photographs covering the entire area, satellite images and field studies. The Northern Volcanic Rift Zone is composed of 5-6 volcanic systems arranged in an en-echelon manner along the rift zone, similar to the Main Ethiopian rift. The eastern boundary of the rift zone is characterized by a few faults, and numerous hyaloclastite ridges which suggest intense fissure eruptions on the boundary during periods when glacier covered the area. Most of the western boundary does not have any boundary faults, except in the northernmost part, where large offset faults could either (or both) be boundary faults or associated with the westernmost volcanic system (Þeistareykir). The volcanic systems consist of central volcanoes and fissure swarms extending in opposite directions from them. Several known rifting episodes have activated different parts of the fissure swarms during the last few hundred years. Those are non-eruptive rifting episodes in the Þeistareykir volcanic system in 1618 and possibly also in 1885, two eruptive rifting episodes in Krafla in 1724-29 and 1975-84 and one in the Askja fissure swarm in 1875. The pattern of fractures and eruptive fissures within the Northern volcanic rift zone give indications of the behaviour of both historical and prehistorical rifting episodes that have taken place there. Eruptive fissures within the fissure swarms are mostly found within 20-30 km distance from the associated central volcanoes, while high density of fractures is common at up to about 70-90 km distance from the central volcanoes, indicating that eruptions usually occur closer to the central volcanoes although dikes often propagate farther along the fissure swarm. The fractures within the fissure swarm are generally subparallel to each other. However, a more complicated pattern is found where the Húsavík and Grímsey transform faults meet the rift zone. There, the fissure swarms often show a branched pattern, indicating interaction between the divergent motion generally controlling the formation of fissure swarms and the transform motion associated with strike-slip faulting.

The 1989 Dôbi earthquake sequence: propagation of seismic normal faulting along the Dôbi Graben (Central Afar)

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Session: HAZ

In August1989, an earthquake sequence including 18 events with 5.0< M ≤ 6.3 occurred in Central Afar along the Dôbi graben, a non-volcanic rift segment lying in between the Manda Hararo-Goba'ad and the Asal Manda Inakir magmatic rift systems. The Dôbi sequence was the largest seismic sequence in the Afar region since the March-April 1969 Serdo sequence (8 events with 5.0< M ≤ 6.3.0 in 11 days) and prior to the Manda Hararo-Dabahu rifting episode in northern Ethiopia, which started in September-October 2005, with a mega dyke intrusion (20 events with 5.0 ≤M≤ 5.4 in 12 days).

During the first two days of the August 1989 earthquake sequence, seismic faulting, which occurred on at least 15 normal faults cutting the ~13 km thick seismogenic crustal layer along the Dôbi graben, produced widespread ground deformation. Numerous surface breaks with complex geometry, including fresh scarplets with vertical throws up to 30 cm high and open fissures up to 30 cm wide, were observed. Coseismic slip incremented the deformation - normal faulting with a small component of dextral slip, block tilting, and counter-clockwise rotation of basaltic slices - accumulated in the last 2 Myrs in the transfer zone between the Dôbi and Hanle graben. By combining maps of surface ruptures, relative event relocations with the local Djibouti network, published focal mechanisms, and source sizes, we tentatively relate most of the main shocks of the sequence to slip on individual faults. The largest shocks at 11h16 on 20/08/89 (Ms=6.2) and at 1h09 on 21/08/89 (Ms=6.3) ruptured the two contiguous segments (D1a et D1b) of the SW bounding fault (D1) of the graben. We infer that seismic slip on the two principal bounding faults (D1 and D3) with opposite dips probably "ricocheted" from one to the other. The southern, NE-dipping section D1a ruptured first. During this rupture, many shallower, second-order, SE-dipping faults branching off D1 distributed slip upwards, through a vertical bookshelf-faulting mechanism. Later, other secondary faults ruptured, transferring elastic stress and strain from the southern segment of D1 to D3, which dips SW on the northern side of the graben. This triggered in turn the second main shock, back on the south side, rupturing the northwestern section D1b. Through a domino effect, triggered seismic faulting propagated about 35 km northwestwards along the graben in about 20 hours.

Although the Dôbi earthquakes ruptured part of the fault array between the Asal rift (1978 sequence) and the Serdo region (1969 sequence), a ~50 km long gap subsists along the Der'êla half-graben. We infer the patterns of surface faulting in the Dôbi sequence, which coinvolved bookshelf-faulting about both horizontal and vertical axes, to typify the complexity of coseismic stress release in Central Afar and in other active zones of distributed extension (e.g.: Iceland, Abruzzi, Basin and Range).

NEW GEOTHERMAL EXPLORATION ADVANCEMENTS IN THE REPUBLIC OF DJIBOUTI

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Session: RES

An exceptional geodynamic situation prevails in the Afar Depression, an emerged triple junction of the Red Sea, Gulf of Aden and East African rifts, where volcanic and tectonic activity occur since 30 My. The Republic of Djibouti (23000 km^2) is characterized by numerous current and past hydrothermal activities. Schematically, the country can be divided in two sectors, westward regions composed of plateaus and plains formed since 3.4 My and Eastward regions elevated and mountaineous lands separated by the Gulf of Tadjourah ridge. Most of the current hydrothermal activities are located in specific zones of the recent western regions formed by the opening of the Afar Depression and the Danakil plate anticlockwise movement. Few other current and past hydrothermal activities are found in the Eastern part around the Gulf of Tadjourah ridge. Already in the early geological explorations these hydrothermal manifestations were described as a result of potential geothermal resources.

About twelve geothermal provinces are identified in the country according the location of surface manifestations. All of the surface manifestations are fracture controled and occur within the recent volcanic and sedimentary rocks or at the contact of recent and old formations. Asal rift and Hanle/Gaggade areas were considered as priority sites for geothermal explorations. Gradient wells and geophysical prospections were undertaken at different stages to assess geothermal reservoirs on these prospects. Deep drillings revealed a high enthalpy reservoir in Asal rift zone and a low enthalpy reservoir at medium depth. Results in Hanle plain demonstrated low temperatures caused by a high underground fresh water flux.

Although potential geothermal reservoirs have been recognized in the Republic of Djibouti, the power generation from geothermal energy is still to be achieved. However, given that energy is a key sector for the economical and social development of the country to alleviate poverty, the Government of the Republic of Djibouti is strongly committed in developping as much as possible the geothermal resources. Over the years 2000, Djibouti conducted a significant policy of capacity building of CERD, the national research center, in order to give the capability to realize prefaisability studies for the geothermal prospects. As a result CERD has completed the Nord-Goubhet surface studies and will finalize the lake Abhé prospect studies by the end of 2011, including well siting. Also the Asal rift geothermal prospect exploration will come on line soon with deep deviated drillings.

A comparison of seismic anisotropy and geoelectric strike around the Manda-Hararo magmatic segment, Afar.

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Session: AMR

Deformation in the crust during continental breakup occurs by faulting and magma intrusion, but the partitioning of these mechanisms of strain, and their variation in orientation with depth, remains ambiguous. We combine observations and modelling of magnitude, location and orientation seismic and electrical anisotropy to infer variations in type and orientation of strain fabrics during rifting in the Afar Depression of Ethiopia.

A geoelectric strike direction can be derived from tensor analysis of magnetotelluric (MT) data, which is either a result of regional scale 2D or 3D structures, or anisotropy of a scale not resolvable by the method (either way broadly referred to here as anisotropy). By looking at the MT results over a range of sounding periods (proxy to depth) and comparing them to models of the conductivity structure we can suggest which mechanisms are likely to be causing the observed dimensionality of the data. Phase splits between the two MT modes of orthogonal propagation are used as an estimator of the magnitude of electrical anisotropy.

We see that phase splits between the MT modes are small in the very short period data (top 5km) and that the strike directions are variable, but resemble surface variations in fault strike. Seismic anisotropy was measured from shear-wave splitting of local earthquakes with hypocentres mostly between 4 and 8 km for the stations in the vicinity of our MT profiles, and thereby sample upper-crustal anisotropy. Spatial variations in fast polarization direction resemble variations in geo-electric strike. Seismic anisotropy is most simply explained by aligned fractures in the upper-crust, consistent with small phase splits in electrical anisotropy. In addition, the MT data show a near surface conductor in our models which is attributed to high salinity fluids in lenses of sediments that have been fractured, faulted and intruded.

At slightly longer periods, our MT models tend to show a ~10 km thick resistive layer of intruded and stretched continental crust where the data exhibit a dramatic increase in phase split and strike orientations which become less variable, generally adopting a NNW–SSE direction (perpendicular to the opening direction of the rift). This feature of the data is most pronounced over the centre of the active and dormant parts of the rift. However, it is non-existent at sites west of Dabbahu volcano where we see very high conductivities from the surface to the resolution depth of our data. This is interpreted as a shallow magma chamber with a very high fraction of melt which does not support any anisotropy.

Our results are consistent with the anisotropic fabric of the upper-crust being dominated by fracturing and faulting, while in the mid-lower crust, aligned melt is dominant.

The seismic results show considerable variation laterally, with sites to the SW of the Tendaho-Goba'ad Discontinuity showing much less anisotropy which is oriented perpendicularly to that at other sites. The MT phase split is also much less pronounced at equivalent sites.

A Rare Magmatic Event on the other side of the Red Sea: The 2009 Dyke Intrusion and Seismic Crisis in Harrat Lunayyir, western Saudi Arabia

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Session: AMR

Extensive lava provinces (called harrats) exist on the western part of the Arabic Peninsula, along the Red Sea. They have developed during the past 30 million years along with the opening of the Red Sea. A few volcanic eruptions during the past centuries, including an eruption in Yemen in 1937 and the 1256 AD Al Madinah eruption, show that these harrats are still active, although the provinces are seismically inactive most of the time. One of these areas, Harrat Lunayyir reawakened in April-May 2009 with an intensive seismic swarm and surface faulting, peaking on 17-20 May with six magnitude 4.6-5.7 earthquakes. The activity prompted the Saudi civil protection authorities to evacuate more than 30000 people from the area. While the earthquake activity significantly decreased after 20 May, it continued throughout June and July with a few earthquakes as large as magnitude ~4, before quieting down in August 2009.

Much of what we have learned about the activity comes from interferometric satellite radar (InSAR) observations and from analysis of the seismic data collected by a broadband seismic network that was installed soon after the earthquake swarm started in April. The InSAR data show that large-spatial-scale (40km x 40km) approx. east-west extension of over 1m took place as well as broad uplift amounting to over 40cm. The center of the uplifted area was transected by northwest-trending graben subsidence of over 50cm, bounded by a single fault to the southwest showing up to 1m of faulting and by multiple smaller faults and cracks to the northeast. The observed deformation is well explained with a near-vertical ~10-km-long and 0.13 km^3 dyke intrusion that almost made it to the surface and caused extensive graben-bounding normal faulting. The strike of the model dyke is 340°N, parallel to the Red Sea rift, providing information about the orientation of the stress field in the region.

Harrat Lunayyir is located over 150 km from the central rift axis in the Red Sea, so the intrusion indicates that active extension is broadly distributed in the region, rather than being entirely focused along the central rift axis. Volcanic vents in Harrat Lunayyir and other neighboring harrats typically show lineations that are oriented northwest-southeast and were probably fed by dyke intrusions similar to the 2009 dyke, which further supports a broadly distributed extension. However, intrusions like the one in Harrat Lunayyir are most probably rare on the Arabic Peninsula.

Mapping the evolving strain field during continental breakup from crustal anisotropy in the Afar Depression

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Session: AMR

Rifting of the continents leading to plate rupture occurs by a combination of mechanical deformation and magma intrusion, yet the spatial and temporal scales over which these alternate mechanisms localize extensional strain remains controversial. Here we quantify anisotropy of the upper crust across the volcanically active Afar Triple Junction using shear-wave splitting from local earthquakes to evaluate the distribution and orientation of strain in a region of continental breakup. The pattern of S-wave splitting in Afar is best explained by anisotropy from deformation-related structures, with the dramatic change in splitting parameters into the rift axis from the increased density of dyke-induced faulting combined with a contribution from oriented melt pockets near volcanic centres. The lack of rift-perpendicular anisotropy in the lithosphere, and corroborating geoscientific evidence of extension dominated by dyking, provide strong evidence that magma intrusion achieves the majority of plate opening in this zone of incipient plate rupture.

Mantle anisotropy at mid-ocean ridges: What does it tell us about rifting processes?

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Session: AMR

Observations of seismic anisotropy at oceanic spreading centres offer insights into mid-ocean ridge processes and the formation of new plates. We use remote observations of seismic anisotropy beneath most parts of the global mid-ocean ridge system using measurements of source-side shear-wave splitting. Over 100 high-quality measurements are made using earthquakes that occur near mid-ocean ridges and transform faults, but recorded at teleseismic distances using land stations. In general, for off-axis ridge events, the polarization of the fast shear-wave is parallel to the direction of plate spreading. Nearer the ridge (<50km), the fast shear-wave polarization direction becomes more scattered and is often ridge parallel. Delay times increase from <1 sec near the ridge, to roughly 3 secs further away. The pattern is more complex at transform boundaries. Coverage beneath the East Pacific Rise (EPR) is especially good and we systematically observe larger delay times with teleseismic S-phases than with previously recorded SKS-phases (i.e, with data from the MELT and GLIMPCE experiments). A compatible explanation invokes the presence of horizontally-aligned, interconnected layers of melt focused at the marginal lithosphere-asthenosphere boundary (LAB), as proposed by Holtzman and Kendall (2010). This is also compatible with other observations, such as a sharp LAB and measurements of seismic anisotropy from surface waves. Cumulatively, these results suggest two mechanisms for anisotropy – one due to the LPO of mantle minerals and the other due to the alignment of melt. The former is a proxy for strain rate and mantle viscosity, whilst the latter reduces the strength of the plate and focuses strain at the plate boundary. Comparatively, mantle anisotropy beneath the East Africa Rift system is strikingly different from that observed beneath the EPR, and more similar to that observed beneath the ultra-slow Gakkel spreading centre.

Tracking melt with earthquakes in the Askja volcanic system, Iceland.

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Session: AMR

The lower crust of magmatically active rifts is usually too hot and ductile to allow seismicity. Unexpectedly, over 1000 small-magnitude lower crustal earthquakes have been occurring persistently during all monitoring periods between 2005 and 2011. They are located mostly at depths of 14-25 km. This is well beneath the local seismically delineated brittle-ductile transition, which is at 4 km depth beneath the caldera increasing to 8 km depth further away. The most plausible explanation for them is rapid melt movement generating sufficiently high shear strain rates to produce brittle failure. Seismic travel time tomography has revealed a low velocity body beneath the main Askja caldera, thought to be the shallowest magma chamber. Some deeper low velocity bodies were also found in the region. The lower crustal earthquakes are located within three spatially separated clusters, which have stable dimensions and locations through time and are interpreted as positions of repeated melt supply from the mantle to the lower crust. The three clusters show that there are multiple positions of melt supply from the mantle within a single magmatic segment and all three positions are simultaneously active, similar to observations from fast spreading ridges. However, the relative number of earthquakes in each cluster shows that two thirds of the melt is supplied to the central volcano Askja, similar to observations from slow spreading ridges. On long timescales melt supply is probably greatest at the segment centre, with melt redistribution in the upper crust, even though there are multiple points of lower crustal injection along the segment.

Lower crustal seismicity has only rarely been recorded in Iceland and in all other cases is associated with discrete intrusion and/or eruption episodes lasting only days to months. In contrast, the Askja earthquakes are persistent and ongoing, representing a long-term feature. The frequency content of the Askja earthquakes is also strikingly different to that of other Icelandic lower crustal earthquakes. As the relatively low frequency content of the Askja earthquakes is thought to be caused by attenuation, something different must be happening in the crust of Askja to cause the attenuation. These observations suggest that the current melt supply patterns at Askja could reflect a previously unseen stage of the rifting cycle involving a phase of lower crustal construction.

A nascent volcanic rifted margin along the Asal-South Danakil rift segment, SE Afar. Structural evidence from the Makarassou fault-flexure.

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Session: RCM

The SE Afar margin in Djibouti is marked by a pronounced NS-trending topographic scarp between the South Danakil range (east) and the Asal rift depression (west), ahead of the westerly-propagating Aden accretionary axis. This highly strained zone of active-recent rifting displays distinct fault networks, previously regarded as part of a transfer zone linking the Asal and Manda Inakir rift segments, and cutting through young mafic volcanics of the <1 Ma Asal modern rift, and 3-1 Ma Stratoid series, on top of the Dalha trap-like basalts (9-4 Ma) further east. The 3D-architecture and the origin of the SE Afar fault-flexure are precised from the interpretation of field-calibrated remote sensing images that allow us to discriminate two recent (<1 Ma) extensional fault networks, in terms of geometry, timing and kinematics. Emphasis is placed on the 10x70 km Makarassou fault system that dissects the downflexed Stratoid sequences involved into the riftward-facing flexure. Its most specific attribute is a closely-spaced network of NS-trending normal faults, dipping consistently to the east, i.e. continentward, and bounding domino blocks of Stratoid tilted lavas, with dips as high as 30°W. This submeridian extensional fault pattern, oblique to the N40°E regional extension and possibly guided by preexisting fabrics, clearly post-dates a NW-SE-oriented network of Asal-type horst-graben structures.

The location of the Makarassou riftward-facing flexure, close to the hinge line marking the limit of pronounced lava thickness in the Stratoid series towards the magmatically-accreted rift domain, further suggests that magma-assisted processes acted as driving forces for crustal downwarping along the western flank of the South Danakil block, during the Stratoid (3-1 Ma) flood basalt activity.

By analogy with coastal flexures involving SDRS-type magmatic prisms along volcanic rifted margins, it is thus assessed that the Makarassou fault-flexure pattern developped as an extensional faulted monocline, in response to differential loading of the Afar accreted transitional crust to the west. The magma-driven vertical tectonics and riftward-facing flexuring that operated during the last 3 Ma, along the eastern flank of the Asal-Manda Inakir future plate boundary, are confidently regarded as the stuctural expression of an incipient volcanic rifted margin in SE Afar. The inferred embryonic stage of continental breakup is in agreement with previous assessments about the transitional type of the Stratoid flood basalt series, and the thinned character of the Afar crust.

The Gravity Field and the Divergent Boundary at the Afar Depression

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Session: AMR

Detailed and high precision gravity survey, assisted by differential GPS survey, was carried out in the Afar depression, to map the subsurface and study structures at depth. Two profiles that run east-west were measured. The first profile run across the Dabbahu (Manda-Harraro) rift, where the 2005 seismo–volcanic crisis occurred, and the other is located 20 km north of the town of Semera.

We model the Bouguer anomaly across the profiles using preliminary depth constraints from borehole information and other works. The modeling is first carried out by separately modeling the high and low frequency anomalies and later by combining the preliminary models to arrive at the final picture of the subsurface. The modeling process mapped four density layers, interpreted as sediment cover, upper crust, lower crust and the upper mantle. Sub-vertical structures are mapped in the upper layer and swelling of the deep layers in the central part of the profiles is observed. The features mapped in the area are typical features of divergent boundaries and comparison of result on the two profiles indicates that the crust is thinning towards the north.

Sub-rift magmatic mantle processes beneath the western branch of the EARS - A key to understanding highly modified lithosphere beneath the Tanzania craton

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Session: MLI

Volcanic fields in western Uganda mark the northernmost magmatic activity in the western branch of the EARS and provide an excellent petrological view into the deeper lithosphere. They consist of CaO-rich and SiO2-poor ultrapotassic lavas. The strongly potassic characteristics of the lavas require source depths greater than 100km that can be explained by a melting of a modified, but preserved, cratonic lithosphere root.

Xenoliths from this area are mainly clinopyroxene and biotite-bearing and were once used as archetypal for modal metasomatism, although it can now be recognized that they show magmatic rather than overprinted mantle features. Trace element patterns and isotopes clearly indicate an affinity with the host lavas. Structures within the nodules indicate a multiphase history of melt introduction, migration and extraction.

The potassic magma compositions can be explained by initial modification of the base of the mantle lithosphere at depths of ca. 150km through very low degrees of H_2O- and CO_2- rich potassic silicate melts. This produced clinopyroxene- and phlogopite- rich veins after migration of the melts to lower pressures; these veins are a main source of the potassium-rich lavas.

The presence of assemblages that differ from peridotite within the lithospheric mantle has consequences for the seismic velocities. We calculated theoretical profiles of seismic velocities (Vp and Vs) through thick lithosphere at different stages of vein infiltration. The average vein composition based on xenoliths from the western part of the craton consists on of about 60% clinopyroxene and 40% biotite. Peridotite compositions from East African xenoliths were used to represent unaffected mantle. The seismic profiles are calculated using experimental data on elastic properties of component minerals and chemical components at differing P/T conditions.

Our calculations demonstrate that peridotite intensively veined by solid mica-clinopyroxenite assemblages will show a strong negative velocity excursion with up to 20% lower Vs and than normal peridotite. Seismological observations in same region indicate a significant shear wave velocity decrease of more than 20% at depths of 70km and a second, smaller decrease at about 150km. Results from shear wave splitting point to anisotropy within the deeper lithosphere with a rift-parallel fast axis (Wölbern, Rümpker et al, this workshop).

The seismic velocity jump at 70km depth is interpreted to mark the upper boundary of an intra-lithospheric zone of intense vein infiltration. The second velocity decrease at about 150km marks its lower end and most probably the lithosphere/ asthenosphere boundary. The veins probably have rift-parallel preferred orientations causing the deep-seated seismic anisotropy.

The integrated model can be tested at the southern tip of the eastern branch of the EARS where sub-branches pierce into the Tanzania Craton. This is associated with increasing potassium in lavas and seismic low velocity zones below 70km.

Finally, we can extrapolate our integrated model to explain the seismic structures beneath the central Tanzania craton with velocity reductions of 15% to 6% at 70 to 100km (Wölbern et al, 2011, Weeraratne et al 2003) by attributing this to moderate vein density at its root.

Lithospheric structure, mantle flow and the state of stress of Africa

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Session: MLI

The topography and tectonic history of the African continent set it apart from all other continental regions on Earth, from the extreme elevation of its southern craton to the plateaus and continental rifting in the northeast. The latter, a perhaps unique example of how continents split apart, remains fascinating to geologists and geophysicists alike, not least because the exact mechanisms for the on-going rupture of the continent remain elusive. The mechanics of rifting depend on the stresses acting upon the continent and the strength of the lithosphere. The former are a product of the structure of the lithosphere, its compensation mechanisms and the shear and radial stresses due to mantle flow acting on it.

I start with a review of the present-day stress field and the contributions from lithospheric structure and a model of mantle flow that matches present-day plate velocities extremely well. I will discuss the effects of critical assumptions about the isostatic compensation mechanisms and the density and thickness of the lithosphere and show how they lead to drastically different predictions of the magnitude and directions of stresses. The effects of mantle tractions (radial and horizontal) match the observed stress patterns, especially when low seismic velocity regions in mantle tomographic models are allowed to drive the flow. Dynamic topography resulting from radial stresses, the presence of and asthenosphere and a lithospheric structure that is not artificially compensated are key to matching the stress observations.

I will show, if time permits, preliminary results of the time evolution of the stress field from the time evolution of mantle flow.

Tectono-Magmatic Evolution of Atlantic Type Rifted Margins

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Session: RCM

The increasing number of high quality reflection and refraction seismic surveys and drill hole data in Atlantic type rifted margins show a divergent style of margin architecture and evolution in which quantity and distribution of syn-rift magmatism and fault structures are the most variable features. These observations led to an oversimplified classification of rifted margins as either volcanic or non-volcanic. Although this simple concept may lead to the idea that margins evolve either under the presence or absence of magma, the available data show that rifted margins are more complex and cannot be characterized based on the volume of observed magma alone. Indeed so-called “non-volcanic” margins are not necessarily amagmatic, as shown by the results of ODP drilling along the Iberia-Newfoundland rifted margins. On the other hand, magma-rich margins, such as the Norwegian rifted margins, show evidence for hyper-extended crust, suggesting that there is more deformation before magma emplacement than previously proposed. This leads to the question of how magmatic and tectonic processes are interacting before, during and after continental breakup.

In my presentation I will review results from the present-day South and North Atlantic and the fossil Alpine Tethys margins and will discuss the tectono-magmatic evolution of so called magma-rich and magma-poor rifted margins. I will show that the commonly proposed end-member type margins, i.e. “non-magmatic” and “non-tectonic” margins do not exist and that rifted margins show a more complex poly-phase tectonic and magmatic evolution than previously suggested. However, it remains unclear whether decompression melting is the driving force, or rather the consequence of extension. In my presentation I will discuss to what extent variable amounts of magma may control the evolution and timing of continental breakup and control the architecture of Atlantic type rifted margins.

Interplay between tectonics and magmatism during the last stages of continental breakup: the Manda-Hararo rift segment, Afar, Ethiopia

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Session: AMR

The Afar depression (Ethiopia) is a triple junction whose crust is believed to be close to the Continent-Ocean Transition. The extension in Afar is organised along rift segments which result from interactions between dyke injection and volcanism, as observed during the well documented 2005 fissure event at Dabbahu volcano.

The Manda-Hararo rift segment represents an ideal natural laboratory to study rift evolution, at the scale of individual segments, during development of the principal morphological features caused by volcanic and tectonic interplay. Our study provides time constraints on the 1 – 100 ka timescale in order to:

- determine the timing of fault growth relative to the creation of rift topography

- determine the timing of lava flow resurfacing

- assess the influence of a terminal volcanic edifice on rift morphology development

- constrain timescales of lava differentiation

- constrain the number and the distribution of magma bodies involved in lava production.

Young (<100 ka), K-poor lavas such as those in Afar are difficult to date using the K-Ar or Ar-Ar methods, and 14C dating is not possible due to lack of vegetation. We present the results of surface exposure dating using cosmonuclides (3He) to accurately date lava surfaces, fault scarp initiation and fault growth rates. Results have been combined with major & trace element compositions, field mapping and interpretations of remote sensing imagery (using Landsat, ASTER and SPOT data), to deduce the links between timing of rift geomorphology acquisition, volcanic history and magmatic & tectonic history.

Results show that the base of the northern part of the Manda-Hararo segment is a remnant of old rift floor consisting of basaltic pahoehoe flows emplaced at 67 ± 5 ka. Subsequently, this area was massively infilled by younger ‘a’ā flows issued from Dabbahu volcano, emplaced between 40 and 20 ka. At about the same time (36 ± 1.7 ka), pahoehoe flows were also emitted from fissures in the rift axis. All the lava flows emitted from the northern part of the segment display the same trace element signature (La/Yb ranging between 8-10) and follow a single continuous differentiation trend through time, suggesting that these were issued from a single magma batch, originating from the northern end of the segment (Dabbahu volcano). In contrast, 5-10km to the south, activity is much more recent with young fissure flows (samples dated <2ka and recent 2007-2009 eruptions). These flows which were clearly produced from a mid-rift reservoir according to morphological features, show distinct chemical signatures (La/Yb ~ 5) confirming a separate magma source.

Dyke injection and volcanic activity seem to be closely linked in the northern half of the Dabbahu rift segment:

- two distinct, separately evolving, magma reservoirs supply the lava flows,

- moreover, the volcanism in the north shows that Dabbahu volcano produced massive ‘a’ā flows that filled the rift axial depression, but also that fissure-fed basaltic volcanism simultaneously occurred at the rift axis. It suggests that the magma reservoir beneath Dabbahu was actively related to dike injection processes during rifting and volcanism for the last 40ka in the same way that magma was injected during the 2005 event.

Answers still awaited to some Ethiopian tectonic provocations

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Session: AMR

The Ethiopian rift valley was first outlined as a tectonic unit by Oscar Neumann in 1901. The structural outline of Afar, a more inhospitable region, emerged only through more than a century of hard-won effort. Today's remarkable understanding of the entire Ethiopian rift system, however, leaves several questions unanswered. The author, after more than 50 years of questing, remains intrigued by some of these:

1. The apparently contrasting structural style of the western Afar margin, south and north of latitude 13°, in conjunction with a change in thickness of the Oligocene flood basalt pile.

2. The significance of the disconnected chain of Quaternary marginal graben along the the western Afar margin.

3. The significance of the active Dubbi-Nabro-Oyma volcanic line, coincidentally on a northerly projection from Ethiopian rift axial volcano-tectonism.

4. Is the relationship between volcano spacing and lithospheric thickness in the African rift system a real one?

5. Is the regional stress pattern suggested by Tertiary dike orientations in Ethiopia, elucidated in 1971, valid?

6. Does the Galema/Sagatu dike swarm along the eastern side of the northern Ethiopian rift mark a transient switch of intense extension from out of the rift valley, or a mid-Quaternary boost to on-going axial rifting?

7. Is the Badditu/Amaro horst at the southern end of the rift valley another if smaller Ruwenzori?

8. Do the recent episodes of fissuring in the sedimentary floor of the rift valley have any tectonic connexion?

Three-dimensional time-varying crustal velocity and strains in the Afar triangle

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Session: AMR

The start of a rifting episode in Dabbahu in 2005 prompted a renewed wave of interest in the tectonics of Afar. Here we use satellite geodesy to investigate the distribution of strain in time and space, the width of the plate boundary deformation zone, its variability in the different volcanic systems of Afar, and the style of deformation of individual volcanoes. The InSAR catalogue over Afar has seen a ten-fold increase in only five years, jumping from a few tens of acquisitions in 2005 to hundreds of images collected to date. Afar has also been the target of other crustal deformation techniques, such as GPS and seismology.

Here, we use a method that combines all the different InSAR and GPS measurements in one common 3-dimensional framework. We use InSAR data from 12 different Envisat tracks and all the available GPS data to obtain large-scale 3D velocity and strain-rate maps in Afar. We obtain line-of-sight (LOS) deformation rates and the associated uncertainties for each InSAR track using a network approach to mitigate planar orbital and linear topographically correlated atmospheric delay errors in the interferograms. Unreliable pixels are not included in the rate maps by removing pixels with uncertainties of deformation larger than an a priori value, about 3-4 mm/yr. The network approach allows inversion for time-varying linear patterns and discrete offsets. Thus our rate maps preserve both linear deformation patterns as well as sudden deformations, ie. due to dyke intrusions, eruptions or faulting. We combine the LOS rate maps with the GPS data and invert for the three-dimensional velocity field based on Tikhonov regularization, following the method of England and Molnar[1], as adapted by Wang and Wright[2] to incorporate InSAR data. A triangular mesh is constructed over the Afar area and then we solve for the best-fit horizontal and vertical velocities on each node.

Our analysis shows that strain in Afar is accumulated not only around the Dabbahu segment. A high strain rate is also observed towards the north in the Erta 'Ale range. This may be caused by high magma flow towards the segment as two eruptions occurred in Erta Ale since 2008. All 3D components of the velocity field are high around the Dabbahu segment, as a result of repeated dyke intrusions and accelerated post-rifting extension. The strain map also highlights the extent of the area affected by post-rifting deformation around Dabbahu, with high strain rates observed over a 400 km wide area centred at the Dabbahu segment. On the other hand, the width of the plate boundary deformation zone over the non-currently rifting Erta Ale volcanic range is ~100 km, comparable to values observed in SE Iceland.

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Sustained magmatic inflation and fault movement in the Asal-Goubbet Rift observed using 11 years of radar interferometry data

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Session: AMR

Radar data acquired by the Canadian satellite RADARSAT during the 1997-2008 time period are used to construct a 2 dimensional surface velocity field of the eastern part of the Afar depression. The main rift system imaged by the data is the Asal-Goubbet Rift, which was the locus of a major seismo-magmatic event in 1978, resulting in 2-3 m of horizontal opening and a basaltic fissural eruption (Ardokoba). During the 11 years of radar observation, the Asal rift shoulders open at a rate of ~15 mm/yr, while the horizontal velocity decreases away from the rift down to the plate motion rate of ~13 mm/yr. The vertical velocity field shows a ~60 km wide zone of doming centered over the rift associated with shoulder uplift and subsidence of the rift inner floor. The differential movement between the shoulders and the rift floor is accommodated by two main antithetic faults: the south-dipping Fault (C), well developed in the topography and the recent north-dipping Fault E with a small topographic scarp. We explain the observed velocity field using a 3-D model combining rectangular faults, dikes and sills embedded in an elastic half space. The least-square inversion of model parameters shows the presence of an inflating body located under the Fieale caldera expanding at a rate of 2 10^6 m^3/yr. Faults bordering the rift show down-dip and opening motions especially at their base where they are connected to the inflating body. These findings suggest that:

- The structure under the Fieale Caldera is the main supplier of magma at shallow depth

- Magma under the Fieale caldera is at a pressure higher than the lithostatic pressure and exerts lateral forces contributing to a divergent push on the adjacent blocks.

- The main faults that were activated in 1978 show continuous opening and down-dip movements. They seem to connect to the magmatic system at depth acting as conduits for the magma toward the surface.

The total geometric moment rate due to the opening of all modelled structures represents 1-2% of the total volume of magma estimated to have been mobilized during the 1978 seismo-magmatic event (Tarantola et al., 1979, 1980). This suggests that the system is still in a transient mode, as the current inflation rate would accumulate the same volume in 40-50 years.

Morpho-tectonic evolution and significance of the marginal graben system along the southern Red-Sea margin (Ethiopia)

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Session: RCM

The western Afar margin represents the southern end of the Red Sea rift system. It developed in the heart of the Afar plume related volcanic province which lies at the famous triple junction connecting the East African, the Gulf of Aden and the Red Sea rifted systems. This margin is presently separating the Afar depression from the Ethiopian Highlands and is topographically expressed by an impressive altitudinal gradient (more than 3000 m in less than 50 km). This topographical passive margin has been developed during Miocene times from the top of an uplifted dome, which has been related principally to the Afar plume impingement and the associated extrusion and differentiation of Ethiopian Continental Flood Basalts 30 Ma ago. This topographical margin is also typically separating the edge of a thick continental block from an extremely thinned domain (the Afar depression), which most probably represents one of the rare worldwide rifting step corresponding to the Ocean Continent Transition zone at the rift to drift transition. Geophysical observations on old passive margins, bounding well developed oceanic domains, have documented that such extreme lithospheric thinning is frequently related to low-angle detachments. However, flat structures have been rarely evidenced and confirmed by field observations during rifting stage. Moreover, in the heart of such a volcanic province, if accommodation of extension has been facilitated by magma injection since early stages of rifting, when and along which type of structures the crust has been thinned ? In this context, the on-shore western Afar margin is an ideal case study to try to precise geodynamic and structural thinning processes because time lapse since the initiation of rifting is so reduce (less than 30 Ma) that outcropping morphological expression of implicated geological and magmatic events have been preserved and can be easily documented and investigated.

A particular geological characteristic of this southern part of the Red Sea margin resides in the well developed marginal basins, morphologically expressed all along the topographical gradient from the Eritrean margin to the heart of the volcanic province at the transition with the East African Rift branch. Such morphological steps have been variously described and interpreted in the past, and are generally considered as abandoned early rift structures with a rift-ward facing master fault. In this study we present a new geomorphological and tectonic interpretation of these marginal basins development.

Climate model studies on the impact of tectonics and Earth's orbital changes on African climate

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Session: CLI

The development of the East African Rift System (EARS) during the last 20 million years caused by tectonic forcing is supposed to influence the regional climate in Africa. However, on these timescales also changes in the Earth's orbital parameters have an influence on climate. The analysis of these impacts is one topic within the research group RiftLink (www.riftlink.de). To analyse the influence of both tectonic and orbital forcing on African climate, first, the global coupled ocean-atmosphere climate model ECHO-G is applied. These simulations have a coarse horizontal resolution of roughly 350 km meaning the EARS is poorly represented in the global model. Therefore, in a second step, the non-hydrostatic regional climate model COSMO model in CLimate Mode (CCLM) is applied with a horizontal resolution of roughly 50 km. The regional simulations are forced at the lateral boundaries with the simulations performed with ECHO-G.

Tectonic forcing is represented in the climate models by changes in model topography. The different topographies can be considered as possible past stages during the development of the EARS. The results indicate that tectonic forcing has a strong impact on precipitation in Africa caused by changes in the circulation. For example, the forcing helps explaining East African aridification during the Neogene. However, additional rather global forcing factors like changes in greenhouse gas concentrations or orbital forcing are necessary to fully explain the aridification.

To analyze the impact of orbital forcing, Earth's orbital parameters are changed in the model in a way that top of atmosphere insolation results in significantly different patterns compared to today. Here, the orbital configuration of the last interglacial at 125000 years before present is chosen, when the seasonality of insolation on the northern hemisphere was strongly enhanced, whereas on the southern hemisphere it was strongly weakened. The simulations of this timeslice show a strong impact of orbital forcing on precipitation over large parts of Africa caused by altered moisture transport.

Both tectonic and orbital forcing can have an equally strong impact on African climate. Therefore, at least these two factors have to be considered when interpreting proxy data and also setting up paleo climate model simulations.

Dynamics of dyke propagation and patterns of dyke-induced seismicity

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Session: AMR

Observations during lateral dyke propagation in rifts reveals recurrent patterns: (1) the seismicity induced during lateral propagation delineates a forefront with an approximately exponential space-time dependency, (2) a backfront is also sometimes detectable, likely due to a moving stress shadow. The backfront seems to have a complicated, but non-random, functional behavior, (3) the moment tensor solutions during the stopping phase indicates sometimes the same fault planes but opposite mechanisms than what observed during the propagation phase, (4) mismatches between volumes gained by the dykes and lost by the feeding sources are becoming the rule more than the exception. Some of these patterns can be explained in terms of current models: Dahm et al (2010) explain the pattern of induced seismicity, Rivalta (2010), models the coupling dyke-magma chamber through mass conservation; however a framework where all four of them play a role is still missing. Here we combine the two quoted studies into one formulation, and apply the rate and state earthquake nucleation theory to model the induced seismicity. We solve the problem for a vanishing tectonic gradient, obtaining a curve for the propagating tip that fits well the observed seismicity forefront, including the stopping stage that was never explained before. Next, we model the time dependent moment tensor that one can expect during fault slip coupled to a propagating dike. Work is in progress to add a non-vanishing tectonic gradient to the dynamics.

The Thermal regime of the Arabian plate, Red Sea and Gulf of Aden

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Session: MLI

The present-day thermal regime of the Arabian plate is primarily affected by the dynamics of the Afar plume and the rifting of the Red Sea and the Gulf of Aden since Early Oligocene. However, the Arabian plate is mostly a Precambrian shield covered on its eastern part by a Phanerozoic platform and its thermal regime, before the Afar plume and rifting activity, should be related to a thick and stable lithosphere. First heat flow measurements on the shield in Saudi Arabia were supporting this idea, with values (36-45 mWm^{-2}) were similar to the typical shields values. Seismological studies have shown that the lithosphere is rather thin, 100 km or less below the shield and 150 km below the platform. Recent heat flow measurements on the Arabian shield in Jordan show higher values (~60 mWm^{-2}) than in Saudi Arabia. We have conducted heat flow measurements in southern and northern Oman and obtained 10 new heat flow values in the eastern Arabian plate. We also derived 20 heat flow values in both Yemen and Oman by processing oil exploration data. The surface heat flow in these different locations is homogeneously low (45 mWm^{-2}). The heat production from the Dhofar Precambrian basement is also low (0.7 μWm^{-3}). A theoretical stable geotherm for the Arabian platform can be inferred and its intersection with the isentropic temperature profile predicts a thermal lithosphere thickness of about 140-150 km, consistent with the seismological observations. Differences in heat flow between the eastern (60 mWm^{-2}) and the western (45 mWm^{-2}) part of Arabia reflect differences in crustal heat production but also differences in mantle temperatures with a higher mantle heat flow in the west. Tomography studies beneath Arabia image this east-west contrast in the mantle. The stable lithospheric thickness for the Arabian plate is 150 km, and the progressive thinning from the Red Sea would be caused by the thermal erosion of the plume material, not old enough to be fully detected at the surface. The Afar plume mostly affects the base of the Arabian lithosphere along the Red Sea and the western part of the Gulf of Aden. This widespread influence is mainly attributed to the channelling of the asthenospheric magma by the rift. The weak penetration into the Gulf of Aden is probably due to the important segmentation of the rift, which introduces discontinuities. Marine heat flow measurements in the Gulf of Aden show a transition from a low heat flow near the continent to a high heat flow near the ocean. This transition is abrupt and occurs at the limit between the continental part of the margin and the Ocean-Continent Transition. These observations may be explained by small-scale convection that homogenizes temperatures in the deep margin. Heat flow measurements in the Red Sea show a fundamental difference with the eastern Gulf of Aden. The transition from high heat flow values in the Red Sea rift to the low values in the continent occurs 50 km within the continent while the Gulf of Aden borders are unaffected.

The Thermo-Chemical State of the East African Mantle

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Session: MLI

Cenozoic magmatism in East Africa has long been linked to the African superplume, one of the most conspicuous features in global tomographic models. This broad slow wave-speed anomaly has often been interpreted in the context of elevated temperatures, but the causes of seismic heterogeneity are many (e.g., temperature, composition, melt), with the relative contribution of each uncertain. To address this issue, we present mantle potential temperatures (TP) using PRIMELT2 in order to examine the spatial and temporal distribution of upper mantle thermal anomalies in East Africa. We combine these thermal data with preliminary high-precision compositional data derived from olivine crystals for East African lavas with the goal of constraining the thermo-chemical conditions of the East African upper mantle. Our estimates of mantle TP show that the East African mantle has remained warmer than ambient mantle conditions over the past 40 Myr, peaking during the Oligocene African-Arabian flood basalt episode (1520°C). Rift-related magmatic activity younger than 10 Ma develops a maximum TP in Djibouti (1490°C) decreasing south along the rift, increasing once more in the Turkana Depression. These maximum TP values are higher than the ambient upper mantle, but they nevertheless fall toward the lower end of the global temperature range of large igneous provinces. Our results are thus inconsistent with a solely thermal origin for the profound mantle seismic velocity anomalies beneath East Africa. Partial melt likely plays an important role in the asthenosphere, but composition must play an important role deeper in the upper mantle. Evidence of compositional heterogeneity in the East African upper mantle is preserved in the Fe, Mn, Ca, and Ni content of olivine crystals in lavas. We have found that Fe/Mn (42-95) extends to values well-outside fields accepted for olivine crystals derived from peridotite-sourced melt, and are therefore evidence of a significant role for non-peridotite lithologies such as pyroxenite in generating melts in the East African upper mantle. The precise location of such lithologies remains equivocal as they may reside in the metasomatized continental lithospheric mantle, or be derived by the reaction with surrounding peridotite of recycled oceanic slabs upwelling in the African super-plume. Recycled materials upwelling within the African super-plume likely contain carbonate, which may generate CO_2-rich melts and associated low-velocity anomalies at depths significantly greater than that of volatile-free mantle lithologies. In the absence of sufficient thermal anomaly, we suggest that CO_2-driven partial melting is a likely mechanism to explain both the depth extent and magnitude of seismic anomalies in the East African upper mantle.

Seismically Imaging Destruction of Continental Lithosphere beneath the Ethiopian and Afar Rift Systems

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Session: MLI

Heating, melting, and stretching destroy continents at volcanic rifts. Mantle plumes are often invoked to thermally weaken the continental lithosphere and accommodate rifting through the influx of magma. However the relative effects of mechanical stretching vs. melt infiltration and weakening are not well quantified during the evolution of rifting. Beneath Afar, Ethiopia continental breakup transitions to oceanic spreading, and observed active volcanism is generally thought to have a plume source, although the location and degree of plume influence today are debated. We analyze three broadband datasets using S-to-p (Sp) imaging, which provide high resolution imaging beneath the rift and surrounding regions: the Ethiopia/Kenya Broadband Seismic Experiment (EKBSE), the Ethiopia Afar Geophysical Lithospheric Experiment (EAGLE), and a new UK/US led deployment of 46 stations in the Afar depression and surrounding area. We use two methodologies to investigate structure and locate robust features: 1) binning by conversion point and then simultaneous deconvolution in the frequency domain, and 2) extended multitaper followed by migration and stacking. We image a lithosphere-asthenosphere boundary at ~75 km beneath the flank of the rift vs. its complete absence beneath the rift, where the mantle lithosphere has been totally destroyed. Instead a strong velocity increase with depth at ~75 km depth matches geodynamic model predictions for a drop in melt percentage at the onset of decompression melting. The shallow depth of the onset of melting is consistent with a mantle potential temperature = 1350 - 1400°C, i.e., typical for adiabatic decompression melting. Therefore although a plume initially destroyed the mantle lithosphere, its influence directly beneath Afar today is minimal. Volcanism continues via adiabatic decompression melting assisted by strong melt buoyancy effects. Afar is an end member of active rifting in which the mantle lithosphere has been completely destroyed, quite different from

the stretched but intact lithosphere that has recently been imaged beneath the Salton Trough of California, an extensional environment where tectonic forces dominate. Improved high resolution imaging of rifting in a variety of stages and tectonic settings will increase constraints on the evolution of driving forces and the factors that dictate the style of continental breakup.

Exploration of the Butiaba- Victoria-Nile Play, Albert Rift Basin Uganda

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Session: RES

Exploration of the northern areas of the Albert Rift Basin straddling the Victoria Nile River in Exploration Areas 1 (EA-1) and the northern portion of Exploration Area 2 (EA-2) began in 2007 with the acquisition of a fairly sparse grid of 2-D seismic lines by Tullow, the operator of EA-2 and Heritage, the operator of EA-1. Interpretation of this data revealed a predominance of NW-SE trending normal faults cross cut by secondary E-W trending faults. The intersection of these two fault trends combined with the consistent structural dip towards the SW led to the definition of a number of triangular shaped fault traps each bounded by two faults with monoclinal dip towards the SW. Some of these potential traps were supported by strong seismic amplitude anomalies at various levels in the interval of strata just above the base of the rift fill. Prospects identified at the time include, Ngege, Kasamene, Kigogole, Ngiri (Warthog), Rii (Giraffe) and Jobi (Buffalo).

The first exploration boreholes to be drilled within this play area were Ngege-1, Kasamene-1 drilled in mid 2008 by Tullow in EA-2. The former was a minor oil discovery in Upper Pliocene fluvio-alluvial reservoirs just above the basement with the latter being more a promising discovery in high quality fluvial channel sandstones within the same interval. Kasamene-1 was sidetracked and the reservoir section cored. This was followed by another discovery at Kigogole-1 before drilling activity switched to EA-1.

The first well to be drilled by Heritage was Ngiri-1 in the portion of EA-1 south of the Victoria Nile. This well was a promising discovery similar to the Kasamene-1 well. Activity then moved to the north of the Victoria Nile and the Most significant discovery so far was made at the Jobi-1 and Rii-1 well which were drilled at the end of 2008 and have been shown to have intersected the same large oil field. Tullow commenced drilling in mid 2009 in EA-2 and made further discoveries at Nsoga-1, Wahrindi-1 and Ngara-1 and also started an ongoing appraisal drilling program with successful wells drilled so far at Kigogole-3 and 5, Nsoga-5, Kasamene-2 , 3 and 3A and Ngiri-2.

Exploration by Tullow and Heritage over the past 3 years has opened up a major new oil play fairway in the Victoria-Nile region with potential reserves currently estimated at about 750MMBO. An extensive appraisal/development programme including extensive 2-D and 3-D seismic acquisition and further exploration drilling aimed at extending the play area are ongoing with first oil production expected to commence by the end of 2011.

The role of melt induced lithospheric weakening on the dynamics of continental rifting

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Session: AMR

Active or passive continental rifting is accompanied by lithospheric weakening and thinning, ascent of asthenosphere and decompressional melting. Melt percolates through the partially molten source region, accumulates beneath its top and is extracted. After extraction it may either be extruded at the surface or intruded at any depth between the top of the melting zone and the surface. In case of intrusion the release of latent and internal heat heats up the lithosphere and weakens it. In a feed-back mechanism this weakening may assist rifting and melt production. First a one-dimensional kinematic lithospheric thinning model is developed including decompressional melting and intrusional magma deposition at shallower depth, as well as compaction and decompaction. The intrusional heating effect is determined as a function of lithospheric thinning rate. It is found that the maximum temperature due to this heating effect increases approximately proportional to the square root of the thinning rate, which may be expressed as a thinning Peclet number. Then, two-dimensional numerical extension models of the continental lithosphere-asthenosphere system are carried out based on Eulerian visco-plastic formulation. The conservation equations of mass, momentum and energy are solved for a multi-component (crust-mantle) two-phase (melt-matrix) system. Temperature-, pressure-, and stress-dependent rheology is used based on laboratory data for granite, pyroxenite and olivine, representing the upper crust, lower crust, and mantle, respectively. Rifting is modelled by externally applying a constant rate of extension. Model series are carried out in which the emplacement depth of extracted melts is varied between the top of the melting zone and the surface. As predicted by the 1D kinematic models it is found that in comparison with cases without melt intrusions these lithospheric regions may be heated by up to several 100 K. Furthermore, this heating enhances viscous weakening by one order of magnitude or more. Consequently, in a feed-back mechanism rifting is dynamically enforced, leading to a significant increase of rift induced melt generation.

The Lake Malawi Scientific Drilling Project: Long-term records of extension and magmatism in the western branch of the Great Rift

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Session: CLI

The Lake Malawi Rift is the dominant extensional feature of the southern part of the western branch of the East African Rift. Scientific drilling in Lake Malawi in 2005 produced more than 600 m of core, including a 380-m hole in the upper sedimentary section at a site in 600 m of water. These continuous cores from two sites in the rift record 1.2 million years of extension, climate variability and episodic volcanic activity in a part of the rift that is known to be relatively amagmatic. Two sites drill in the lake in the northern and central basins of the lake preserve evidence of episodic volcanism from the Rungwe Volcanic complex located to the north of the lake.

Sediment types recovered in the cores vary from organic-rich, finely-laminated muds, deposited during intervals of high-productivity in a deep, stratified lake, to dense, massive, carbonate-rich, and organic matter-poor intervals deposited during periods of very low lake levels. Tephras are a maximum of 5 cm in thickness at the northern site, and less than 2 cm in thickness at the more remote central basin site (~300 km from the volcanic complex). During extreme low lake stages, waters levels were reduced 550 m or more (lake volume reductions of at least ~98%). The dramatic climate shifts included periods of megadrought, and occurred more than 20 times in the past ~million years. Such climate-driven variability, linked to orbitally-driven changes in insolation, led to repeated, extreme changes in both rift valley landscapes and lacustrine benthic habitats. Preservation of tephras observed at various intervals in cores was likely influenced by these pronounced climate and landscape variations. Future scientific lake drilling planned for other parts of the Great Rift Valley can contribute high-fidelity histories of extensional magmatic activity, in addition to records of tectonic and climatic changes.

State of the art geophysical data acquisition; the first step to unlocking the petroleum potential of the volcanically influenced eastern arm of the East African Rift

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Session: RES

In an attempt to replicate success in Uganda, Tullow Oil acquired license areas in the eastern arm of the East African Rift, with coverage extending from southern Ethiopia (South Omo and Chew Bahir Basins), to Northern Kenya (Lake Turkana and surrounding basins).

Northern Turkana and Southern Ethiopia are located between two intersecting rift systems. An older east-west trending Cretaceous Rift extending from Southern Sudan to the Lamu Embayment on the Kenyan coast, is cross-cut by the north-south trending Tertiary East African Rift System. There has been a fair amount of academic research in the Gregory Rift and Northern Ethiopia, but very limited work has been done over Southern Ethiopia, and in particular, the intersection of these two major rift systems.

Understanding structural development within this major rift intersection is further complicated by a history of volcanism dating back to 45-35Ma. It is important that we consider the affect of volcanic activity, not only on data acquisition, but also during interpretation and modelling of potential petroleum plays.

Tullow Oil acquired Full Tensor Gravity data (FTG) upfront in order to plan seismic programs, since FTG defines the basin geometry, especially in areas where volcanics adversely affect seismic imaging of the subsurface. The FTG data included magnetic acquisition which helps us distinguish probable igneous related gravity anomalies from basement highs and rotated fault blocks that might be of interest as prospect leads.

The FTG has been integrated with all other available data to create paleao-environmental interpretations within the rift. These studies facilitate our understanding of potential source, seal and reservoir sequences in the basin, thereby providing insight for planning and optimising seismic surveys over target areas within this complex geological setting.

Anatomy of Iceland's Volcanoes: Crustal Deformation and Magma Movements

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Session: AMR

Iceland has over 30 volcanic systems of different character, providing opportunities to study magma movements and associated crustal deformation in sub-aerial segments of the slow spreading Mid-Atlantic ridge. Space geodetic techniques, precise Global Positioning System geodesy as well as interferometric analysis of synthetic aperture radar images (InSAR) have been extensively used to reveal deformation patterns. These have been interpreted in terms of models of magma transport and storage; an integral element in understanding volcano dynamics.

Some of the most active central volcanoes in Iceland (including Grímsvötn, Hekla, Krafla, Askja) show persistent “reversible” deformation pattern of inter-eruptive gradual inflation (mm and cm/yr), and sudden co-eruptive deflation (typically tens of cm). This kind of deformation pattern is interpreted in terms of pressure change in crustal magma chambers at a depth of 2-20 km, which receive inflow of magma continuously or intermittently over years until a breaking limit is received; then an eruption or dike intrusion occurs. Deformation pattern during the Krafla rifting episode 1975-1984 is of this type, as well as at Grímsvötn prior to and in relation to its eruption in 1988, 2004 and 2011.

Less active central volcanoes may have a different plumbing system, where one single magma chamber does not receive all magma inflow; rather initial signs of renewed activity may be individual magmatic intrusions stalling at different locations. This was the case prior to the Eyjafjallajökull eruption in 2010; magma had been intruding intermittently over a period of 18 years prior to the catastrophic explosive eruption that caused the widespread airspace closure. That eruption was finally triggered when intruding basaltic magma interacted with residing more evolved magma under the summit area of the volcano.

Magmatic intrusions can occur outside the central volcanoes in still less active part of the plate boundary. A well documented case of such an intrusion occurred in 2007-2008 in the lower crust north of the Vatnajökull ice cap at 12-18 km depth, below the otherwise brittle-ductile boundary of the crust. In that case, the dike plane appears to have formed in direction perpendicular to the least compressive deviatoric stress setup in the crust due to present day glacial retreat, caused by warming climate. Magma movements in Iceland are therefore not only influenced by plate tectonic process; presently they are also influenced by retreating ice caps.

The observations of crustal movements and magma dynamics in Iceland are put into context of models for generation of the oceanic crust at slow spreading oceanic ridges in general.

Insights into the Spatial and Temporal Geometry of Subaxial Magma Reservoirs and Diking Processes from Individual Volcanic Eruptions along Mid-Ocean Ridges

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Session: MOR

Variations in chemical composition of lava flow fields produced during single eruptive events on the seafloor provide direct evidence of the contemporaneous heterogeneity of the magma reservoirs that feed them. Along-axis gradients in Mg# within flow fields of the early 1990's Aldo-Kihi eruption at 17.5°S EPR, the 1991-2 and 2005-6 eruptions at 9°50'N EPR, the 1993 Co-Axial eruption of Juan de Fuca Ridge, and the 1996 N. Gorda eruption are unlikely to be related to fractionation during emplacement. Rather they reflect temperature variations in sub-axial magma reservoirs prior to eruption. This observation has implications for the limits and time-scales of mixing within sub-axial reservoirs beneath mid-ocean ridges. Variations in mantle-derived isotopic and trace element ratios (including short-lived radioisotopes) within the Aldo-Kihi eruption suggest recent injection (within 20 years prior to 1993) and limited along-axis mixing with resident magma lying 1-1.5 km deep in the crust. The spatial variation in these tracers suggests 10-15-km spacing of recent injection centers to the crust. The preservation of likely reservoir properties in lava flow fields on the surface requires near-vertical (< ~1 km lateral) transport of magma. Similarly, there are striking correlations of changes in flow field chemical compositions across boundaries in surface geological structures or seismically imaged sub-axial magma chamber reflectors in the S. Hump (S. EPR), 9°50'N EPR, N. Gorda and 1975-1984 Krafla (N. Iceland) eruptive units. These spatial correlations between surface lava compositions, volcanic structures, and sub-axial magma chamber properties, likewise suggest near-vertical transport of erupted magma from the underlying reservoirs to the surface. In the case of the Krafla eruption, coincident deformation suggests a component of lateral melt migration at depth, despite chemical evidence for vertical transport of erupted lava from two chemically distinct reservoirs. In addition, along-ridge migration of earthquake epicenters during the 1993 Co-Axial and 1996 Gorda eruptions implies migration of stress release during these eruptions, even though vertical transport better explains chemical patterns. Significant lateral transport of magma can accompany diking events that do not lead to eruption, and the evidence for vertical magma transport applies only to those lava flow fields that retain systematic chemical variations within them. Homogeneous lava flow fields can arise either from homogeneous magma reservoirs or significant mixing during diking and emplacement.

Co- to Post-diking deformation in the Manda-Hararo rift (Afar, Ethiopia): insights from high-resolution InSAR time-series

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Session: AMR

The 2005-2010 rifting episode in Manda-Hararo (Afar Ethiopia) generated the intrusion of a series of 13 lateral dikes that could be monitored with an unprecedented resolution using SAR interferometry and local seismic networks. Between these magmatic intrusions, that lasted each no more than a few hours, the ground deformation is going on in the rift area, revealing a complex pattern. InSAR time series show the inflation or deflation of 6 deep magma sources that constitute the plumbing system active during the rifting episode. In particular at the center of the rift, transient ground movements are consistent with the slow opening and inflation of a 3-4km deep source of magma. The detailed analysis of the dynamics of this source of magma conducted to interpret it as the central magma chamber, responsible for the feeding of most of the dikes that were emplaced during the rifting episode. Only the initial mega-dyke emplaced in September 2005 showed clear interaction with other deep magma sources, indicating that its feeding required additional sources of magma.

Following the “instantaneous” diking events, full resolution SAR interferograms image the deformation going on in the rift area, away from these well-individualized deep magma chambers. The monitored movements are compatible with slow, residual dike expansion at shallow depth, occurring in the months following the main dike injection, that likely generates creep on the dense network of normal faults that controls the rift topography. We describe the evolution of faults growth following the 2005 mega dyke intrusion, correlate it with the faults segmentation as defined by detailed faults mapping and discuss the implications in terms of topography generation and magma – faults interactions.

Mapping and characterising volcanic risk

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Session: HAZ

Assessing volcanic risk requires the integration of information on hazard, exposure, vulnerability and capacity. Risk can be defined in diverse ways; e.g. loss of life, threats to critical infrastructure, economic losses and adverse effects on sustainable livelihoods. We present the results of a pilot study on the risk posed by volcanoes in the priority countries of the Global Facility for Disaster Reduction and Recovery (GFDRR) of the World Bank, which included Ethiopia. The aim of the study was to establish science-based evidence for better integration of volcanic risks in national Disaster Risk Reduction (DRR) programmes in priority countries, as well as regional cooperation in DRR programmes for all countries supported under GFDRR. The study comprised a preliminary assessment of the potential volcanic eruption impacts in the GFDRR priority countries, assessment of exposure of population and important infrastructure to various volcano hazards, and an assessment of the national capacities to cope with the volcano risk. A method for measuring the physical threat posed by individual volcanoes inside the GFDRR priority countries was developed. The method is used to assign each volcano to a Hazard Level 1, 2 or 3 and an Uncertainty Level 1, 2 or 3. Additionally, a Population Exposure Index was applied for measuring the number of people threatened by each volcano in order to give an indicator of population vulnerability. A simple estimate of population risk for each volcano was computed by combining the Hazard Level and Population Exposure Index. Data on magnitudes and ages of explosive volcanic eruptions was used to estimate global and regional recurrence rates of large magnitude volcanic eruptions. The project also evaluated a Monitoring Index with four levels from no or minimal monitoring (level 0) to well-monitored (level 3). Sixty-five Holocene volcanoes have been identified in Ethiopia, 34 classifying as predominantly effusive and the remainder having records of significant explosive eruptions. Historic records indicate about 160 fatalities in 3 eruptions, the greatest loss of life being in Dubbi in 1861. 9.5 million people live within 30 km of an active volcano in Ethiopia but these volcanoes yield ostensibly low and medium Hazard Levels. This is misleading as most of the volcanoes have little or no detailed documented volcanic history or geology resulting in high Uncertainty Indices. Using the Population Exposure Index, five volcanoes classify as high risk: Bilate River Field; Bishoftu Volcanic Field; Butajiri-Silti Field; Corbetti Caldera; and Hobicha Caldera. However, this analysis likely underestimates the number of high risk volcanoes due to poor baseline geological and hazard knowledge. Return periods of explosive eruptions in Ethiopia are estimated at 7 years (VEI3) 29 years (VEI4) and 100 years (VEI4). Using the monitoring criteria, all Ethiopian volcanoes are assigned Monitoring Level 0. Taken together the analysis indicates an urgent need for investment in hazard assessment and monitoring to characterize and address volcanic risk in Ethiopia.

The crustal structure of Afar: what does it tell us about rift evolution?

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Session: AMR

Crustal structure evolves as rifting progresses to seafloor spreading. Imaging this change will help control models of continental break-up. The recent Afar Consortium seismic experiment provided a unique opportunity to determine crustal structure beneath the Afar Depression: a region of the Earth where the effects of extension and magmatism on the crust are seen on land. Here we present our recent results from receiver function analysis and surface wave tomography.

Receiver functions show a crust between 20 km and 26 km thick in southern and central Afar, outside the magmatically and tectonically active rift segments. Beneath the incipient oceanic spreading segments in the Danakil the crust thins to <16 km. The crust thickens dramatically across the border faults to ~40 km beneath the western plateau and ~35 km for the southeastern plateau. For crustal thicknesses < 26 km the average crustal Vp /Vs ratios of greater than 2.0 are indicative of partial melt, signifying large amounts of magmatic intrusions in the lower crust. The western plateau shows crustal Vp /Vs ratios ranging between 1.7 and 1.9, suggesting a maficaltered crust, probably associated either with Cenozoic flood basalts, or current magmatism. The southeastern plateau, on the other hand, shows Vp /Vs more typical of silicic continental crust (~1.78). surface wave inversions highlight similar low velocities close to active magmatic segments.

Our Rayleigh wave group velocity tomography images significant low velocity anomalies within the crust below the sites of recent dyke intrusions or magmatic activity. We invert two typical group velocity curves to compare the Vs crustal structure within an active magmatic segment with that of adjacent areas; the active region has a low velocity zone (Vs ~3.2 km/s), between about 6 – 12 km, which we infer to be due to the presence of partial melt within the crust.

Our study highlights the importance of magma injection into the crust during rifting episodes and suggests that emplacement of melt plays an important role in late stage rifting. Our results

suggest that eastern Afar contains less partial melt, has undergone less stretching/extension and has preserved a more continental crustal signature than the region to the west of the current rift axis. The Red Sea rift axis appears to have migrated eastward through time to accommodate the migration of the Afar triple junction.

Using microearthquakes to track repeated magma intrusions beneath the Eyjafjallajökull volcano, Iceland

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Session: AMR

We have mapped several thousand microearthquakes caused by magma migration beneath the Eyjafjallajökull volcano in South Iceland prior to, and during, the eruptions in March–June 2010. We have located earthquake hypocentres using an automatic Coalescence Microseismic Mapping technique and then refined a subset of these by manual picking and double-difference relative relocation. Spatial and temporal clustering of 5,000 microearthquakes under the eastern flank of the volcano illuminates several northeast–southwest striking sub-vertical dykes at 2–6 km b.s.l., emplaced before the March 2010 Fimmvörðuháls flank eruption. Subsequently, during the April–May explosive summit eruption, microearthquakes extended from the upper mantle at ~30 km depth to the summit crater, on a sub-linear trend inclined ~5–10° from vertical. All microearthquakes display characteristics of brittle fracture, despite many events being at depths that would be in the ductile regime for normal tectonic strain rates. This supports the interpretation that the seismicity is caused by locally high strain rates that are induced by magma migration through the crust. Several subsets of earthquakes exhibit closely similar waveforms within clusters. This suggests similar, repetitive source processes. The deeper microearthquake clusters may be caused by fracturing solidified magma plugs that form constrictions in an otherwise aseismic melt conduit. Or they may occur at exit points from melt pockets, in which case they indicate positions of magma storage at depth. The deep seismicity starts three weeks after the onset of the summit eruption, after which the largest clusters occur at progressively greater depths. This temporal pattern may result from pressure release at shallow levels in the magmatic plumbing system progressively feeding down to mobilize deeper melt pockets.

Counterclockwise Block Rotation Linked to Southward Right-Stepping Propagation And Overlap of The Red Sea Rift Segments at The Nascent Passive Margin, Afar Depression; Insight From Paleomagnetism.

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Session: AMR

Thirty-four cooling units from the Pleistocene extrusive volcanic rocks in the northwestern central Afar depression were sampled for paleomagnetic study. Most of the samples are collected from Kori and North of Saha region, where they are bounded to the west by the active magmatic segments of Dabbahu and Northern Manda Hararo segment; to the northwest by the Alayta segment and to the northeast by the Tat'ale magmatic segment. While some of the samples are collected from south of Afdera, located within the southern continuation of the Tat'ale magmatic segment. Seven to twelve samples were collected from each cooling unit and on average 5 samples per unit were treated with Alternating Field (AF) demagnetizations while one sample was treated by Thermal (TH) demagnetization technique for a check, all at the department of Earth Sciences of Addis Ababa University. The Natural Remanent Magnetization (NRM) direction reveals two simple and straightforward components of magnetizations. Generally, the first and low stability component is isolated by heating to 100°C-300°C or by AF of 10-20mT. The magnetization directions after these steps have defined straight lines that are directed towards the origin, which are then interpreted as primary NRM or ChRM (Characteristic Remanent Magnetization). Results of the magnetization decay curve plots and rock magnetic analyses using Variable Field Translation Balance (VFTB) at the paleomagnetic laboratory of LMU, Germany indicate magnetic mineralogy is dominated by titanium poor titano-magnetite and magnetite with magnetic grain sizes with in the pseudo single domain range. The paleomagnetic site mean directional analyses reveal, 3 reversed, 30 normal and 1 transitional direction. When an overall mean direction calculated for the entire sampled region excluding one of the most removed transitional direction resulted in; D=355.8^0, I=12.0^0, N=33, K=31.1, α_{95}=4.5^0, and a separate mean direction for Saha and Kori area, found between magmatic segments above; D=354.2^0, I=13.8^0, N=26, K=39.3, α_{95}=4.6^0 is obtained, which when compared with expected Geomagnetic Axial Dipole (GAD) Field from Apparent Polar Wander Path (APWP) Curve (Besse & Courtillot, 1991, 2003), a difference in declination ΔD = -6.7^0 ± 5.1^0 is obtained for the latter. This negative declination difference is interpreted as counterclockwise rotation about a vertical axis, in agreement with rift propagation and right stepping overlap geometry of the Alayta – Dabbahu magmatic segments. An overall mean direction for the north of Silsa and Afdera area indicates; D=2.5^0, I=1.2^0, N=8, K=23.6, α_{95}=11.6^0, with ΔD = 1.6^0 ± 11.8^0, showing statistically insignificant rotation consistent with what is expected with in the propagators (Tat'ale segment) and with what were previously reported (Acton et al. 2000; Kidane et al. 2003). Moreover, two short magnetostratigraphic sections in the Silsa and Afdera area reveals both normal and reversed

magnetozones and using available age information (Lahitte et al. 2003) and the Geomagnetic Polarity Time Scale (GPTS) of Cande & Kent (1995) these reversals are respectively dated at about 0.8 and 0.2 Ma.

The lithospheric structure beneath mature continental rifts : New insights from a dense seismic profile across the Asal-Ghoubbet rift (Djibouti)

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Session: AMR

The Asal-Ghoubbet Rift in Djibouti is a young segment on land at the propagating tip of the Aden Ridge. This segment represents an ideal laboratory to observe the mechanisms of extension and the structural evolutions involved, from the continental break-up to the first stage of oceanic spreading. However, we lack first order information about the crustal and upper mantle structure in this region, which for example prevent detailed numerical modeling of the deformations observed at the surface.

From November 2009 to March 2011 we have deployed a temporary network of 31 seismic stations along a 150 km-long profile. Station spacing varies from 25 km on the edges to less than 1 km in the central part of the rift where we expect rapid variations of the lithospheric structures. Most of the stations were equipped with a broadband sensor and recorded in a continuous mode.

Here we present some preliminary results deduced from the analysis of receiver functions and from a surface wave tomography obtained from the cross correlation of seismic noise between stations. These two techniques are complementary each other and have been used in a linked inversion scheme to deduce an absolute velocity-depth profile in the central part of the rift. Two major interfaces are observed at ~12 and ~23km depth, both corresponding to a velocity contrast in the range of what would be expected for the Moho. We also observe a strong low velocity layer between these two interfaces, which also exhibits an abnormally high Poisson's ratio. This probably indicates the presence of partially molten rocks in a magmatic reservoir either within or just below the crust. Other low velocity layers are also observed at shallower and deeper depths and are confined to the central part of the rift. These observations confirm the strong role played by magmatic intrusions in the deformation pattern observed at the surface.

Development of central volcanoes and rift axial volcanism in the Manda-Hararo rift segment, Afar, Ethiopia

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Session: HAZ

The Manda-Hararo rift segment in Afar (Ethiopia) has been actively undergoing a concentrated period of dyke injection, extension and volcanism since an initial fissure event in 2005. We present the results of a detailed mapping, remote sensing, geochemistry and geochronology project to characterise the spatial and temporal distribution of volcanism in this rift segment. Constraining the extent, volume and architecture of volcanism from both central volcanic complexes and rift axial fissures compliment the multi-disciplinary research themes of the Afar Rift Consortium to investigate the interplay between tectonism and magmatism in this active extensional setting at the continental-oceanic crust transition.

We establish the eruption history of the Manda-Hararo rift segment at the scale of individual eruption units through the use of 3D visualisation and remote sensing data. These enable identification of the structures, textures and spectral signatures of volcanic complexes that can be combined with fieldwork to ground validate the composition, character and age of lavas. Results from these investigations show a spread of eruption sites, vent character, and young volcanic ages (<10 ka) dispersed throughout the segment suggesting that crustal accretion is not limited to the central spreading centre. This observation is similar to models of slow-spreading magmatic mid-ocean ridge (MOR) segments, in contrast to repetitive eruptions from central fissure vents in fast-spreading MORs. Linear basaltic fissure vents dominate the topographic rift axis whilst point source basaltic vents are located up to 7 km away from the rift axis. Off axis central volcanic complexes host the products of young eruptions that are up to 12 km from the centre. Detailed mapping of these units is combined with models of subsurface melt bodies and plumbing systems to provide an insight into the evolution of magmatism and volcanism over time within the Manda-Hararo rift segment. This information will be used for hazard planning in combination with real time data provided by EVOSS (European Volcano Observatory Space Services) to colleagues in Ethiopia.

Dynamics of dyke intrusion in the northern volcanic rift zone of Iceland

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Session: AMR

We have captured a remarkable sequence of microearthquakes showing progressive melt intrusion of a dyke into the mid-crust of the northern volcanic rift zone in Iceland. The seismicity was recorded on a 27-seismometer array and was caused by a dyke intruding at 50° dip from 18 km to 13 km depth on the Icelandic rift. Moment tensor solutions show double-couple failure, with fault mechanisms sometimes flipping between normal and reverse faulting within minutes in the same location. The inferred fault planes from microearthquakes align precisely with the overall plane of the dyke delineated by hypocentres. We attribute the seismicity to melt injecting along the dyke, sometimes breaking plugs of previously frozen melt. Changes in fault polarity are caused either by breaking the plugs of frozen melt or by dyke propagation above a deflating sill.

Although the crust at these depths is normally aseismic, high strain rates as melt intrudes generate microearthquakes up to a maximum of magnitude 2.2, although most are much smaller than this. Melt injection occurs in bursts propagating at 2–3 m/min along channels 0.15–0.20 m wide, producing swarms of microearthquakes lasting several hours. Intervening quiescent periods last tens to hundreds of hours. I discuss a new rheological model for the dyke propagation which explains both this episodicity in microseismicity and the orientation of failure planes. We have captured the igneous crust in the process of being generated by melt moving upward along an inclined plane from a sill at 18 km depth to another shallower crustal sill at 13 km depth, where it froze in situ.

Geotourism in Afar and the Ethiopian Rift Valley

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Session: RES

Ethiopia, with its unique location at a tectonic triple junction and its abundance of spectacular geological features, has great potential for geotourism. Afar and the Rift Valley in particular are of exceptional geological significance and this talk will focus on the potential for, and challenges faced by, geotourism in these two regions.

Geotourism aims to stimulate the interest of all visitors, whether or not they have a prior interest in geology, in the geological features around them, and to attract visitors to sites of particular geological interest. This requires the provision of facilities such as transport, access, accommodation, security and, most importantly, information about the sites to be visited.

The two localities under consideration face different challenges in the provision of such facilities. The Rift Valley is readily accessible and a variety of accommodation is available. Afar on the other hand, and especially its most spectacular geological attraction, the active volcano Erta Ale, is accessible only to the more adventurous visitor. Accommodation and other facilities are lacking and security can be an issue. But a fundamental problem common to both localities is lack of geological information. Although a great deal of specialist geological literature exists, there is almost nothing available for the general reader. Few of the many visitors to the Rift Valley are aware of its geological significance and the geological features that abound. Although even the most casual visitor to Afar cannot fail to be aware of its geologically activity, and to be impressed by its salt lakes, lava flows, hotsprings and active volcanism, s/he is provided with little or no information as to how these features came about, or of the unique situation of Afar in the scheme of global tectonics.

In this talk it is suggested that the first step in the promotion of geotourism in these regions should be to provide information in a form that is attractive and easily assimilated by the non-specialist visitor. Some steps have already been taken in this direction, and further suggestions will be put forward.

As well as provision of facilities and information, promotion of geotourism necessitates protection of geological sites. This issue urgently needs addressing in both of the localities under discussion. It is important that government and local authorities are aware of their tourist potential, and are encouraged to take steps to preserve them as geological monuments and to establish procedures for their sustainable development as tourist attractions. Not only will this encourage visitors, it will also benefit local communities. Already a number of Afar villagers, recognising the attraction of their region to tourists, have begun to take advantage of the situation by providing simple facilities. Encouragement of and assistance with these initiatives, together with site protection, facilitation of access and provision of information will enrich the experience of every visitor and bring much needed tourist revenue to Ethiopia and particularly to some of its less privileged communities.

Evidence for melt infiltration of the mantle lithosphere beneath the East African Rift from receiver functions, seismic anisotropy, and petrological modeling

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Session: AMR

A number of seismological studies in East Africa have focused on the northern and eastern branches of the East African Rift System (EARS). However, the seismic activity along the western branch is much more pronounced. Here, the Rwenzori Mountains, at the border between Uganda and the D.R. of Congo, are unusual as they are situated within the graben and reach elevations of up to 5100 m. We have analysed data from local and teleseismic earthquakes to study the lithospheric structure beneath the rift and its surroundings. P-wave receiver functions reveal that the crustal thickness decreases from 32 km beneath the rift shoulders to about 24 km beneath the rift. The analysis of S-wave receiver functions provides evidence for two consecutive discontinuities at depths of 50-100 km and 140-200 km, which correspond to significant S-wave velocity reductions under the Tanzania craton and the Albertine Rift. Conversion depths decrease from the Tanzania craton towards the rift. By comparison with synthetic waveforms we show that the lower discontinuity likely coincides with the LAB, whereas the shallower discontinuity marks a melt-infiltration front, i.e. the upper boundary of the altered lower lithosphere. This is further supported by modeling of S-velocity variations based on xenolith samples which exhibit a dense system of veins acting as pathways of the infiltrating melt. Additional evidence for subcrustal lithospheric alteration comes from the analysis of teleseismic shear waves which exhibit relatively uniform fast polarizations oriented parallel to the rift axis. Splitting analyses from local events show that anisotropy within the crust and uppermost mantle does not contribute significantly to the observations. Also, the splitting observations cannot be explained by assumptions on asthenospheric mantle flow for the region. We therefore favour models of anisotropy related to rift-parallel dykes or veins ascending from the asthenosphere and infiltrating the lower lithosphere to depths of about 50 km. The observation of mantle earthquakes at this depth may be indicative of magmatic fracturing during dyke emplacement.

Witnessing the birth of a new ocean? The first 6 years of the Dabbahu rifting episode, and other activity in Afar

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Session: AMR

Intense earthquake activity and a small rhyolitic eruption in September 2005 heralded the onset of an unprecedented period of geological activity in the Afar Depression. The seismic activity accompanied dyke intrusion in the upper 10 km of crust along 60 km of the Dabbahu (northern Manda-Hararo) Magmatic Segment (DMS) of the Nubia-Arabia plate boundary, a nascent seafloor spreading centre. InSAR observations of the resulting deformation showed that the initial dyke was up to 8 m thick, with a total volume of 2-2.5 km^3. Urgency funding from the UK Natural Environmental Research Council (NERC) and US National Science Foundation (NSF) enabled us to deploy a local array of seismometers in October 2005, continuous GPS instruments in January 2006, and to acquire a dense time series of satellite radar images. The medium-term viability of these instruments was secured with major follow-on funding from NSF and NERC; these projects supported the collection and analysis of additional unique data sets, including data from a broader array of seismic and GPS instruments, magneto-telluric transects of the rift, airborne LiDAR, petrological sampling and micro-gravity work. The combination of these data has allowed us to quantify the processes associated with crustal growth at divergent plate boundaries for the first time.

Here, we present a broad overview of geological activity in the Afar depression in the hyperactive 21st century. Activity in the DMS began after September 2000, when Gabho volcano at the north of the segment began uplifting, as its magma chamber, ~3 km below the surface, was replenished. It is likely that the inflation at Gabho ultimately triggered the onset of the Dabbahu

rifting episode. The rifting episode began with intense seismicity at the northern end of the DMS, before jumping to the Ado Ale Volcanic Complex at the segment centre. This initial dyking was fed from shallow (~3 km) chambers at Gabho and Dabbahu as well as a deeper (~10 km) source at Ado Ale. The initial dyke was followed by a sequence of smaller dyke intrusions, which began in June 2006. To date, there have been 14 dyke intrusions in total, with the most recent occurring in May 2010. These later dykes were typically 2-3 m thick and 10-15 km long, and have a cumulative volume approaching 1 km3. Three dykes broke the surface to produce basaltic fissural eruptions. Seismicity data show that they were all fed from the AVC and propagated at rates of 0.2 – 0.5 m/s. Overall, the locations of the dyke intrusions appear to be guided by tectonic driving stress, with the later dykes filling in areas that opened less in the initial dyke. However, the location of individual dyke intrusions is also influenced by their immediate predecessor.

Activity in the 21st century in Afar has not been restricted to the Dabbahu Magmatic Segment. In the Erta Ale Magmatic Segment (EMS), a large basaltic eruption occurred at the Alu-Dalafilla range in November 2008, and the Erta Ale lava lake itself overflowed in November 2010. In addition, we have recently identified a shallow dyke intrusion at the north of the EMS, which propagated south from Dallol in 2004. Further afield, Nabro volcano in Eritrea, near the border with Eritrea, began erupting explosively in June 2011. Many of the eruptions were first detected by satellite observations of SO_2 emissions and thermal hotspots, which enabled reliable alerts to be transmitted to local and national authorities, sometimes before eye-witness reports were communicated. Nabro was the 7th eruption in Afar in less than 6 years.

An intense and immense collaborative effort involving numerous Ethiopian and international scientists, with crucial support from local and national authorities, has enabled us to document and learn from this unique period of activity in Afar.

Poster session

Remote sensing and GIS based mapping on landslide phenomena and evaluation of causative factors: a case in the southern Afar escarpment, Ethiopia

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Session: HAZ

Debresina area is one of the most landslide prone sites located in the Southern part of the Afar rift escarpment. Information obtained from woreda administration shows that losses of over 900 hectares of arable lands, displacement of more than 4049 peoples and over 75% crop harvesting failure had been caused by the massive landslide occurred in September 2005. To address this problem, Remote sensing and GIS based mapping and evaluation of landslide is carried out by this study. The main objectives include 1) mapping of the landslide occurrences and the various causative factors such as lithology, structure, land use, slope, elevation and drainage 3) evaluation and correlation of these various variables to slope failures in the area of interest. Aster image of varoius years, Landsat images of 2001, Google earth and detailed field survey are used to prepare the landslide inventory, geology and land use while slope, drainage and elevation maps are drived from the DEM of 30m resolution.

Rainfall (from Ethiopian National Metrological Services Agency) and earthquake (from the United States Geological Survey and Geo-observatory of Addis Ababa University) data were collected to see their triggering effect to the landslide. Analyzing of earthquake data shows that there had been 169 occurrences in an area located between Lat.11.720 - 12.750N and Long. 40.2-40.700E from June to October 2005. This area is found at about 170 to 300km NE of the study area. Several researchers such as Wright et al.(2006); Yirgu et al.(2006); Ayele et al. (2007, 2009); Rowland et al.(2007); Grandin et al.(2009) also reported that a major diking episode occurred in various localities of Afar depression in September 2005 causing a number of associated earthquakes of magnitude ≥ 3.5 mb. Interviews with local people also confirm that the then volcanic explosion and earthquake shake was felt around the study area. Thus, the dominant landslide triggering factor is the earthquake associated to the dike episode of the region.

Results show that more than 140 landslide occurrences are identified. The large scale landslide occurrence in September 2005 has an area of 15km^2. It is very complex and composite type of failure consists of bedrocks, debris and earth materials and has a rotational, translational and combined type of movement. Intense geological structures, deeply weathered basic tuffs, agglomeratic basalts, igimbrite are some of the main causes for the slope failures among the others. Rock slides, debris and earth slide are common occurrences in the slope ranges of 10-25% and 25-35% while the rock falls and toppling dominate in the slopes greater than 35%.

Map overlay techniques and stereonet analysis and field evidence show that landslides of Debresina are mainly controlled by the NNE-SSW, NNW-SSE trending rift margin faults.

Geodetic determination of plate velocity vector in the Ethiopia Rift

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Session: AMR

The Red sea, Gulf of Aden and the Main Ethiopian rift form a triple junction in the Afar Region. Although the East African Rift, the diver-gent plate boundary between Nubian and Somalia, is often cited as a mod-ern archetype for rifting and continental breakup, its current kinematics isthe least known of all major plate boundaries. Moreover, geodetic datum in such tectonically active area is subject to distortion that increases with time. Therefore, a close study of the positions and velocities of reference stations in such tectonic active areas is necessary, if one wants to have high precise geodetic measurement for any developmental activity. In this study phase and pseudo-range GPS measurements were processed to derive the daily solutions of positions in reference to the ITRF05. This solution from 8 continuous stations in Ethiopia, with a length of 0.75 to 3.5 years, is then combined into a cumulative solution with position and velocity estimates. Here a method that combines GPS observation data from 2007 to 2010 to es-timate time-dependent motion of stations in a region of active deformation is implemented. First, observations were analysed separately to produce loosely constrained estimates of station positions and coordinate system parameters which are then combined with appropriate constraints to estimate velocities and co-seismic displacements. The result archived gives a good insight about the velocity at which the three major plates, namely the Nubian, Arabian and Somalia plates are moving with respect to each other. The study shows the relative velocity between Nubia and Somalia plates with 4.6±0.3mm/yr. While, the Nubia and Arabia plates are moving with 33±0.15mm/yr. Beside to the horizontal velocities, the preliminary results of the vertical velocities are shown uplift in the country which will be an important result in further Geodynamic studies.Moreover; positions of stations are computed with high precession for any future reference purpose. Due to short duration of mea-surements at some stations further observation are recommended to compute positions and velocity fields after all stations have data at least for two years time.

Structure, magmatism and rapid breakup of sheared margins

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Session: RCM

Observations of sheared and transtensional margins indicate that continental rupture follows rapidly the onset of pull-apart basin formation. These basins thus develop in a short timespan (often ten million years or less) from continental pull-apart basins into rifted margins. Examples can be found in the Gulf of California where rifting began 15-12 Ma, and individual basins reached breakup between 6-2 Ma. Compared to orthogonal magmatic and magma-poor margins that generally rupture after 15 -70 million years of extension, pull-apart basins thus seem very effective in localizing extensional stresses. Orthogonal rifted margins vary from narrow magma-dominated to wide magma-poor; the same variation in magma volume and structure is found on sheared and transtensional margins. On orthogonal rifted margins such lateral variations in width and magma volume are often explained by thermal anomalies in the mantle, but temperatures are unlikely to vary largely over the small spatial scales of transtensional margins.

We present results of a numerical modeling study in which we address these observations. Three-dimensional crustal models show the evolution of pull-apart basins from their onset to conditions favorable for rupture. The models include two strike-slip faults, and a range of fault overlap and separation configurations are tested. At the onset of shear the models produce separate deposition centers near the strike-slip fault tips, as observed in nature, that under certain conditions may develop rapidly into rupture. The models show how the configuration of strike-slip faults affects the final width of sheared margins.

Seismicity of Afar and the main Ethiopian rift from 2000 to 2002

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Session: HAZ

Earthquakes data recorded between 2000 and 2002 are used to study the seismicity of Ethiopia mainly focused around Afar and the Main Ethiopian rift. The locations of 238 local earthquake are determined using P- and S- wave arrival times recorded on three or more stations that resulted to a maximum of 1.5 root mean square (RMS). Previous studies of seismicity by Brazier et al., 2006 has been revisited using the same data from IRIS/PASSCAL broadband seismic experiments and adding more from ESSN (Ethiopian Seismic Station Network) sources. Comparing the results in this study with Brazier et al., 2006's, it is found that eight bogus events (earthquakes that didn't occur in the real world) and six more teleseismic earthquakes are reported as if they occurred in the Ethiopian neighbourhood. On the other hand, it is observed that Brazier et al's work, which is published in Bulletins of Seismological Society of America (BSSA), reported 25 earthquakes that are located with readings from seismic stations less than three which puts doubt on the accuracy of the seismicity study. Another 53 new earthquakes are identified in the database and located in this study which has improved details of the seismicity of the region for the time period considered.

A Fortran program is written in 0.5 by 0.5 degree window and with 0.5 degree sliding window in order to map the seismic energy release. The distribution of epicentre in this study shows high seismic activity around 90°N and 40.50°E; 9.50°N and 39.50°E during the study period, these epicenters are close to the N - S trending Ankober region, Kessem area and Dofen volcano. Coda magnitudes are also estimated for the reported events. Similarly b-values are estimated using both the least squares method and the maximum likelihood method. b-value of 0.9□□ ± 0.09 and 1.10 were obtained using the maximum-likelihood method and using least square method determined respectively for the highly seismic Ankober-Dofen region during the study period. On the other hand, seismic energy map is developed for the whole region. The relatively high b-value estimated and the seismic energy mapping showed that seismic energy are released in the form of small magnitude.

Geochemistry of the Woranso-Mille Pliocene Basalts and its implications on the evolution of the Afar rift

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Session: AMR

Woranso-Mille (WORMIL) is a relatively new paleontological site located in the northwestern part of the central Afar depression of Ethiopia. The Woranso-Mille multidisciplinary paleontological research project has been conducting extensive geological and paleontological research at the site since 2003. The study area contains sub-horizontal Pliocene volcaniclastic strata consisting of several tuffs interbedded with fossiliferous clastic units as well as various basalt flows. The strata are transected by steeply dipping NW-SE trending normal faults. Multiple basalt flows interbedded with dated tuff layers in the WORMIL area exhibit geochemical features linked with the evolution of the Afar rift. Preliminary geochemical data and major and trace element composition of basalt samples indicate at least two different sources of magma for the various lava flows exposed in the area. Most of the basalt flows older than ~3.7Ma have higher Nb (12-31ppm), Ba (82-215ppm), Zr (120-250ppm), TiO2 (2.0-2.8%) and P2O5 (0.2-0.34%) while those younger than ~3.7 Ma indicate lower Nb (1.5-6ppm), Ba (24-97ppm), Zr (47-72), TiO2 (1.11-1.3%) and P2O5 (0.10-1.17%). The younger basalts have a tholeiitic composition similar to MORB whereas most of the older basalts display characteristics transitional between E-type MORB and within-plate basalt compositions. These geochemical variations are interpreted to indicate a shift from mainly plume-influenced deeper source to extension-related shallower source magmatism of the Afar rift. If so, the WORMIL basalts may represent the precursors of a widespread tholeiitic volcanism characteristic of the Afar Series in the late Pliocene and the Quaternary.

The impact of Red Sea rifting on the northern Arabian Shield

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Session: AMR

The total magnetic intensity (TMI) map of the Red Sea shows that there're rifting activities reflects by large transform faults, which impact on the Arabian Shield by creating a big fold with direction NS.

As known, the sea floor spreading activities separates the Red Sea by transform faults to blocks, each block has different acceleration according to the mantel convection velocity and the crustal fracture criteria of the Red Sea.

In our study we used TMI map associated with satellite image and earthquake distribution along the transform faults northern Arabian Shield.

GRAVIMETRIC EXPLORATION OF THE RIVERA-COCOS BOUNDARY AND THE COLIMA RIFT, WESTERN MEXICO

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Session: AMR

The Rivera-Cocos boundary is ill defined; up to now it has been considered a “diffuse boundary”. Seismicity is spread out in the region where the plates meet, contributing to the lack of definition of the frontier. The Colima rift, also called the Colima graben, has been suggested to be part of the plate’s boundary. It is well defined about a hundred km inland; however, close to the coastal area the presence of the graben is elusive. In the continental platform, also lying along the assumed boundary, there are three well developed canyons: the Manzanillo canyons. Offshore, beyond the Middle America Trench, a graben (El Gordo) showing active volcanism is also aligned with the above structures. We measured the gravimetric field along three lines across the southern Colima graben, sub parallel to the trench, at station separations between 2 and 3 km. A fourth line was obtained offshore from the satellite-derived, free air anomaly. The lines’ lengths range from 80 to 150 km. The four gravimetric profiles show a concave upwards geometry, locally modified by the signature of the canyons. The gravity anomalies along the lines were modeled (2-D) to depths of ~30 km in order to include the subducting slab. From top to bottom the layers are: ocean (1.03 g/cm^3), sediments (2.3), crustal rock (2.67), slab (2.85), and mantle (3.30). From the group of four consecutive models it can be inferred that the presence of the canyons continues inland, where they are concealed by sediments deposited by several rivers that discharge to the ocean in that region. The canyons diminish their widths as they progress inland; the evidence suggests that the canyons are associated with faults that reach down to the slab. The slab itself shows a perturbed geometry with its surface varying in depth from 3 to 4 km along the surveyed lines. The average depth of the slab is observed to increase as distance from the trench increases. Distance of the profiles from the trench ranges from 45 to 100 km, while the average depth of the slab varies from ~12 km to ~28 km. A 20 km isodepth line for the slab was calculated elsewhere interpolating seismic data along a trench perpendicular profile. Our results roughly coincide with theirs for the location of the slab at such a depth, although we consider ours of grater accuracy in the depth estimation. Additionally, they considered the slab as having a smooth geometry, which is an assumption not valid under the scrutiny of the gravimetric analysis. Although the tectonic processes responsible for the slab deformation at the boundary of the Rivera and Cocos plates cannot be ascertained presently, we submit that the deformation is responsible for the lack of definition of their boundary.

Observation of various LF earthquakes at distances of hundreds of kilometers in Afar and the Main Ethiopia rifts: implication for source and/or path effects

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Session: AMR

Afar and the main Ethiopian rift host several active volcanoes and fissure eruptive centers which can potentially pose hazards to human life and development activities in the region. These risks are enhanced by the extensional tectonic setting, where volcanoes and fissures form in highly fractured crust that is undergoing active faulting. After the advent of digital broadband instrumentation with wide dynamic range, volcano seismology has become one of the strongest disciplines contributing to assessment of volcanic unrest for hazard mitigation. In particular, seismicity due to fluid and/or magma movement is characterized by low frequency (LF) events, in contrast to higher frequency volcano tectonic (VT) earthquakes. Several volcano-tectonic events have occurred in Afar and the main Ethiopian rift during the last ten years that have been recorded by broadband digital seismic stations. The most notable sequences are; the May-June, 2000, Gewane sequence; the 2003/2004 Melka Sedi/Werer sequence and the Dabbahu-Manda-Hararo sequence that commenced in September 2005. A wide range of seismic signals are recorded from high frequency micro-fractures to tilt signals during those sequences which all explain the various dynamics underway around the volcanic source regions. While such phenomena are manifestations of active rift process by faulting and/or magma emplacement that have been occurring since initiation of rifting, the instrumental records that we are collecting to date are very rare and just a snapshot of a quasistatic geologic process that needs due consideration.

LF earthquakes with dominant frequency of 0.2 Hz are observed trailing high frequency VT events which are recorded at hundreds of kilometers from the source region. These types of LF events are Rayleigh type, nearly monochromatic and high amplitude ringing waves which are not seen at all stations. This may imply that their unusual frequency content is either not related with the source but related to the source-station path or may possess azimuth dependent radiation patterns at the source. Other earthquake sequences show anomalously long coda dominated by low frequency signals and very low attenuation, suggesting scattering from fluid-filled cracks in the highly fractured rift zone. These signals are diagnostic tools for identifying whether the local

earthquakes that are recorded on a routine basis are a tectonic type or an event originated from a volcano source region.

Geosites in the Pearl of Africa- Uganda (Pictorial)

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Session: RES

The country is located in the heart of the great African plateau with relief altitude ranging between 900 to 1500m above sea level and extremes of lows and highs as 600m (in the rift) and 5100m (Rwenzori Mountains) respectively. Uganda is crossed by the equator and occupies an area of 241,000km^2. There are varied landscapes with national parks, and natural resources such as breath taking flora and fauna giving Uganda another name 'the Pearl of Africa'.

Uganda is endowed with impressive geological sites that must be protected and sustained ably as geosites. These are spots with special geological significance, rarity or beauty. They deserve to be preserved for everyone to appreciate. They are a potential pro-development occurrences for any country. The Rwenzori massif 5100m with snow peaks, the trough of the Albertine rift valley, the headwaters of the River Nile, the terraced southern highlands, volcanic crater lakes, vast papyrus wetlands, dark tropical forests and rolling savanna plains are amongst the many touristic features.

The pictorial collection so far includes documentation and description of rock shelters and caves, volcanic features, hot springs, waterfalls, escarpments, fossil sites and archaeological spots.

Of recent, within the framework of the Uganda Geological Mapping Project, for each visited site parameters such as GPS co-ordinates for location, access geological significance in terms of regional geological setting, stratigraphy and lithology, size of the site, present use, state of preservation, and protection status have been recorded. Where applicable, also the cultural and traditional background has been documented.

The collected information has been summarized in reports, and extracted information has been fed in an excel sheet, which was imported to form another GIS layer and shown as 'geosite spots' on the new geological maps of Uganda.

We hope, that our interaction at the Conference will enrich and enhance our appreciation and importance of the subject on a regional or pan African scale.

MT studies in the surrounding of the geothermal power plant at Alutu volcano

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Session: RES

The East African Rift system is one of the privileged areas for potential geothermal energy extraction including power generation. Currently the only geothermal power plant in Ethiopia is located on Alutu volcano 140 km south of Addis Ababa between the lakes Ziway and Langano. During the 1980s 8 deep wells up to 2500 m were drilled, reaching temperatures of 300°C. A 7.3 MW pilot power plant was installed in 1999, but was not fully operational due to technical problems. In 2007 the plant has been partially rehabilitated and put back into an operation of about 5 MWe. For 2012 a general overhaul of the power plant and additional drillings are planned.

Satellite observations using Interferometric Synthetic Aperture Radar (InSAR) showed two pulses of inflation (20 cm) in 2004 and 2008 separated by subsidence at an averaging rate of 3-5 cm/yr. At present it is not clear whether this rapid deformation will enhance or hamper the plants productivity and it may even constitute an unacceptable level of threat. To assess the implications of unrest for geothermal production, it is necessary to identify its source. The working hypothesis is that causative source for the observed deformation is either the hydrothermal reservoir (located at 1-2 km depth), or the magmatic system at depths of greater than 3 km, or a hybrid of the two.

In order to determine the nature of the deformation source and to delineate the source it is planned to conduct magnetotelluric (MT) measurements in January-March 2012 in this region. The reasoning for using the MT is two-fold. Firstly, this method – by deciphering subsurface electrical conductivity – is especially sensitive to high conducting zones, that geothermal and magma reservoirs are. Secondly, it easily covers the necessary exploration depth down to approximately 10 km. The project will be part of collaboration with the IGSSA, Addis Ababa University, and the University of Bristol and will also involve seismic techniques to achieve the aforementioned objectives.

Due to the intrinsic 3-D geometry of volcanic regions like the Alutu-Langano geothermal field, we will carry out a 2-D MT survey (with expected spatial resolution of 1 km x 1 km amounting to around 100 sites in total), and 3-D interpretation of the MT data. To cover the desired exploration depth, data in a frequency range from 10 kHz to 0.01 Hz are planned to be acquired. In order to interpret the data in the frame of 3-D conductivity models, and to avoid the static shift problem we are developing a new, efficient 3-D inverse solver which is based on a joint analysis of tippers, elements of horizontal magnetic tensor, and the phase tensor. Expected outputs of our study are: (a) a novel and fast 3-D MT inverse code; (b) 3-D geoelectric model of the deforming region.

Landscape evolution of the Rwenzori Mts and adjacent Albertine Rift, from low-temperature thermochronology

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Session: CLI

In East Africa, the feedback between tectonic uplift, erosional denudation and associated possible climate changes is being studied by a multidisciplinary research group, 'RiftLink'.

The Rwenzori Mts, located SW of Lake Albert, form a striking feature within the Albertine Rift of the East African Rift System. They are built up by a dissected Precambrian metamorphic basement block that has been uplifted to heights of more than 5 km.

Samples taken along and across the Albertine Rift, cover the area around the Rwenzori Mts and the mountain range itself. From thermochronological analysis (AFT, AHe & ZHe) and subsequent thermal modelling a protracted cooling history since Paleozoic times can be revealed.

From cooling ages and derived cooling histories different blocks can be distinguished along the Rwenzori Mts. In the central part a northern and a southern block are separated by a proposed NW-SE trending fault; with the northern block showing much younger apatite fission-track ages (AFT: ~130 ±8 Ma) than the southern block (AFT: from 284.4 ±12.3 Ma to 319.8 ±33.3 Ma). Cooling ages in both blocks do not vary significantly with elevation, despite differences in relief of more than 3 km. Thermal modelling reflects protracted cooling histories, with individual t-T paths demonstrating that the Rwenzori Mts were not exhumed homogeneously as one block. They show decoupled blocks that were relocated separately along distinct fault planes, with the blocks revealing different rates of exhumation during Paleozoic and Mesozoic times.

Since Miocene differentiated erosion and rock uplift movements affected almost the entire Rwenzori Mts, with more pronounced surface uplift along the western flank. AHe cooling ages of ~25 (0.5) Ma, obtained from this area point to a near surface position of these rocks since Miocene/Oligocene times and very recent (Plio-/Pleistocene) final surface uplift, where erosion could not compensate for.

Thermokinematic modelling, applied to samples from different parts of the working area allow to better constrain the cooling history and landscape evolution of the Rwenzori Mts as well as surrounding Albertine Rift which will be discussed in the frame of this presentation.

Distribution of Quaternary faulting in the Main Ethiopian Rift, East Africa, and its implications for rift evolution

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Session: AMR

Recent geological and geophysical data have greatly improved our understanding of the process of continental rifting in the Main Ethiopian Rift. These data evidenced that the different sectors (Northern, Central and Southern MER) display distinctive volcano-tectonic activity and geophysical signatures which in turn are believed to reflect a different evolution of the rifting process. In the Northern MER, inactivity of the boundary faults coupled with the presence of a well-developed system of volcano-tectonic segments in the rift centre have been used as evidence for an incipient break-up stage. Magmatic segments in this area are characterised by dominance of magmatic over tectonic deformation and are interpreted to represent incipient oceanic spreading centres. Conversely, in the Central MER magmatic segments are less-developed, extension seems to be mostly accommodated by tectonic deformation at rift margins and crustal thinning is less pronounced, indicating a less evolved stage of rifting. Overall, a general decrease in thinning and tectono-magmatic modification of the crust and lithosphere is hypothesised proceeding from the Northern MER/Southern Afar southwards.

However, knowledge of the distribution and style of Quaternary volcano-tectonic deformation in the Central-Southern MER is comparatively less constrained than in the Northern MER. Structural data have been thus carried out to better constrain the time-space distribution of faulting in the Central-Southern MER. The field structural data coupled with new 14C radiometric dating of faulted rocks suggest a localization of faulting at both rift margins of the Central MER, where radiometric dating of faulted material has allowed establishing a Late Pleistocene-Holocene activity of border faults. In-rift faulting (Wonji Fault Belt, WFB) is instead subordinate highlighting a major difference with the northern sector of the MER where deformation is essentially accommodated within the axial zone.

The MER thus offers a complete record of the time-space evolution of a continental rift, i.e., from early stages (Southern MER), to transitional stages (Central MER), to more evolved stages characteristic of incipient continental rupture (Northern MER). This along-axis time-space variation in rift evolution is very similar to the evolution of deformation inferred from scaled sand-silicone analogue models.

Regarding fault-slip measurements, cumulative stress inversion of these data determined for the three MER sectors reveals a variation in the extension direction between the rift margins (N105°-110°E) and the rift floor (N90°-95°E). The N90°-95°E-trending extension is similar to the ~N100°E regional extension related to the Nubia-Somalia kinematics. This is likely because the enhanced tectono-magmatic weakening of the rift floor is expected to allow the faults to respond more efficiently to the regional stress; conversely, boundary faults may be influenced by a local reorientation of the regional stress directions controlled by the reactivation of deep seated inherited fabrics. The variation in extension direction across the rift suggest a slip partitioning between in-rift WFB faults and the boundary faults during oblique rifting.

Stratigraphy and volcanic facies architecture of the Torres Syncline (Paraná-Etendeka CFB Province) in South Atlantic Margin

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Session: RCM

The Torres Syncline is a large structure that constitutes the eastmost outcrop of the Paraná-Etendeka CFB in South American side, and this work focuses the stratigraphy and facies architecture of the volcanic pile in the syncline. The volcanic sequence along the study area permits the division of three regions: main valley, intermediate zone and south hinge, each of them with distinct stratigraphy, which probably reflects syn-volcanic subsidence process related to structural evolution of the syncline. The stratigraphy of the Torres Syncline is composed by: 1- Botucatu palaeoerg; 2- Basic volcanic episode I; 3-Basic volcanic episode II, 4- Acidic volcanic I, 5- Basic volcanic episode III and 6- Acidic volcanic episode II. The five volcanic episodes recognized in study area can be related to five volcanic facies architecture: compound-braided, tabular-classic, tabular/lobate escoriaceous, dome-field (acidic lavas) and tabular-flows (acidic lavas). The Botucatu paleoerg is dominantly composed of fine- to coarse-grained sandstones with large-scale cross-bedding whose origin is ascribed to simple, locally composite, crescentic and complex linear aeolian dunes. The basic episode I is composed by pahoehoe flows with a compound-braided facies architecture that covered the Botucatu palaeoerg and preserve the dune´s morphology. The basic episode II is a tabular-classic facies architecture predominantly composed by simple flows (10-20m thick) reaching the total thickness of ~500m in main valley and correspond to volcanic climax. The acidic episode I is exposed in main valley and south hinge, and is composed by acidic lavas forming lava dome-field facies architecture with a thickness of ~150m. The basic episode III is predominantly constituted by ´a´ā flows with tabular/lobate escoriaceous facies architecture. The average thickness of flows is ~20m, and these are composed by an escoriaceous top, massive core and an escoriaceous base. Transitional lava type similar to rubbly pahoehoe composed by an escoriaceous top that grade a coherent vesicular upper crust, a dense core and a thin lower vesicular crust also occur associated with ´a´ā flows. The acidic episode II is constituted by tabular-flow volcanic facies (acidic flows) and outcrops all along the study area. In general, at the base of the flows occurs vitrophyres with marked sub-horizontal flow foliation, that grade upwards to granophyres with well developed sub-horizontal jointing. The contacts between the five episodes are smooth and palaeosoils are not observed, indicating that the volcanic pile along the syncline was erupted in a short time interval. The Torres Syncline constitute the eastmost on-shore exposures of the Paraná-Etendeka CFB in South American side and detailed stratigraphic, volcanological and structural studies in these area, coupled with correlation with Huab Basin (NW Namíbia, Africa) will aim the understanding of the Gondwana breakup process and the early stages of the South Atlantic margin opening.

Fault and fracture systems at oceanic spreading centers

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Session: MOR

Highly magmatic rifts make up a significant percentage of ancient and active rifts worldwide. Though diking accommodates most of the extension in magmatic rifts, fracturing and faulting that accompanies diking may be equally important for some local strain accommodation and for potentially providing fluid (and melt) pathways. Direct geological investigation of fracture and fault systems in active or ancient rifts is inhibited by lack of exhumed sections, and the general poor preservation of rifted crust in the geologic record. However, several suitable analogs are available to understand processes that occur in rifts, such as exposures of oceanic crust in deep submarine canyons. These windows into deeper crust provide geologic examples of deformational structures that formed in a spreading environment where diking and volcanism dominate. Two localities of ~1-3 Ma-old ocean crust off the East Pacific Rise (EPR) axis are exposed in deep submarine canyons, allowing a close inspection of fractures and faults that developed in a true end-member for dike-accommodated extension (fast-spreading ocean ridges). One way to evaluate brittle deformational processes in these environments is to study the meso- and microstructure of the deformed materials. One method is to measure the particle size distribution (PSD) of fault rocks. Previous PSD work in sedimentary rocks indicated that grains follow a power-law distribution (in log size vs. log frequency or cumulative number). The D value in these studies is the slope of the power-law function, and is generally around 2.5 in 2D, 3.5 in 3D. This power-law is a cumulative reflection of the hierarchical way that stresses are distributed, and grains interact over time, and therefore can be generally related to incremental shear strain, as well as more instantaneous measures of porosity, fabric data, and permeability. However, since basalts do not have in initial grain size distribution like sedimentary rocks, they may behave differently, though little work on PSDs of deformed basaltic rocks has been undertaken. The method for determining PSD includes analysis of both thin section and hand samples that spans three orders of magnitude. Surprisingly, PSDs follow not only power-law (D in the basalt fault rocks range from 0.753 to 1.396 in 2D), but also exponential and logarithmic distributions, sometimes all in the same sample at different size scales. Therefore, the processes that control faulting in basalts could be scale dependent. For example, fracturing (and accompanying fluid flow) may give rise to breccias with a specific grain size during an increment of deformation. Subsequent fault-slip may be very restricted in its displacement, and again be dominated by grain-size dependent brecciations. The superposition of numerous deformation increments may give rise to fault rocks that look on the surface like cataclasites from sedimentary materials, but in fact differ in their microstructural qualities.

Magma driven extension in an immature continental rift, based on InSAR observations of Nyiragongo Volcano in 2002

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Session: AMR

Analysis of InSAR displacements associated with the January, 2002, Nyiragongo eruption show that the most likely eruption model corresponds to two subvertical dike intrusions. Both dikes trend parallel to the rift axis in the region. A first, shallow dike, 2 km high, is associated with the eruptive fissure, and a second, deeper dike, 6 km high and 40 km long, with its top located about 3 km below the city of Goma, extends for 20 km beneath the gas-rich Lake Kivu. Because the dikes are parallel to the rift and have sub-vertical dips, the direction of the 2002 eruption dikes, as well as the 1977 eruptive fissure, are probably controlled by the rifting process. We infer low overpressures (1 – 10 MPa) for the dikes, which is not expected for a tectonically driven rift. These values are consistent with isotropic lithostatic stresses close to the dikes, which can be attributed to the high eruption rate producing compressive stresses which are too great to be relaxed by the rift extension. Such a stress state is incompatible with stretching of the crust via normal faulting and indicates that, although the rift is considered immature, strain localizes in magmatic segments and the rift extension is driven by the supply of magma from depth, rather than the tectonics. As faulting and magmatic activity have coexisted, and magmatic activity is now more intense than previously, it is likely that a change from a tectonic to a magmatic driven rift has occurred recently. The small amount of extension of the western branch of the East African Rift indicates that magma can not come from adiabatic decompression of the mantle, but that it is probably supplied by a lateral flow of the mantle plume beneath East Africa.

Influence of magma supply on Galápagos Spreading Center magmatic and eruptive processes

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Session: MOR

A significant increase in the time-averaged rate of magma supply to the crust with proximity to the Galápagos hotspot along the Galápagos Spreading Center (GSC) makes this area ideal for studying the effects of variable magma supply on mid-ocean ridge (MOR) magmatic and eruptive processes. We have identified lava flow fields from individual eruptive episodes in two ~20-km-long study areas along the spreading axis of the GSC, one at 95W and the other closer to the hotspot at 92W; over this interval the rate of magma supply increases by 40%, while the spreading rate remains nearly constant (52-56 mm/yr). Detailed geologic maps of each study site were prepared using geological observations of flow contacts, sediment thickness, and lava morphology, in addition to sample mineralogy and chemical composition and inferences from high-resolution bathymetry.

At the lower magma supply study area, eruptions typically produce irregularly-shaped, steep-sided clusters of pillow mounds with total eruptive volumes ranging from 0.04-1.3 km^3. Lavas are restricted to relatively unfractionated compositions (6.2-9.1 wt. % MgO), but have widely variable crystal contents (3-25 % phenocrysts). Considerable inter-flow compositional heterogeneity exists among the less fractionated eruptive units, while disequilibrium textures are more common among the more fractionated eruptive units. These observations are consistent with discrete batches of magma mixing with resident crystal mush and residing intermittently in deep (4 km) magma chambers, before feeding large volume, low effusion rate eruptions from point sources. At the higher magma supply study area, lava morphologies characteristic of higher effusion rates (lobate and sheet flows) are much more common, and most form relatively low relief ridges or lava plains that are elongated parallel to the spreading axis. On average, individual eruptive units are an order of magnitude smaller (0.002-0.2 km^3) than those mapped at the lower magma supply study area. There is a similar range in MgO content within individual eruptive units at both study areas (0.2-1.0 wt. % at low magma supply vs. 0.4-1.2 wt. % at high magma supply), but much greater degrees of differentiation are reached at high magma supply (2.7-8.0 wt. % MgO). At high magma supply, phenocrysts are rare in sampled lavas (<1%; microphenocryst contents may be significantly greater). In contrast to the low magma supply study area, it appears that at high magma supply, magma resides in shallow (~1.5 km), frequently replenished, melt-rich magma reservoirs, from which relatively small volumes of lava are erupted more frequently and at higher eruption rates, primarily from eruptive fissures that range from 1.5 to 7.5 km in length. Localized units with as little as 2.7 wt. % MgO and as much as 54.3 wt. % SiO2 suggest that small bodies of magma may become isolated from the larger, more frequently replenished, magmatic system, allowing more extreme degrees of fractionation. The differences in lava morphology and inferred eruption rates observed between the two areas with contrasting magma supply along the GSC are similar to those that have previously been generally related to variable spreading rates on the global MOR system.

Slip partitioning during oblique rifting: comparison between data from the Main Ethiopian Rift and laboratory experiments

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Session: AMR

Oblique rifting in the Main Ethiopian Rift (MER) has resulted in a complex structural pattern characterized by two differently oriented fault systems: a set of NE-SW-trending boundary faults and a system of roughly NNE-SSW-oriented fault swarms affecting the rift floor (Wonji faults). Boundary faults formed oblique to the regional extension vector, likely as a result of the oblique reactivation of a pre-existing deep-seated rheological anisotropy, whereas internal Wonji faults developed sub-orthogonal to the stretching direction. Previous works have successfully reconciled this rift architecture and fault distribution with the long-term plate kinematics; however, at a more local scale, fault-slip data reveal significant variations of the orientation the minimum principal stress across the rift valley. Whereas this direction is consistent with the current roughly E-W Nubia-Somalia motion on the Wonji faults, a ≈20° rotation of the minimum principal stress is observed along boundary faults. Measurements on these faults indicate a significant deviation from the regional stress field and point to a roughly pure dip-slip motion on the faults, despite their orientation (oblique to the regional extension vector) should result in an oblique displacement.

To shed light on the process driving the variability of data derived from fault-slip analysis we have run crustal-scale analogue models of low- and moderate-obliquity rifting. The models are deformed in a large-capacity centrifuge by using materials and boundary conditions described in several previous modeling works. The experiments show the development of two fault systems, boundary and internal, whose pattern strikingly resemble that observed in previous lithospheric-scale modeling, as well as that described in the MER. Whereas internal faults develop orthogonal to the extension direction, boundary faults form oblique to the imposed stretching vector: as a group, the faults follow the rift trend, controlled by a pre-existing weak anisotropy, but individually they form in response to a local re-orientation of the imposed stress field and orient oblique to both the rift margin and the extension vector. Detailed analysis of fault displacements suggest that the local stress re-orientation results in a roughly pure dip-slip motion, which gives rise to a marked difference in fault-slip direction between internal faults (where slip orientation follow the regional extension) and boundary faults (where displacement is oblique to the “regional” extension, and orthogonal to the local maximum extension). Minor counterclockwise block rotations accommodate the different slip along the different fault systems.

Thus, analogue models allows reconciling the across-axis variability observed in natural fault-slip data. Modeling results suggest that whereas internal faults form within a weaker, more uniform lithosphere and respond to the regional extension direction resulting in a fault slip sub-parallel to the Nubia-Somalia motion, boundary faults are affected by a local stress re-orientation imposed by a deep seated anisotropy. Their stress trajectories deviate from those imposed by the regional extension, resulting in a pure dip-slip motion in an overall oblique rifting kinematics, as observed in other sectors of the East African Rift. Both in nature and experiments minor counterclockwise block rotations accommodate the difference in slip along the different fault systems.

Thermal and tectonic histories of the Jabel-Bura per-alkaline granite on the south-eastern margin of the Red Sea (Yemen)

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Session: RCM

The Red Sea rift system is one of the best-exposed examples of a continental rift that lead to continental break-up and new ocean floor. However few data allows to constrain precisely spatial and temporal distribution of tectonic structures which accommodated lithosphere thinning along the Red Sea continental margins. In the heart of the Afar volcanic province (Yemen & Ethiopia), these structures have been developed on a thick pre-rift continental flood basalt pile with very few associated onshore syn-, and post-rift sediments. This widespread occurrence of monotonous tertiary volcanic cover prevents precise quantitative estimation of motion along these faults.

However, the south-eastern margin of the Red Sea in Yemen is characterized by emplacement of syntectonic per-alkaline granite plutons at about 20 Ma which intruded mesozoïc pre-rift sediments and show faulted contact with Oligocene basaltic traps. These differentiated magma bodies, which have been emplaced at depth, now outcrop at the surface and potentially represent key geological objects to study tectonic deformation and unroofing associated with extensionnal structures.

Due to their low P205 concentration, these granites are devoid of apatite minerals and therefore are not suitable to perform very low temperature thermochronology with Fission track or (U-Th)/He. Consequently, in this study we investigate the cooling history of these plutons on a vertical cross-section of 1300 m in the Jabel-Bura granite, using an higher temperature thermochronometer measured on zircons. The (U-Th)/He ages measured on zircons (Zr-He ages) generally provide robust cooling informations when rocks are unroofed from an isotherm higher than the closure temperature of 4He in this mineral (about 180-200 °C), which corresponds to a depth of 5 - 6 km. According to their texture and their location in the stratigraphic units, the syntectonic Yemeni granites have most probably been emplaced at a depth close or shallower to this Zr-He closure temperature, in a range of temperature called "helium partial retention zone" (He-PRZ : 140-200 °C). In this He-PRZ, the attenuation of helium diffusion with decreasing temperature is a complex depth and crystal size dependent process which generally spread the He-ages from an old pre-cooling end-member to a young end-member corresponding to the age of cooling.

For the Jabel-Bura section, preliminary results suggest a potential correlation between Zr-He ages and cristal size, with large cristals (200 μm diameter) displaying ages close to the K-Ar age determined by Capaldi et al. (1987) at 20.4 ± 0.7 Ma, whereas smaller ones (100 - 80 μm diameter) yield significantly younger ages from 18 to 16 Ma. If this correlation is confirmed, this will indicate that these plutons have been emplaced in the He-PRZ, at a depth of approximately 3 - 5 km, and stayed there for a relatively long duration (5 Ma), so that the smaller grains could have been reset to 16 Ma, before tectonic unroofing completely cooled the granites. New data on single zircon grains, and precise thermal modelings, will be necessary to go further on this tectonic scenario and precise the amplitude and timing of unroofing along major southern Red-sea tectonic structures.

$^{40}Ar/^{39}Ar$ radiometric ages of rare Plio-Pleistocene strata for interpreting basin evolution and hominin paleoenvironments in southern Afar Depression, Ethiopia

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Session: CLI

The time period between 2.9 and 2.6 Ma is of particular interest in east Africa because a shift towards a cooler and drier climate coincided with a clustering of first appearance and extinction events in the faunal record, including the diversification of Australopithecus and the emergence of the genus Homo, and significant changes in African landscapes. Tectonic rifting processes altered the paleogeography, for example by creating and modifying basins in which paleo-lakes could develop. Yet 2.9 to 2.6 million year old sediments are sparse in eastern Africa, and are especially rare at paleoanthropological sites such as Hadar and Dikika in southern Afar, Ethiopia. This paucity of sediments significantly impedes our ability to resolve important paleoenvironmental, evolutionary, and geological changes in the southern Afar sedimentary record.

Here we present eight new $^{40}Ar/^{39}Ar$ radiometric ages of tephra deposits from the eastern Ledi-Geraru (ELG) project area in the lower Awash Valley, southern Afar (adjacent to Hadar and Dikika). Results confirm that sediments exposed at ELG span 3.0 to 2.8 Ma (likely to 2.7Ma), thus providing the first glimpse of depositional landscapes and associated sediments that existed at that time. Our mapping and stratigraphic analysis at ELG show at least 65 vertical meters of lacustrine to fluvial sediments are well exposed west of the Awash River. These sediments lie near the northern- and eastern-most exposures of the Hadar and Busidima Formations (mapped 10-12 km southwest) suggesting they are contemporaneous. The results of our work provide an important opportunity to test proposed links between biotic events, global/regional climate change, and local tectonic events during what is a particularly interesting period of evolutionary and structural change in southern Afar.

Dynamics of opening at the western tip of the Aden Ridge: Insights from geodetic and seismic data.

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Session: AMR

At the western tip of the Aden slow-spreading ridge, the main part of the extensional deformation related to the divergent Arabia/Somalia plate motion occurs along the youngest en-échelon opening segments. The first segment, only partly above water, is the Asal-Ghoubbet Rift and has been studied extensively since the 1978 rifting episode. An important set of geophysical data offers the opportunity to follow the time evolution of the deformation precisely over its whole post-rifting period. Together with recent geodetic results, including GPS campaign measurements, InSAR time series, and low-magnitude earthquake catalogues, we investigate the mechanisms responsible for the transient displacements observed during this period, specifically the role of the volcanic centre on the distribution or localisation of the extensive deformation.

At the segment scale, the horizontal velocity field over the last decade suggests that the opening dynamics are still controlled by the 1978 dyking event. However significant time variations reveal a non-steady-state horizontal opening and vertical re-adjustments.

A large part of the micro-seismicity within the rift reveals the activity of the central geothermal/magmatic reservoir and underlines its significant role on the activity of tectonic features (mostly normal faults, some open dry fissures).

At the regional scale, the aftershock sequence of the 1978 event already emphasised the relation between the main Asal-Ghoubbet Rift system and the neighbouring zone of transfer of extensive deformation between the Asal-Ghoubbet Rift and the underwater Tadjoura Rift. More recently, the lack of seismicity within the rift is coeval with an increase of the seismicity in the transfer zone in Central Afar, which corresponds to the overlap of the spreading ridges of the Red Sea and Aden branches, where a small amount of extension is currently taking place.

From these results and observations, we propose a model where the dynamics and the location of the opening in Afar is controlled by the transient activity of volcanic centres.

Timing and Composition of Volcanic Activity at Harrat Lunayyir, western Saudi Arabia, and its Relation to Regional Mantle Flow

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Session: AMR

Extensive Cenozoic basaltic lava fields occur in the western part of the Arabian peninsula, erupted from N-S oriented volcanic centers and forming one of the largest alkali basalt provinces in the world (area: 180,000 km^2). These young volcanic fields ("harrats") lie within 200 km of the NW-trending eastern margin of the Red Sea, and are partially related to the regional extensional stress field that began ~30 Ma. Interestingly, there is no counterpart to these volcanic centers on the western margin (African plate) of the Red Sea. In contrast to the tholeiitic basalts of the Red Sea, lava compositions in this province are ol-transitional to alkali ol-basalt to hawaiites and even more evolved compositions. Within several large centers, volcanic activity began (10 Ma) with predominantly tholeiitic to transitional compositions, then became more alkalic for younger eruptions (<10 Ma). A prominent volcanic lineament, the N-S Makkah-Madinah-Nafud line, appears to coincide with the axis of uplift of the Arabian shield, beginning ~15 Ma. Hence flexure or asthenospheric flow could explain the timing and distribution of volcanic centers.

The lava field of Harrat Lunayyir, on the western edge of the central portion of the N-S trend, has been selected for high-resolution age, composition and geophysical investigation. This study has been initiated because Harrat Lunayyir experienced multiple seismic swarms since 2007. Recent studies (e.g. Pallister et al., 2010) have indicated that these swarms are associated with magma that has risen to shallow levels beneath Harrat Lunayyir, potentially increasing the likelihood of a volcanic eruption. It is estimated that at least twenty-one different eruptions have occurred in western Arabia over the past 1500 years (Camp et al., 1987), including one near Harrat Lunayyir about 1000 years ago. New age determinations by the ^{40}Ar-^{39}Ar incremental heating method detail the volcanic history, which is generally younger than previously thought. Most eruptions occurred within the Quaternary period, beginning about 0.5 Ma, and increased in frequency into historic times. Primitive and evolved lavas were erupted throughout the volcanic history, with no apparent trend in degree of crystal fractionation and hence length of residence time of mantle melts in a crustal magma chamber.

Trace element ratios from centers aligned perpendicular to the N-S lineament, including Harrat Lunayyir, are compatible with variations in depth and degree of mantle melting such that centers near the axis were derived from shallower and more extensive melting, while centers at the margins were derived by deeper and less extensive melting. Additional geochemical tracers will be used to examine whether upper mantle flow from the Afar region is more likely than local mantle upwelling in the origin of these volcanic fields.

Hydroacoustic evidence that rapid magma intrusion leads to eruptions and hydrothermal plume release during seafloor spreading events

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Session: MOR

The creation of ocean crust by rapid injection of magma at mid-ocean ridges can lead to eruptions of lava onto the seafloor and release of “event plumes,” huge volumes of anomalously warm water enriched in reduced chemicals that rise up to 1 km above the seafloor. Here hydrophone recorded seismic data is used to show that seafloor eruptions and the release of hydrothermal event plumes correspond to diking episodes with high injection velocities and rapid onsets to emplacement within the rift-zone. These attributes result from high excess magma pressure at the dike source, likely due to a new influx of melt from the mantle. These dynamic magmatic conditions can be detected remotely and may predict the likelihood of event plume release during future seafloor spreading events.

Discovery of pyroclastic surge deposits in Bamenda volcano (West-Cameroon, Cameroon volcanic Line): importance in chronostratigraphy of the massif.

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Session: AMR

Mounts Bamenda (600 km^2) which constitute in volumetric importance the fourth largest volcano of the Cameroon Volcanic Line, are the NE extension of the Mounts Bambouto. This massif extends between 10°00'-10°30' East and 05°45'-06°10' North and culminates at 2621 m at Lake Bambili borders. Petrographic and geochemical studies (Kamgang et al., 2010) show that the mounts Bamenda consist of basanites, basalts, hawaiites, mugearites, benmoreites, trachytes, rhyolites and ignimbrites. The radiometric dating of this active volcano gives ages ranging from the current to 17.4 Ma for the basaltic lavas and from 18.98 Ma to 27.40 Ma for the felsic lavas.

Deposits of pyroclastic density currents have generally categorized according to lithology and sedimentary structure, as ignimbrites, block-and-ash flow deposits and pyroclastic surge deposits. Until now, only welded and non-welded ignimbrites with their massive lapilli tuff (mlT) and massive lithic breccias facies (mlBr) have been described in the mounts Bamenda (Gountié Dedzo et al., 2011). The ignimbrites sheets constitute about 7.5% of the rocky outcrops of the volcano representing approximately 45 km^2 with a volume estimated at 6.3 km^3.

Field studies in Bambili locality (NE of Bamenda city) have recently permitted us to discover above the welded mlT (whitish unit), the relictual blocks (up to 6.5 x 11 m) of pyroclastic surge deposits characterized by well sorted and distinctly stratified layers with thickness raging between 15 to 35 cm showing a graded bedding. In addition to ashy matrix, the different layers of the deposits are made up of lithic fragments of various natures, represented by devitrified fiammes, vitrophyres, trachytes, rhyolites, granites and ignimbrites. The mineralogy of these surge deposits is quasi identical to those of welded mlT; they are made up of alkali feldspar, quartz, plagioclase, clinopyroxene, biotite and Fe-Ti oxides.

The discovery of the pyroclastic surge deposits of Bambili, emitted from mount Oku vent (Gountié Dedzo et al., 2011), permit to reconsider the chronostratigraphy of the Bamenda volcano. In fact, after the trachytic flow, the pyroclastic flow deposits have then permitted the formation of the welded ignimbrites; pyroclastic surge deposits have then cover the massif followed by basaltic flows. Because of less thickness and weak consolidation, the surge deposits have been rapidly removed by erosion except their incipiently welded parts. The stratified character of the deposits observed at Bambili is attributed to a spatial and temporal variation of the nature of pyroclastic current, which would have been transformed into pyroclastic surge with a current, became weakly concentrated and rich in ashy and gaseous fraction.

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Mineralogical, Geochemical, and Isotopic Investigations of the northern Afar/Danakil Depression, northeastern Ethiopia

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Session: AMR

The Danakil Depression is the most important volcano-tectonically active portion of the Afar region and the East African Rift system. In its center, over an area that is ~120 km long and ~35 km wide, there are several volcanic edifices constituting seven major NNW-SSE aligned shield volcanoes and low-lying fissure-fed basalts. The petrology of the lavas in this area ranges from transitional alkali to tholeiitic basalts, with significant across-axis variation both in mineralogy and geochemistry. The variation in the contents of the major elements (TiO_2, Al_2O_3, and Fe_2O_3), incompatible trace elements (Nd, Hf, Th, Ta), and the contents and ratios of the rare earth elements (REE) (e.g., (La/Yb)n = 5.3–9.3) indicate some variation in the petrogenetic processes of the basalts. However, the variation in isotopic compositions of the basalts is minimal ($^{87}Sr/^{86}Sr$ = 0.7036 - 0.7041, $^{143}Nd/^{144}Nd$ = 0.51286–0.51289), which suggests that there is only one source region for all the Danakil Depression basalts. The Ce/Pb, Ba/U ratios, and isotopic data indicate that continental crust is not a major component for the petrogenesis of the volcanic rocks; instead, depth and degree of melting of the source reservoir underneath the Danakil Depression played a major role for the production of incompatible element-enriched, transitional alkali basalts (e.g., AleBagu Shield basalts) and the incompatible element-depleted tholeiitic basalts (e.g., Erta'Ale Shield basalts).

Surface Deformation Associated With a Historical Diking Event in Afar From Correlation of Space and Aerial Optical Images, and DEM Differencing

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Session: AMR

We present new measurements of the surface deformation associated with the rifting event of 1978 in the Asal-Ghoubbet rift, Republic of Djibouti using an optical image correlation technique. The 1978 rifting event was marked by a 2-month sequence of small to moderate earthquakes (Mb ~3-5) and a fissural eruption of the Ardokoba volcano. Deformation in the Asal rift associated with the event included the reactivation of the main bordering faults and the development of numerous open fissures on the rift floor. Trilateration data (Tarantola, 1979), indicates up to 2.5 m of opening in the N40E direction across the rift.

Our data include historical aerial photographs from 1962 and 1984 (0.4 and 0.8 m/pixel) along the northern border fault, three KH-9 Hexagon (~8 m/pixel) satellite images from 1973, and recently acquired SPOT5 (2.5 m/pixel) data. The measurements are made by correlating pre- and post-event images using the COSI-Corr (Co-registration of Optically Sensed Images and Correlation) software developed at Caltech. Correlation results from the satellite images indicate 2-4 meters of opening across the rift, much of it concentrated on northern side of the rift, on faults alpha and gamma. Preliminary results obtained from correlation of the 1962-1984 aerial photographs also indicate extension across the faults on the northern side of the rift. However these preliminary results are affected by an undulating signal, which may be due to film distortions, making offsets on individual faults difficult to quantify.

DEM's were generated from both aerial surveys using the normalized cross-correlation technique. A DEM difference was calculated over the area of the Ardokoba lava flow. A plane was fit to the area immediately surrounding the flow, in order to set a vertical reference. The elevation difference indicates the volume of the Ardokoba flows to be ~0.013 km^3, ~20% less than the previous estimate of ~0.016 km^3 by Allard, et al. (1979).

A time history of micro-seismicity leading to volcanic eruption at Axial Volcano, Juan de Fuca Ridge

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Session: MOR

A small array of Ocean Bottom Hydrophones (OBHs) has been deployed and annually maintained at Axial Volcano on the Juan de Fuca Ridge in the northeast Pacific Ocean from June 2006 through present. The U. S. Navy's SOSUS hydrophone array has been the main observational tool used to monitor for volcanic seismicity at Axial since 1991. However, several key elements of the SOSUS system have gone offline in recent years, necessitating deployment of an in situ seismic array to record volcanogenic activity. The OBH records have captured increasing rates of local microseismicity emerging from the post-eruptive period of seismic quiescence following the 1998 eruption up to a recently discovered (April 2011) volcanic event. The locations of at least 11 earthquake swarms that occurred during the last 5 years leading up to the 2011 volcanic eruption are focused in the southeast region of Axial's caldera with focal depth estimates of ~1.5 km. Of the thousands of local micro-earthquakes recorded by the OBH array at Axial from 2006 to present, only two small events (ML 3.0 and 3.7) associated with the April 2011 seafloor eruption were large enough to be detected by land-based teleseismic stations and a total of four earthquakes were detected on SOSUS hydrophones in the central Pacific. A recent submersible cruise to Axial Volcano recovered two OBH moorings, with a third mooring encased in a new lava flow where it remains buried beneath the seafloor in the southern part of the caldera. Data from the two recovered OBH moorings will provide information regarding the timing, duration and intensity of the most recent volcanic event at Axial Volcano.

An application of INSAR and airborne LiDAR to analyse fault slip at the Dabbahu rift segment, Afar, Ethiopia

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Session: AMR

The influence of magma in extensional tectonic settings is widely recognised. Magmatic intrusions can cause surface fault displacement in the range of meters accompanied by only moderate seismicity. The nature of fault growth generally enables us to study only a static image of its evolution. The Dabbahu (Afar) rifting episode, which commenced in 2005 within the Afar Depression, is providing a unique opportunity to study progressive magmatically-driven fault growth. Since its onset, a total of 14 individual dyking events have been identified through InSAR and seismicity intruding the same section of the segment.

In addition to InSAR observations, a high-resolution airborne LiDAR survey was carried out in October 2009 covering the central section of the Dabbahu segment. The resulting Digital Elevation Model (DEM) covers 800 km^2 with a resolution of 0.5m. This enables us to process InSAR data at higher resolution. We calculate interferograms covering four of the dyke intrusions using L-band (23 cm wavelength) radar data from the ALOS satellite. These provide better coherence over the area of faulting and simplify the complex phase unwrapping problem. We use the interferograms to estimate the slip on some of the faults that occurred during the dyke intrusions. Here we present preliminary results comparing the observed incremental slip with the cumulative fault displacement-length patterns which have been extracted automatically from the LiDAR DEM.

Deep Structure of Aden and Red Sea margins – insight from teleseismic tomography in western Yemen

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Session: RCM

Continental rupture processes under the influence of a hot spot as well as the influence of a mantle plume on the lithosphere are still poorly known although extensively studied. The Afar plume has been largely investigated in Ethiopia by various geophysical methods, but the deep structure of continental part of Yemen, only few kilometers away, has never been imaged with enough resolution.

The YOCMAL project (YOung Conjugate MArgins Laboratory) allowed the installation of a broadband seismological temporary network on western Yemen, running from the Red Sea margin to the Gulf of Aden, and crossing the Yemeni highlands and the city of Sana'a. We used 119 teleseismic events recorded by 23 broadband stations between March 2009 and March 2010 together with a permanent GFZ station to realize a teleseismic tomography. We thus get a velocity model for the propagation of P waves in this region down to 300 km depth with a horizontal resolution reaching 25 km.

The model thus obtained shows a dramatic and localized thinning of the crust in the vicinity of the Red Sea and the Gulf of Aden, characterized by a lateral change from high velocities (+3%) to much slower velocities under the Yemeni highlands (-4%). We also illustrate the presence of magmatic underplating under the volcanic margins of Aden (velocity anomalies of about +3%) and Red Sea, in relation with the presence of seaward dipping reflectors. We also image the presence of two granitic syn-rift intrusions on the border of the great escarpment. Deeper, the repartition of velocity anomalies let us suppose a dynamic support of the highest topographies (more than 1000 m high) by an abnormal hot mantle. Our model shows a low velocity anomaly (-0.6%) that may correspond to the signature of the Afar plume beneath the SW corner of Yemen between 150 and

200 km depth. This signature does not persist beneath 200 km, but our synthetic tests indicate that its existence deeper in the mantle can not be ruled out. Finally, a low velocity anomaly under the Moho under the thick series of Yemeni Oligocene trapps could be a relic of a hot mantle that gave birth to more recent magmatic events (from 15 to 6 Ma) and active volcanism (for example at Dhamar or Sana'a).

Rifting to spreading in the Gulf of Aden

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Session: RCM

We present here a synthesis of the evolution of rifted continental margin systems in the Gulf of Aden. These margins are volcanic to the West of the Gulf of Aden, where they are influenced by the Afar hotspot, and non-volcanic East of longitude 46°E. Magnetics, gravity, seismic reflection, field observations (tectonic, stratigraphic and sedimentological) and oil-well data allow us to obtain better constraints on the timing of continental rifting and seafloor spreading. From the Permo-Triassic to the Oligocene, the Arabian-African plate is subject to distributed extension, probably due, at least from the Cretaceous, to tensile stresses related to the subduction of the Tethysian slab in the north. In Late Eocene-Early Oligocene, 34-33 Ma ago, rifting starts to localise along the future area of continental breakup.

Initially guided by the inherited basins, continental rifting then occurs synchronously over the entire gulf before becoming localised on the northern and southern borders of the inherited grabens, in the direction of the Afar hotspot. In the areas with non-volcanic margins (in the East), the faults marking the end of rifting trend parallel to the inherited grabens. Only the transfer faults crosscut the inherited grabens, and some of these faults later developed into transform faults. The most important of these transform faults follow a Precambrian trend. Volcanic margins were formed in the West of the Gulf, up to the Guban graben in the southeast and as far as the southern boundary of the Bahlaf graben in the Northeast. Seaward dipping reflectors (SDRs) can be observed on many oil-industry seismic profiles. The influence of the hotspot during rifting was concentrated on the western part of the gulf. Therefore, it seems that the western domain was uplifted and eroded at the onset of rifting, while the eastern domain was characterised by more continuous sedimentation.

The phase of distributed deformation was followed by a phase of strain localisation during the final rifting stage, just before formation of the Ocean-Continent Transition (OCT), in the most distal graben (DIM graben). About 20 Ma ago, at the time of the continental break-up, the emplacement of the OCT started in the east with exhumation of the subcontinental mantle. Farther west, the system was heated up by the strong influence of the Afar hotspot, which led to breakup with much less extension. In the Gulf of Aden (s.str), up to the Shukra El Sheik fracture zone, oceanic spreading started 17.6 Ma ago. West of this fracture zone, oceanic accretion started 10 Ma ago, and 2 Ma ago in the Gulf of Tadjoura.

Post-rift deformation of the eastern margins of the Gulf of Aden can be seen in the distal and proximal domains. Indeed, the substantial post-rift uplift of these margins could be associated with either the continental break-up, or activity of the Afar hotspot and related volcanic/magmatic activity. Uplift of the northern proximal margin was still active (e.g. stepped beach rocks exposed at 60m of 2Ma; 30m of 35200y; 10m and 2m) and active volcanoes can be inferred at depths of between 70 and 200 km beneath the margin (at 5-10 km distance from the coast). On the distal margin, heat flow measurements show a high value that is associated with post-rift volcanic activity and the development of a volcano (with flows and sills) shortly after the formation of the OCT.

The Afar hotspot is therefore important for several reasons. It allows the localization of deformation along the Red Sea/Aden system and the rapid opening of the Gulf after the continental break-up; its influence also seems to persist during the post-rift period.

Lithospheric rupturing and magmatic processes in the Rwenzori region, East African Rift

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Session: AMR

We have analysed the microseismic activity within the Rwenzori Mountains area in the western branch of the East African Rift. Recordings of a temporary station network reveal more than 800 events per month with local magnitudes ranging from -0.5 to 5.1. The hypocentre distribution is highly heterogeneous and exhibits a peak of seismic energy release in 15 km depth. The maximum extent of seismicity ranges from 20 to 32 km and correlates well with Moho depths that were derived from teleseismic receiver functions.

Additionally, we detected a small group of earthquakes at depths between 53 and 60 km in the mantle. The epicentres are located NE of the Rwenzoris, in an area where the mountains are connected to the eastern rift shoulder and where the northward propagating Lake George rift segment is presumably in its early stage. We therefore conclude that the deep fracturing is caused by magmatic impregnation and dike intrusions in the mantle lithosphere.

Relocation of the crustal events with double difference methods reveals numerous earthquake clusters in the same area. They are located in the middle crust and form pipe-like patterns with vertical extensions of 3 to 6 km. The seismic activity within each cluster lasts between a few hours up to one month with periods of quiescence of several weeks. In some cases we observe a systematic migration of the earthquake hypocentres. The corresponding magnitude distribution exhibits a b-value of close to 1 with maximum magnitudes during swarm activity between 2.0 and 4.0. Fault-plane solutions predominantly show normal faulting with T-axis trends oriented uniformly WNW-WSW, which is perpendicular to the rift axis. We think that these earthquake clusters are connected to magmatic feeding channels through the crust that originate from the heated and impregnated lithospheric mantle. Together with the detected mantle earthquakes these observations may be indicative of the initial stages of rifting and lithospheric break-up.

Comparison of seismological, geodetic, and geological observations of continental rifting in East Africa: Diffuse vs localized plate deformation

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Session: AMR

The rift valleys of eastern and central Africa transect cratons, Precambrian orogenic belts, and oceanic lithosphere, and they exhibit profound along-strike differences in the volume and composition of magmatic products, the timing of rift initiation, the pre-rift plate structure, and rift morphology. The growing evidence of frequent and sometimes volumetrically large magma intrusions, combined with the historic-recent record of damaging earthquakes, motivates our systematic comparison of seismic and geodetic moment release along the length of the southernmost Red Sea and East African rift systems. We use NEIC and historic seismicity catalogues and published sparse geodetic data to quantify the distribution and rates of seismic and geodetic strains, and we invert well-determined centroid moment tensors (CMT) for strain rate vectors within distinct rift sectors, allowing for finite width deformation zones. The maximum fault length within each sector is used to predict a maximum earthquake magnitude, providing a crude basis for evaluation of seismic hazard and catalogue completeness. The spatial pattern of moment release shows that significant deformation occurs outside the fault-bounded rift valleys and across the uplifted plateaus, extending from South Sudan through Botswana. Seismic moment rate is everywhere much less than geodetic moment rate, and the discrepancy increases with increasing degree/longevity of magmatism within the rift sectors. Thus, much of the plate boundary deformation is accommodated aseismically over the time period of observations, and short-term patterns suggest that largely aseismic dike intrusion accounts for much of the discrepancy. Opening rates are an order of magnitude less than predicted from models of geodetic data that assume deformation in narrow zones between rigid plates. Comparison of seismic moment release and effective elastic thickness shows that seismic moment release is greatest where the rift transects strong cratonic lithosphere lacking surface volcanism, as in the Western and Southwestern rift arms. Opening directions from a summation of CMT solutions within the volume of sectors with more than 5 CMTs are parallel to geodetically determined opening directions, except in the < 5 Ma N. Tanzania sector where extension initiated in deeply rooted cratonic lithosphere. The broadly distributed deformation zone may indicate metasomatic modification and bottom-up weakening of thick, cold cratonic lithosphere above the African superplume.

Afar geothermal energy resources inferred from electromagnetic (MT, TEM) and seismic data

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Session: RES

Ethiopia's modern forms of energy (foreign petroleum and hydroelectricity) are expensive and unpredictable; meanwhile energy availability is a key component for many sustainable development initiatives. Ethiopia's active volcanoes and hot springs suggest an abundance of geothermal energy, however subsurface geophysical analysis is necessary to constrain exact energy potentials and identify drilling targets. The aim of this project is to use recently recorded magnetotelluric (MT), transient-electromagnetic (TEM) and passive seismic data to quantify regional geothermal reservoir parameters (i.e. geology, temperature, fluid properties, etc.) and then interpret reservoir heat flow, energy potential and economic viability. We are exploring a potential collaboration with the Ethiopian Geological Survey that would enable sharing of data and comparison with similar studies at Tendaho geothermal field.

The propagation path of dikes under the effect of a topographic load: a boundary element approach.

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Session: AMR

The orientation of principal stresses controls the direction in which magma-filled dikes propagate. The topography of volcanic edifices modify the orientation of the stress fields in the crust and play an important role among the controlling factors of dike propagation. Here we study the path of dikes propagating under the effect of the stress field induced by the load of a volcanic edifice and by the topographic depression of a graben. By means of a 2D boundary element model, we describe the shape and the path of propagating dikes along with the stress and displacement induced in the surrounding rock. The model accounts for a possible discontinuity in elastic parameters, density and fracture toughness of the host rock and for the presence of an external stress field. The path followed by the crack is found by maximizing the release in total energy, given by the sum of the elastic and gravitational contributions. Propagation is allowed when the energy release exceeds a fracture threshold. We study the spatial distribution of the dike arrivals at the surface as a function of the initial dip angle, or as a function of the starting point of the dike. We consider three different configurations: i) a topographic load with dikes starting right under the volcanic center with different initial dip angles; ii) a topographic load with dikes starting vertically at different horizontal distances from the volcanic edifice; iii) a topography depression with dikes starting at depth of the crust-mantel boundary. We find volcanic edifices to focus dike trajectories and that a 'shadow' region with no dikes arrival and relatively shallow sills formation surrounds the volcanic center. In case of graben the dikes concentrate at a certain distance from the ridge that depends on the graben width and depth, volume and buoyancy of dikes and the magnitude of the tectonic extension. We observe deep sills formation for initial dip angles lower than a threshold value that depends on the set of parameters employed.

The stress shadow induced by the 1975-1984 Krafla rifting event

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Session: AMR

Stress changes on seismically active areas can favour or inhibit the occurrence of earthquakes. While increases in earthquake rate have been studied extensively from a theoretical point of view and demonstrated in several cases, stress shadows are rarely observed and addressed. The 1975 - 1984 Krafla rifting event is held responsible for a significant drop in the earthquake rate on the Húsavík Flatey fault (HFF), although this has never been quantitatively demonstrated. Here we apply the rate and state earthquake nucleation model to study the changes in seismicity rate due to the rifting-induced stresses. We correlate the theoretical predictions with observations from an earthquake catalogue (1995 - 2011) and historical accounts. We find the pattern of negative Coulombe stresses induced by the rifting to match very well with the zones where seismic rates are lower than expected from the historical seismicity. In particular, the HFF was invested by a large range of strongly negative to strongly positive Coulomb stresses. Positive ΔCFF values are expected to cause peaks in seismicity rate within a few years after the event, while negative ΔCFF values are expected to cause a sudden drop followed by a slow recovery with time scales depending on the magnitude of the ΔCFF. We find the cumulative seismicity from regions with small negative Coulomb stresses to display significant seismic rates increases over the 17 years period analysed and to correlate well with theoretical predictions.

Active Fault Mapping in Karonga-Malawi after the December 19, 2009 Ms 6.2 Seismic Event

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Session: AMR

Eastern and Southern Africa has potential natural hazards like earthquakes and volcanoes. Strong damaging earthquakes have occurred in the region along the East Africa Rift System. The most recent damaging earthquake is the Karonga earthquake in Malawi, which occurred on 19th December, 2009 with a magnitude of 6.2 (Ms). The earthquake claimed four lives and destroyed over 5000 houses. In its effort to improve seismic hazard assessment in the region, Eastern and Southern Africa Seismological Working Group under the sponsorship of IPPS carried out an active fault mapping project in the region targeting the Rukwa – Northern Malawi as a pilot area.

The fieldwork employed multidisciplinary techniques: geological and geophysical techniques. The geophysical techniques used are ground magnetic, seismic refraction and resistivity surveys. We give findings from geological techniques. Geological techniques aimed primarily at active fault mapping of the area in order to delineate presence or absence of fault segments. Results show that the Karonga fault , is dominated by dip slip faulting and it is made up of several fault segments (3 to 4 fault segments). Each of these fault segments can generate earthquakes of the order of 5.4 to 5.5 ±0.3.

This event has important implications, not only in terms of seismic hazard. The main interests of this event are:

- The earthquake sequence occurred on the shoaling side of the half graben, not along its master border fault,

- The event happened close to the Rungwe volcanic province (RVP), just south of it, but apparently did not involve magmatism and dyking as in the Gelai case (Calais et al., 2008).

- Both the earthquake focal mechanisms and the surface ruptures show a dominant normal faulting mechanism, which is confirmed by the modeling of Biggs et al. (2010). This area is just south of the Mbeya triple junction (RVP) where Delvaux and Barth (2010) show dominantly strike-slip stress field, with a N-S direction of horizontal principal extension. Therefore, this shows that the stress field of the RVP did not continue southwards but is restricted to the RVP.

- The North Malawi is considered in some models as a dextral transcurrent fault zone, together with the Rukwa and South Tanganyika. Here, we have a clear indication that this is not valid for the North Malawi rift. We have now have clear indications (not only focal mechanisms, but also observed surface breaks) that provides some progress on that question.

- Biggs et al. (2010) do not report surface ruptures and their interferograms are not clear about this possibility. However, in their best models are all consistent with a rupture that “either broke or came close to the surface”. We are now providing this missing information that renders the modeling results more realistic as they were predicting such surface rupture.

Magmatic Evolution of the North Tanzanian Divergence Zone: Evidence from Essimingor Volcano

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Session: AMR

The role of magmatism in continental rift initiation and evolution is of much debate. Our research focuses on a section of the magmatic-rich eastern branch of the East African Rift in Northern Tanzania that depicts the complex early stage of tectono-magmatic rift evolution. This area, the North Tanzania Divergence (NTD), is currently volcanically active with a magmatic history that initiated in the Miocene, prior to documented extension. Some of the NTD volcanoes are among Earth's largest (Kilimanjaro, Ngorongoro), and have produced a diverse array of lavas from basalt to rhyolite, trachyte, phonolite and carbonatite. Their distribution is widespread, both N-S along the rift axis and E-W across the valley floor and onto the adjacent rift margins.

The oldest NTD magmatism is recorded at the centrally located Essimingor volcano. We report 12 new $^{40}Ar/^{39}Ar$ ages, 26 major and trace element analyses and several Sr-Nd-Pb radiogenic isotopic signatures on well-located lavas representing the observable variation in lithology and stratigraphy from the S and SW slopes of Essimingor. Laser-incremental heating $^{40}Ar/^{39}Ar$ analyses of whole rock, matrix and nepheline separates yield plateau ages ranging from 5.76±0.02 Ma to 5.91±0.01 Ma, suggesting a duration of ~150 kyr. Our $^{40}Ar/^{39}Ar$ ages are roughly 2 myr younger than K-Ar ages reported previously (~8 Ma; Bagdasaryan *et al.* 1973). It is unclear if this difference is due to limitations of the K-Ar method or if the K-Ar ages were obtained from flows unsampled by our team. We note that nepheline separates from some of our samples give anomalous integrated (K-Ar equivalent) ages as old as 16 Ma, possibly reflecting excess or trapped Ar in nepheline. Incorporation of anomalously old nepheline in the whole rock samples of Bagdasaryan *et al.* could explain their older ages. Nonetheless, our $^{40}Ar/^{39}Ar$ ages support Essimingor as the oldest NTD volcano.

Essimingor major element data define narrow compositional variations consistent with fractional crystallization. Open system processes of mixing or contamination are inferred from an increase in Sr isotopic values with indices of fractionation. Ce/Pb varies over a large range (59 to 7), the lower end of which implies crustal assimilation that overprints the mantle signature. The Sr-Nd-Pb isotopic values indicate mixing between a HIMU-like component and an enriched mantle component. Trace element abundances of the more primitive samples (MgO 9 wt%) suggest partial melting of a metasomatized lithospheric mantle peridotite characterized by the presence of residual garnet and phlogopite combined with minor amphibole and apatite.

The coexistence of garnet and phlogopite in the source suggests melting at ~80–150 km depth, consistent with the base of the lithosphere in the eastern branch identified using Rayleigh wave tomography (120-160 km; Weeraratne *et al.* 2003) and indicating that Essimingor represents the initial phase of lithospheric removal. Given the absence of recorded Miocene extension we favor a model of lithospheric erosion rather than one of extensional thinning. Ongoing analysis of younger NTD volcanoes should help constrain the timing and location of the progressive lithospheric thinning during early rifting.

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Absolute gravity measurements in Afar

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Session: AMR

Absolute gravity measurements are useful to study mass transfers and to set up reference benchmarks for gravity mapping.

In the framework of the DORA project, absolute gravity measurements have been performed in 2010 in Ethiopia and Djibouti. 5 sites have been measured in Ethiopia (one in Addis Ababa and four in Afar) and 2 sites in Djibouti (one in Arta observatory and one in the Asal rift). Measurements have been done with a FG5 absolute gravimeter on concrete pillars anchored in the bedrock allowing small noise and high precision gravity values (about 1 to 2 microgals). Simultaneously microgravimetry using relative gravimeters has been performed in the Afar rift to measure again sites which had been measured twice in the 90s.

A second absolute gravity campaign will be performed in 2013 and the variation of gravity will be interpreted in term of deep mass transfers. To do this, vertical movements will be corrected using geodetic data.

In this poster, we will present the absolute gravity network and the first measurements and show the developments we would like to apply to our network (e.g. introduction of secondary sites measured by CG5 relative gravimeters along the axial part of the Ethiopian rift). Results from relative gravity measurements performed in the Afar rift will be also presented.

Local Earthquake Tomographic Imaging of Magma Chamber beneath Askja, Iceland

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Session: AMR

We have used a tomographic travel time inversion to map a pronounced low velocity anomaly interpreted as a magma chamber ~ 7 km below the caldera of the Askja Central Volcano in Iceland. We have operated a high quality seismic network of 25-30 broad-band seismometers around the Askja Volcano in the Northern Volcanic Zone since 2006. Using a subset of ~1100 well constrained earthquakes distributed across the region, P and S-wave arrival times have been used to constrain a 1D velocity model of the Askja region using the program VELEST (Kissling et al 1994). The arrival picks were then input into a finite difference tomographic inversion program (Roecker et al 2006) and used to invert for a 3D velocity model beneath Askja.

Strong (ΔVp ~ -10%) low velocity anomalies are recorded beneath the most recent caldera within the central volcano and beneath the plain to the west of Herðubreiðartögl. These low velocity anomalies are both interpreted as large magma accumulation bodies. Beneath the strong low velocity anomalies within the mid crust, poorly resolved low velocity regions extend sub-vertically into lower crust and are interpreted as melt channels linking the magma body beneath the volcano with melt ponding in the lower crust or at the Moho. Synthetic model recovery tests show that the shape of the two large low velocity anomalies are well resolved though the magnitude of the velocity anomaly could be underestimated. Additional work using travel time delays and S-wave attenuation from regional and teleseismic arrivals will add further constraints to the size and magnitude of the low velocity bodies.

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The Ogaden Dyke Swarm and other volcanic features of southeast Ethiopia

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Session: AMR

A new map of Tertiary volcanics occurrences in the Ogaden region of southeast Ethiopia and adjacent areas of Somalia has been prepared. Outcrop areas, mapped using satellite images and helicopter-supported field work in 2008, are more widespread than previously recognized, while magnetic and drill data reveal the vast subsurface extent of the magmatism. Several spectacular ‘meandering’ outcrops, over 100 km long, are undoubtedly exhumed canyon-filling flows and magnetic data show that many other apparently isolated outcrops are actually part of similar flows, the bulk of which are now subsurface. Age dating and well intersections show several volcanic episodes, with the major outpouring occurring across a broad peneplain in the Oligocene.

Geological and aeromagnetic mapping, and $^{40}Ar/^{39}Ar$ age dating, reveal a dyke swarm extending SSE from the southern Afar margin more than 600 km across the Somali Plate, and coeval with dyke injection in the Red Sea rift at ~25 Ma. The Ogaden Dyke Swarm, which occurs in an area historically considered remote from the impact of the Afro-Arabian rifting and volcanism, appears associated with the Marda Fault and marks a zone of crustal dilation along the Red Sea trend across the Horn of Africa. Contemporaneous rifts, also trending WNW/ESE and over 120 km long, occur in NE Somalia, confirming the predominantly NE/SW-directed crustal stress regime in the Ogaden and adjacent region at this time.

Evidence of Magmatic fluids contribution in epithermal gold mineralization in the SE Afar rift, Djibouti

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Session: RES

Epithermal gold mineralization have been recently investigated in the SE Afar rift (Djibouti). Mineralization are spatially associated with acidic volcanic edifices, and they occur within hydrothermal veins controlled by fracture networks. Mineralogical analyses allow us to identify different types of mineralization that correspond to different depths in the hydrothermal system: (1) surface and subsurface mineralization characterized by carbonate chimneys, gypsum, silica cap, and quartz ± carbonate veins that are depleted in metals and Au; (2) shallow banded chalcedony ± adularia mineralization related to boiling that contains up to 16 ppm gold, occurring as native gold, electrum, pyrite, and tetradymite; (3) quartz veins with sulfides (Cu, Pb, Zn, Fe) and (4) epidote alteration in the deepest hydrothermal zones. In order to infer the origin of the fluids, sulfur and strontium isotopic ratios were performed on hydrothermal veins of chalcedony, and/or quartz, ± carbonate containing gold and sulfides. Sulfur isotopic compositions of sulfides vary from –7.4 to +6.8‰. Values close to 0 ‰ are classically reported for volcanic rocks and hydrothermal fluid while the negative $\delta^{34}S$ values of sulfides can be explained by the disproportionation of magmatic SO_2 that causes the enrichment of ^{32}S in the sulfides. Strontium isotopic ratios ($^{87}Sr/^{86}Sr$) of mineralized veins range from 0.70391 to 0.70799. The lowest values of $^{87}Sr/^{86}Sr$ ratios indicate volcanic source of fluid while the highest isotopic composition indicate significant seawater contribution.

Thus, in most of epithermal mineralization in the SE Afar rift, many isotopic evidences suggest that gold-bearing fluids may have a magmatic contribution. Gold is precipitated at depth, in the high temperature part of the epithermal system in relation to phase separation.

Short living earthquake bursts in Afar region

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Session: AMR

Since 2005, during the Manda Hararo – Dabbahu rifting episode, we observed several short living seismic swarms related to dykes intrusions. These were characterised by earthquake migration from an initial point, along lengths of ten to twenty kilometres, and by durations from few hours to few days. Another point is that these swarms included several main shocks of comparable magnitudes.

Since the regional geophysical observatories of Ethiopia and Djibouti exist, several other earthquake sequences/swarms were recorded. These short living seismic bursts share common features with the swarms accompanying the dyke intrusions during the Manda Hararo – Dabbahu rifting episode, except the fact that some of them were not related to magmatic events (i.e. the 1969 Serdo and 1989 Dôbi sequences). Some of these earthquake bursts were well documented, as they were recorded by local networks.

Despite the heterogeneity of available and factual observations, we try to analyse a collection of selected seismic bursts in order to characterise their magmatic or tectonic origin, using time, space, magnitude distributions and finally waveforms.

Study of the structural evolution of the Precambrian around of the Tete city

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Session: AMR

In this study we evaluate the structural and tectonic evolution of Tete Province, through analyses of the structural elements in the area, the deformation sequence and the associated metamorphism. The basement of Tete Province is considered to be the Southern termination of the Mozambique belt of the Precambrian age. We compared the metamorphism and structural evolution of three different geological formations around Tete city. In the field we measured structural elements and collected samples. From the structural analysis we got that there are three different deformation phases (D1, D2 and D3) in the Barue Complex. As result we got that the Barue Complex shows that the Matambo's quarry and Matambo's Sub-station F2 folding oriented NW-SE and NE-SW are cut by shear zones of strike slip type with NE-SW direction (perpendicular to S2) and compressive (parallel the S2) with NS orientation resulting from the third phase of deformation. For the case of the folding, the M'Pandi F1 possesses a NE-SW shear zones that formed during the second deformation, with ductile strike slip, NE-SW orientation perpendicular to S1 and N-S extensional parallel to S1. From microscopic analysis we observed that the trend of the shear zones in the study area is NE-SW. We identified granulitic and amphibolitic facies representing the first and the second phases of metamorphism and associated deformation phases (D1 and D2) while the green schists facies can be associated with the third stage of metamorphism (regional). However, except for the outcrop of the M'Pandi, the green schists facies may be associated with a retrograde metamorphic event.

A probabilistic approach for the classification of earthquakes as 'triggered' or 'not triggered': application to diking-earthquake stress transfer

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Session: HAZ

Stress transfer in the crust can anticipate or delay the occurrence time of earthquakes by inducing a strain energy change on faults. Significant effort has been made in recent years to investigate the physical mechanisms governing stress transfer and in estimating how the probability of earthquake occurrence on faults is changed by external events. At present, earthquakes are generally labeled as `triggered' when an external event causes a dynamic or static stress increase on the fault plane. However, given that multiple error sources make it hard to establish with 100% confidence, we argue that this statement should be given probabilistically, taking into account errors in earthquake location, stress model and statistical parameters. We present a methodology to calculate the probability of the `triggered' and `not triggered' scenarios based on Bayes' theorem and the rate-and-state earthquake nucleation theory. We apply this methodology to the Jan 13th 1976 Kópasker earthquake, which is generally considered triggered by the Dec 20th 1975 dike intrusion in the nearby Krafla fissure swarm. We find that the probability that the earthquake was indeed triggered by the dike is larger by three orders of magnitude than the probability that the earthquake was due to purely to accumulation of tectonic strain. The methodology we propose can be applied to estimate hazard on active fault systems in rift zones or volcanic areas.

Multi-instrument measurements of stable cycles at Erebus lava lake, Antarctica

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Session: AMR

Persistently active lava lakes, such as that at Erta 'Ale volcano, are a rare form of volcanism exhibited by just a handful of volcanoes worldwide. These lakes, representing the exposed tops of volcanic plumbing systems, provide a unique opportunity to observe directly the magmatic processes that are normally hidden from view. The benign nature of most of their activity allows close-range measurements to be made in relative safety. During the past few years a number of techniques have been developed to exploit this and allow the study of different aspects of lake behaviour.

We present an overview of the ground-based instrumental techniques used in studying active lava lakes, some of which will be demonstrated at Erta 'Ale for those attending the Afar field trip. In particular, we introduce high temporal resolution SO_2 flux measurements using dual-field-of-view DOAS (ultraviolet spectroscopy), Fourier Transform infrared spectroscopy for measuring gas composition, radiative heat output using thermal cameras, and the use of advanced motion tracking algorithms with thermal infrared imagery to analyse the two-dimensional velocity field of the lake's surface. Limitations and pitfalls associated with each technique are discussed, as well as the practicalities of field deployment.

As a case study for these methods, we look at data collected on Mount Erebus volcano (Ross Island, Antarctica), which also hosts a continuously active lava lake. A multi-instrument study of the lake has been carried out through annual field campaigns, resulting in data from the 2004 season onwards. Periodicities are observed in many of the measurements and, using simple signal processing techniques, we are able to demonstrate that this is a stable feature of the lake's behaviour.

Analysis of EQ Catalogues Data and Remarks on EQ Forecasting

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Session: HAZ

Modern IT facilities open a wide spectrum of new opportunities and set new requirements for efficiency in both natural hazard forecasting and risk-management. We discuss the problem and illustrate some methods for estimating seismic risk. We follow a cross-disciplinary paradigm in approaching this complex scientific problem, and use statistical forecasting methods to detect patterns hidden in catalogues of recorded earthquake data.

First, we suppose that all signals collected at earthquake recording stations reflect the processes of an open dynamical system which is chaotic in both time and space. Then, we suppose that every natural catastrophe has a set of precursors, related in both the space and time scales, leading to the self-organized criticality which triggers the event. The challenge is to use these data to create a logical procedure to identify precursors and mainshocks as well as to filter out false events.

It was shown that opportunities to collect the geoinfo and to analyze the data flows let us rely on solving the problems such as crucial events forecasting, as well as the problem of short-term seismic control in a real-time mode. The problem to control the geoinformation data streams, the reasons for so-called “system-time” to be introduced, as well as the seismic shocks forecasting opportunities by means of so-called “reversal time” tools are the subjects of our approach.

We realized that restricted series like Kamchatka’s EQ Catalogue with about 50000 records since the beginning of 1962, and the Iranian EQ Catalogue with about 17000 records since the year 1900 provide us with statistical information on probabilities and return periods for EQs of given magnitudes.

We consider both general practical and theoretical results obtained with analytical processing of catalogues. For example, we found that the Entropy method could be applied to reduce a complexity of the medium term EQ forecasting problem.

We start with analysis of standard US Geological Survey EQ Catalogue collected since 1971 and compare it to the Kamchatka and Iranian analogues. Unexpectedly, we found out that the global distribution is driven with the classical Fibonacci numbers.

Then, if we introduce the inter-disciplinary parameter of Efficiency E we obtain that the differential given at the seismic mode of M=4.5 tends to E over all period of observations.

Finally, if we apply the Entropy method to estimate the predictability for Kamchatka and Iranian EQs events, we obtain the hypothesis that the Kamchatka and Iranian EQ distribution Entropy functions coincide.

Lithofacies architecture of vent proximal pyroclastic deposits and ’a’a lavas from a fissure eruption: Port a’ Chroinn, Kerrera, NW Scotland

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Session: RCM

The Port a’ Chroinn area of Kerrera, NW Scotland, preserves a spectacular sequence of vent proximal pyroclastic rocks and lavas that record eruption from a volcanic fissure. Here we present a detailed lithofacies architecture of the fissure and its associated pyroclastic deposits and lavas, and develop a model of the eruption sequence.

The main fissure zone is represented by small cones and ramparts of spatter and scoriaceous breccia that represent vent proximal pyroclastic fall deposits. The breccias are locally interbedded with basaltic-andesite ’a’a lavas fed by the fissure. Linear feeder dykes of coherent basaltic-andesite cut earlier deposits. The breccias are poorly sorted and comprise twisted spatter rags, irregular clasts of vesicular to scoriaceous basalt, and rarer blocks of coherent lava. Fluidal shaped clasts drape the spatter and scoria and represent bombs.

The fissure feeds blocky, prismatically-jointed basaltic andesite ’a’a lavas. These lavas typically have basal and flow top breccias comprising variably vesicular clinker that grades into coherent crystalline cores with abundant deformed, typically aligned, vesicles. The breccia also includes accretionary lava balls with clinker cores. In some flows the clinker is normally graded and records a transition from coherent lava blebs to rough, broken fragments. Locally, the lavas display fluidal peperitic bases indicating that they were emplaced into unconsolidated, possibly wet, sediment.

Volcanic deformation in Kenya, East African Rift

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Session: AMR

The East African Rift (EAR) system is a 5,000 km long series of fault bounded depressions that run from Djibouti to Mozambique. In Kenya, the EAR hosts 12 Quaternary volcanoes that lie along its central rift axis. An earlier InSAR study, covering the period 1997-2008, discovered that four volcanoes underwent geodetic activity during this time. These volcanoes are: Longonot, Suswa, Menengai and Paka.

We present the results of an InSAR survey of the Kenyan Rift between 2008 to 2010. During this period, frequent Envisat acquisitions were scheduled under the ESA Changing Earth Science Network. We also process a parallel dataset collected by L-band satellite ALOS, which allows us to image volcanoes obsured by vegetation at C-band. Subsidence of ~2 cm is seen at Longonot volcano, following the ~9 cm of uplift observed between 2004 and 2006. Otherwise, there have been no subsequent periods of volcanic deformation since that of Paka in May 2006 to March 2007.

The northern flank of Paka volcano uplifted by 21.3 cm over the 9 month period between 2006-2007 and the interferograms suggest some lateral transport of magma prior to the main inflation pulse. No deformation was seen in interferograms before or after these dates. Due to the large number of overlapping Envisat wideswath acquisitions, the temporal resolution possible with wideswath data is significantly greater than in background image mode. For example, during the 9 month period of inflation at Paka, there are four image mode acquisitions from one track, whereas, during the same time period, there are six wideswath acquisitions from three different tracks. Thus, by using Envisat wideswath imagery, we will better constrain, temporally and spatially, the period during which Paka deformed.

Volcanic surface deformation is traditionally interpreted as the change in volume due to the movement of incompressible magma. However, magmatic intrusions deep within the crust can provide an input of heat and volatiles perturbing an overlying hydrothermal system that may cause ground deformation. Future work will be concentrated on determining the driving mechanisms of the volcanic deformation in the Kenyan East Africa Rift between 1997-2008.

'Melange': A lattice-particle model applicable to lithospheric extension

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Session: AMR

The software 'Melange' is a newly developed 3D lattice-particle hybrid model. The software was specifically designed in order to simulate tectonic processes in the lithosphere. It allows the calculation of the stress field, of dynamic fracture formation and of ductile creep as a result of externally applied deformation. It does also allow the simulation of the topographic surface due to tectonic processes such as rifting.

The software development was motivated in order to study continental breakup and rift formation caused by 1st order extension. Special focus is on the development of the Albertine rift system in the Western Branch of the EARS, including the formation of the Rwenzori transfer zone. Thus, a number of examples from this field are presented. These examples include the structural development and the state of stress of intra-continental rifts and rift transfer zones.

A model for the deformation of the lithosphere has to consider the different rheologies of upper and lower lithospheric layers. Thus, both relevant yield mechanisms are taken into account: dynamic brittle failure and ductile creep. The software is further capable to consider the effects of the local geology, the inherent disorder of geo-materials and the rheological layers of the lithosphere. Also, the role of gravity is adequately considered.

The most important innovation of the software is a new scheme which permits the physically consistent modelling of viscoelasticity. The scheme couples the local lattice-geometry to the time-dependent deformation of particles. Deformation is caused by the local deviatoric stress tensor. With this procedure the typical ductile/viscoelastic stress-strain relationship is achieved, while volume conservation of the system and of individual particles is guaranteed. Further, the scheme allows adequate consideration of gravity, a vital precondition for the simulation of large scale geo-tectonic systems.

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Tsunami hazard from the continental Dead Sea rift

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Session: HAZ

Historical accounts of earthquakes and tsunamis in the Levant show that most of the tsunamis in the eastern Mediterranean followed strong earthquakes that were originated along the on-land Dead Sea Rift System. Such was the 1202 earthquake of which there are paleoseismic evidence in Lebanon and Israel and written reports of a tsunami along the coasts of Lebanon and Cyprus.

Detailed analysis of the historical reports together with the seismotectonic framework and the bathymetry of the Eastern Mediterranean region, allowed for the construction of its tsunamigenic framework, including a rough estimate of the worst case scenarios and its return periods. The marine earthquake sources include the Cypriot and the Hellenic arcs and the continental margins of Egypt and Sicily. Regarding the on-land tsunamigenic earthquakes, it appears that the Dead Sea fault system, mainly the transform and its associated branches, trigger considerable submarine slumps along the continental slope of the Levant, and those landslides generate the tsunamis.

It was thus possible to define and simulate tsunami scenarios from all the various sources and learn about the maximum expected wave height and downdraft at the shoreline and most importantly, delineate the zones of potential inundation.

Furthermore, understanding the tsunamigenic architecture of the Levant helped us to modify the tsunami decision matrix of that region. The basic matrix has already been constructed by the IGC/NEAMTWS (Intergovernmental Oceanographic Commission, North Eastern Atlantic and the Mediterranean and Connected Seas, 2009), in accordance with the worldwide experience, and it focuses mainly on large-scale earthquakes that may generate regional and basin-wide tsunamis. However, most of the historical tsunamis that hit the Levant are considered local and as such are not covered by the matrix. Therefore, the matrix was calibrated according to the maximal distance (100 km) and minimal magnitude (M~ 6) of the assumed epicentre and magnitude of those historical tsunamigenic earthquakes.

Since the majority of the tsunamis in the Levant will most probably originate from local M6 earthquakes, the first warning signal will be the strong shaking. Therefore, there is no need to wait until a sophisticated warning system gets into operation and people should be taught to protect themselves from a tsunami by moving away from the sea as soon as they feel the strong shaking. The second natural warning signal, although may not always appear, is a drop in the sea level and retreat of the water. Indeed, some tsunamis may arrive from remote sources that will not be strongly felt and may start with a rise in sea level, but these are the minority of the events.

Multidimensional time series analysis of ground deformation from SAR data acquired in various orbital geometries

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Session: AMR

In this work we present methodology for producing multidimensional time series of ground deformation from SAR data acquired by sensors with various acquisition geometry, ground resolution, and wave band. This technique is based on the Small Baseline Subset (SBAS) method that is modified to produce horizontal and vertical time series of ground deformation.

The proposed method has four main advantages:

1) it achieves combined temporal coverage over an extended period of time when data from many different sensors with different temporal coverages are available;

2) temporal resolution of produced time series increases since it includes the combined sampling from all data sets, which helps to observe signal in more details and also to improve the quality of post-processing (i.e. filtering);

3) two or three components of ground deformation vector are computed, which helps in interpretation of observed ground deformation and further modeling and inversion;

4) various sources of noise (i.e. tropospheric, ionospheric, topographic, orbital, thermal, etc.) are averaged out during the processing improving a signal-to-noise ratio.

We apply this technique to SAR data acquired by ERS-1/2, ENVISAT, Radarsat-2 and ALOS starting from March of 2003 until July 2010 over Virunga Volcanic Province (DR Congo) in order to produce time series of ground deformation. We successfully observe pre- and co-eruptive signals and lava compaction signals with good precision.

On the importance of geosites that may become a national heritage - with examples from the Albertine Graben in Uganda and sites close to the Gregory Rift (on Ugandan side)

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Session: RES

Geosites are important and/or unique geological or geographical features of significance such as natural/geological, palaeontological and archaeological sites. They should be regarded as sites deserving to be preserved and protected, e.g. from elements such as weather or from destructive human activities, for the community and future generations. A good knowledge of geological heritage, and a healthy respect for it, is an important factor in the holistic approach for sustainable development.

About 10 years ago Schlueter et al. (2001), Schumann et al. (2001), Schumann and Muwanga (2003) made a first attempt to list some of the relevant sites in Uganda. However, while more sites have been mentioned, many of them were still lacking a proper documentation of the location, including GPS co-ordinates, the status of its preservation, protection status, geological environment, or other general details about the site itself.

Within the framework of the Uganda Geological Mapping Project, under the umbrella of the Geological Survey of Finland (GTK) and the Department of Geological Survey and Mines (Uganda), about 60 sites have been visited, and essential information has been recorded in a more descriptive manner. Such sites will be incorporated in the new geological maps of the country. The sites are a fundamental part of Uganda's natural heritage and can be a source of revenue as tourist destinations, with great scientific/educational and cultural importance.

Few examples of Ugandan geosites will be given, with a special focus on sites where additional research has been done. This improves on the knowledge about the spot, and bridges the gap between a more descriptive documentation of a site and its scientifically explained significance, history, and value.

It is hoped, that further research is done on Ugandan geosites, and the information collected shall be documented in a national registery.

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Nyiragongo volcano (D.R. Congo): study and monitoring of the lava lake

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Session: HAZ

Nyiragongo volcano (North Kivu, Democratic Republic of Congo) is one of the most active volcanoes in Africa and probably also one of the most dangerous as it directly threatens a population estimated to about 1 million persons. Its main activity corresponds to the presence of a ± 200m wide active lava lake hosted in its main crater and from which a semi-permanent SO_2-rich gas plume is released.

In 1977 and 2002, fissure opening on the volcano flanks drained the lava lake and triggered fast lava flows that destroyed villages and a part of the city of Goma within few hours only. Since the reappearance of the lava lake in late 2002, magma in the central open conduit frequently overflows the crater's bottom platform. The level of that platform and the magma level in the open conduit rise up to tens of metres per year, increasing the edifice instability and the amount of molten lava present in the crater. A new eruption similar to the 2002 event could lead nowadays to a major disaster with severe social and economical impacts for the Great Lake Region of Central Africa.

Paradoxically, there is currently no continuous monitoring of the lava lake activity. The lava lake level has so far been estimated subjectively using punctual field observations or photographs. Given the importance of that parameter in assessing the eruption risk level, new efforts are deployed to monitor the lava lake level rising. A Stereographic Time-Lapse Camera System (STLC) has been developed and installed in the crater during the last 10-days field expedition on top of Nyiragongo and inside its main crater in September 2011. That system should enable us to create repeated 3D models and quantitatively assess the lava lake level variations. During the field expedition, other physical and chemical parameters were measured, such as seismicity, ground deformation, CO_2 concentrations and temperature in fumaroles, and radon emissions.

Geodynamic framework of the western part of the Virunga Volcanic Province (North Kivu, D.R. Congo)

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Session: AMR

The western branch of the East African Rift (EAR) is formed by the succession of rift basins linked by transfer zones. These accommodation zones are characterized by Volcanic provinces and oblique-slip transfer faults. This is the case of the Virunga Volcanic Province (VVP), which is located between the Lake Edward basin to the North and the Lake Kivu basin to the South. Nyiragongo and Nyamulagira volcanic fields form the western part of the VVP. Both volcanoes represent a serious hazard for the region and directly threaten a population estimated to about 1 million persons.

Understanding the volcanic and tectonic activity and assessing their related hazards in the VVP cannot be made without understanding its complex geodynamic framework. The existing literature offers several structural maps. However, these maps present large differences.

We present here new insights into the geodynamic framework of the western part of the Virunga Volcanic Province based on field observations and geomorphological analysis of the SRTM DEM, the bathymetry of Lake Kivu (Lahmeyer-OSAE, 1998) and very high resolution optical images. This is complemented with an extended literature review of peer-reviewed articles published in international and local scientific journals, as well as unexploited archives available at the Royal Museum for Central Africa (Belgium) such as unpublished field reports, field notes and Theses dating from the Colonial times.

The preliminary results suggest some large differences with the most recent structural maps (e.g. Villeneuve, 1980), especially for the western end of the VVP and the northern part of the Lake Kivu basin.

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Uppermost mantle (Pn) velocity model for the Afar region, Ethiopia: An insight into rifting processes

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Session: AMR

The Afar Depression, Ethiopia, offers a unique opportunity to study the transition from continental break-up to oceanic spreading because the process is occurring onland. Using travel-time tomography, we describe the first regional study of uppermost mantle P-wave velocities (Vpn) from a recent temporary seismic deployment in Ethiopia. The results show two very low Pn velocity (as low as 7.2km/s) zones in regions of localized stretched and thinned crust, near to and beneath areas of contemporary crustal intrusions of magma (active magmatic segments). This suggests that these localized magmatic segments are fed from areas of melting in the uppermost mantle. Both ongoing plate thinning causing decompression melting and removal of melt from the asthenosphere into the plate could be contributing to the process. The low Vpn areas in northern Afar also share spatial characteristics with the uppermost mantle beneath slow-spreading mid-ocean ridges, indicating that discrete areas of mantle upwelling and partial melting during seafloor spreading are initiated by localized thinning during the final stages of breakup.

Tsunami Disaster Management: A Study of Indian Ocean Tsunami 2004 in Sri Lanka

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Session: HAZ

Natural disasters have affected mankind the world over since time immemorial leaving behind a trail of fury and havoc of unimaginable proportions. Natural disaster such as flood, cyclone, drought and earthquake and tsunami has become a regular in our life. They are catastrophic events with multi-dimensional impact on pattern of life. This necessitates an effective disaster management mechanism that could provide immediate relief followed by future reconstruction and rehabilitation efforts. It calls for a multi-pronged approach at the national and local levels to reduce to the risks and vulnerability of the populace affected by disaster. On December 26, 2004 a severe earthquake measuring 9 on the Richter scale struck the Indian Ocean near Banda Ache province of Indonesia resulting in a devastating tsunami which affected several countries across Asia and Africa. This tsunami is the biggest ever, in terms of the earthquake that triggered it as well as the extent of destruction it caused, in recent history. Sri Lanka was paralyzed by the tsunami. It was the most serious catastrophe in the country's history that created a worldwide display of sympathy for Sri Lanka. This paper mainly focuses on the impact of Tsunami on Sri Lanka. It also focuses on the subsequent management activities undertaken to mitigate, minimize, and prevent, if possible, the havoc caused by this natural disaster.

Empirical Statistical Modeling of Seasonal Rainfall Prediction over Southern Ethiopia

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Session: CLI

Statistical-empirical models were developed to investigate how global rainfall predictors relate to the March-May (MAM) and September-November (SON) rainfall seasons over southern Ethiopia. Data utilized in this study include station rainfall data, oceanic and atmospheric indices. Because of the spatial variations in the interannual variability and the annual cycle of rainfall, an agglomerative hierarchical approach and Ward's minimum variance method of cluster analyses were used to delineate a network of 21 stations over study area into five homogeneous rainfall regions in order to derive rainfall indices. Time series generated from the delineated regions were later used in the rainfall/teleconnection indices analyses. The methods employed were correlation analysis, multiple linear regressions. Results obtained from the analysis revealed that SST variations and atmospheric anomalies were the main drivers of seasonal rainfall variability. Although SSTs account for the majority of variance in seasonal rainfall, a moderate improvement of rainfall prediction was achieved with the inclusion of atmospheric indices in prediction models. When the adjusted coefficient of determination is considered, the September- November (SON) rainfall explained by the model ranges from 67.3% - 91.9%, while the March-May (MAM) rainfall explained by the model ranges from 52.6%-77.7%. An inspection of the results of the model validation using different statistics clearly indicates that the models are reproducing and describing the pattern of the rainfall for the sites of interest. Therefore these models can be exploited further in operational seasonal climate prediction over southern Ethiopia.

Thermochemical state of the mantle transition zone beneath east Africa

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Session: MLI

The mantle transition zone (MTZ, roughly 410-660 km depth) beneath east Africa is a key region to our understanding of mantle convective processes, upper-lower mantle mass flux and, ultimately, continental rifting. How the African Superplume interacts with this region is still a matter of considerably debate, and the presence of either a broad zone of upwelling vs. a narrow plume-like feature remains unresolved. Here, we present new constraints on the MTZ beneath Ethiopia by integrating seismic data from the EAGLE, EKBSE, RLBM, Afar Rift Consortium, and new deployments in Eritrea along with permanent stations across the horn of Africa. The combination of these networks will give us unprecedented coverage of the MTZ across a suspected plume-affected region. The relative positions of the 410 km and 660 km seismic discontinuities, along with their frequency-dependent amplitude characteristics, will give insights into the thermochemical state of the MTZ beneath east Africa. Comparison with complimentary seismic, geochemical and geodynamical studies will also provide an opportunity to link the results to the regions tectonic evolution.

Geochemistry of Rwenzori Hot Springs, Western Uganda

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Session: RES

Mountain Rwenzori is located in the western rift valley in Uganda and it comprises a host block elevated between faults. Rwenzori up warp lies between two down warps of the rift valley. On the eastern front it is bordering with Fort Portal volcanic field whose relationship is not investigated. The mountains are covered by permanent ice and snow, with a total of 37 small glaciers and ice fields covering an area of 64 km^2. The mountains are surrounded by hot springs, hydrothermal deposits and gaseous emissions on either side. Under the GEOTHERM programme, funded by the Germany Government, a study was carried out on the hot springs of Buranga. It was felt appropriate to study the surrounding hot springs and other geothermal features to investigate the relationship anticipated. Several geochemical trends, highly correlated, indicate a genetic relationship of these springs having been subjected to different degrees of mixing and partial equilibration. Stable isotopic studies favor recharge of Buranga hot springs from high up in the mountains.

The hot spring waters have no detectable amounts of tritium indicating; possibly they are older than 60 years. These hot spring waters range from bicarbonate to sulphate chloride. Using the Na-K-Mg ternary plot a linear trend is discernable pointing to a possible genetic link of these hot springs possibly affected by different degrees of mixing and partial equilibration. Geothermometry cannot be applied to some of these hot waters (like Rwimi) because they are too immature. The rest of the springs have a predicted sub-surface temperature of about 150°C consistent with outflow systems discharging carbon dioxide. Qualitatively high bicarbonate contents can be taken as an indicator for comparatively low temperature systems possibly outflows. Most of these hot springs deposit travertine with the exception of Kibenge and Muhokya. Br/Cl ratios of Buranga hot springs fall in the range 0.00451 to 0.0112. This is somewhat higher than sea water (typically 0.00347) and possibly points to a non-marine, non-evaporate source of bromide and chloride.

The high salinity and presence of predominant sulphate may suggest that magmatic of volcanic sources are of major importance. Isotopic range of carbon-13 and oxygen-18 of travertine at Buranga indicates magma-derived carbon as the probable origin of the CO_2 that dissolved into fluid from which travertine precipitated. Strontium values indicate water rock interaction with granitic gneisses. Since Rwenzori is made up of crystalline basement metamorphic rocks the plausible reservoir would be a fracture controlled one. Helium studies favor a magmatic heat source for Buranga hot springs.

Geological mapping of the Manda-Hararo rift, Afar

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Session: AMR

We present a new geological map of the Manda-Hararo rift segment in the Afar Depression. The mapping approach involved remote sensing and three-dimensional image analysis of topography and surface rock chemistry based on mineral maps generated from false colour Landsat, ASTER, hyperspectral (Eagle and Hawk) imagery and aerial photographs. Combinations of different remote sensing images, band combinations and processing maximised the opportunity to identify geological boundaries. We combined the datasets within GeovisionaryTM software with Lidar, SPOT5 and ASTER derived DEMs for interpretation within an immersive visualisation suite enabling simulation of a fieldwork-based investigation. Interpretations derived from this approach were ground-truthed by targeted field studies. This high-resolution mapping technique established eruption history of the area at the scale of individual eruption units. As a result, basaltic fissure vents and the volumes and extent of individual lava flows have been identified for central volcanoes and the Manda-Hararo rift axis. Results show a spread of eruption sites and vent character about the axis of the rift segment rather than repetitive eruptions from central fissure vents. High-resolution mapping is an important tool for interpretation of the timing and relationships of rifting and volcanism in the East African Rift and for future hazard mitigation and risk reduction work.

Melting and Fast Melt Transport - Ingredients for plausible Rift Induced Delamination

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Session: MLI

Basic physics of our numerical models is the thermomechanics of visco-plastic two-phase flow including phase transitions, depletion and enrichment. It is approximated by FDCON, a code applying Finite Difference Method with markers in an Eulerian formulation in 2-D. The equations of conservation of mass, momentum and energy are solved for a multi-component system. Rheology may be temperature-, pressure- and stress-dependent. By numerical experiments and systematic studies later on, we try to explore conditions and parameter ranges for rift induced delamination (RID).

The motivation origins in the special situation of the Rwenzori Mountains (RWZ) located inside the western branch of the East African Rift System. It is one of the key issues in the RiftLink project. The old metamorphic horst is encircled almost completely by the southward propagating Lake Albert Rift and northward spreading Lake Edward Rift. Despite the extreme topography up to 5 km the RWZ crustal thickness has rift values of about 24 km. Nearby young low volcanic activity and intense seismicity match bull's eye pattern, often a fingerprint of delamination.

Instead applying a strong ad hoc initial temperature anomaly, as in former one-phase flow models (Wallner & Schmeling 2010, 2011), and due to observations, indicating on partial melts, a sophisticated concept of melt induced weakening (MIW) is employed.

By MIW we conceive an assemblage of intertwining processes. Additional heating (supplied by a plume branch, seen in tomography) generates incipient melts in the upper astheno-sphere. Percolation and accumulation of these partial melts lump to regions with high melt fractions. Exceeding a certain threshold, melt is extracted and transferred energetically to a higher level. For this, we assume a short time scale transport mechanisms such as channelling or dyking, which we do not model. Within the mantle lithosphere or even in the lower crust the melt's energy weakens its surrounding after probably repeated emplace-ments. Thus, advective heat transport is accelerated by non-linear rheology. Depletion and enrichment associated with phase changes is considered.

Essential conditions and parameters controlling successful RID models are searched and studied. Temperature background level with respect to the melting curve, especially in the asthenosphere, is important; an increase about 100 K intensifies convection and lets the lithosphere-asthenosphere boundary rise up. Additional temperature anomalies in the asthenosphere, offset ca. 50 km from central axis, focuses uprising melt batches, its amplitude determines the delay time of detachment; for some million years 150 K are needed. The level of an emplacement zone for extracted melt must comprise the uppermost strong mantle lithosphere, which has to weaken to allow mechanical decoupling of the laterally clamped central block. Yield strength in the lower crust must be low to enable it to fail, if stressed.

Seismicity distribution, low velocity zones seen in receiver functions (Wölbern et al. 2010), tomography (Jakovlev et al. 2011) and the localization of an anomalously deep earthquake cluster (Lindenfeld et al. 2011) as well as petrological and geochemical arguments (Foley et al. 2009, Link et al. 2010) establish RID hypothesis.

Phanerozoic basalts dykes from the Precambrian basement of the southern continental part of the Cameroon Volcanic Line: Geodynamic implications

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Session: AMR

The Precambrian basement of the southern continental part of the Cameroon Volcanic Line (CVL) is cut by two regional lineaments: the N70°E Adamawa Shear Zone (ASZ) of Precambrian age which extends from Central Africa to the Red Sea and the CVL with a N30°E orientation and an extension from the Atlantic Ocean in the Gulf of Guinea to Lake Chad. Geologically, the region is formed by a granitic Precambrian basement crosscut by phanerozoic basalt dykes and a volcanic cover with dominant basaltic rocks of alkaline and tholeiitic affinities. If the ASZ is well known as the prolongation into Africa of the Pernambuco shear zone in North East Brazil (before the opening of the south Atlantic Ocean during the Mesozoic), the CVL is subject to various interpretations including an oceanic rift at its initial stage.

Basalt dykes found in the Precambrian basement of the southern part of the CVL are centimetric to metric and are mainly oriented N25°-35°E. The study of brittle deformation resulted in the determination of the following dominant directions of fracturing: N10 -20 ° E, N80 -100 ° E, N120 -130 ° E and N170 -180 ° E. Interpretation of these preliminary results in the framework of the Riedel fracturation model considering a sinistral shearing along ASZ indicate that:

-Major directions of fractures in the studied area are consistent with a Riedel model in which the Cameroon Volcanic Line appears as a tension gash.

-Directions of mafic volcanic dykes are consistent with the major direction of the Cameroon Volcanic Line

-Tectonic relations thus exist between the studied dykes and the Cameroon Volcanic Line and the modeling of basalt dykes propagation and the tectonic evolution of the region are needed for a good contribution to the discussion on the nature and origin of the Cameroon Volcanic Line

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Geophysical mapping in a Geothermal field

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Session: RES

Geophysics is the study of the earth by the quantitative observation of its physical properties. In geothermal geophysics, we measure the various parameters connected to geological structure and properties of geothermal systems. Geophysical field mapping is the process of selecting an area of interest and identifying all the geophysical aspects of the area with the purpose of preparing a detailed geophysical report. The objective of geophysical field work is to understand all physical parameters of a geothermal field and be able to relate them with geological phenomenons and come up with plausible inferences about the system. Four phases are involved and include planning/desktop studies, reconnaissance, actual data aquisition and report writing. Equipments must be prepared and calibrated well. Geophysical results should be processed, analysed and presented in the appropriate form. A detailed geophysical report should be compiled. This paper presents the reader with an overview of how to carry out geophysical mapping in a geothermal field.

Assessing lava flow hazard at Mount Cameroon Volcano, West-Central Africa with a probabilistic maximum slope model

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Session: HAZ

Mount Cameroon is a steep volcanic horst covered by successions of lava flows and scoriae deposits. It has a flat summit plateau, a rift zone defined by a linear cluster of eruptive vents, a deep valley in the northern flank, topographic steps at the base together with numerous faults and fissures mostly trending N40E. It has erupted seven times in the last 100 years: 1909, 1922, 1954, 1959, 1982, 1999, 2000 and stands as the most active volcano along the Cameroon Volcanic Line (CVL). The CVL is a major tectonic feature in West-Central Africa that runs SW-NE following a major left-lateral fault system that extends for more than 2000 km, from Pagalu Island into West-Central Africa. At Mount Cameroon, the frequent emplacement of lava flows reaching agricultural land and villages e.g. in 1922, 1959 and 1999; the rapidly increasing population density on the lower flanks of the volcano (~ 450,000) and the intense agricultural activities taking place on the fertile volcanic soils increased the need to assess lava flow hazard and risk from this volcano. This paper utilises a combination of techniques: fieldwork, remote sensing (RS) and numerical modelling to map historical lava flows, investigate lava flow dynamic processes from its morphology and produce lava flow hazard maps for the Mount Cameroon region.

This was realised by intensive field survey of the 1982 and 2000 lava flow fields achieved by means of cross-sections made at the proximal, medial and distal portions. The results indicated dominant channel-fed aa-flow field morphologies for the 1982 flow and site 1 of the 2000 flow field. Tube-fed pahoehoe morphologies dominated at sites 2 and 3 of the 2000 lava flow field. Field observations for these lava flow fields were supplemented with satellite images (Landsat, ASTER, SRTM, MODIS) and textural analysis to better interpret their eruption chronology and dynamics. Channels and levees were the observed large scale structures on these flow fields. The significance and possible mode of emplacement of the observed features was interpreted based on processes observed at other basaltic volcanoes.

The rheology of these lava flow fields were retrieved from their surface morphologies. This information together with petrographic and channel geometrical data collected were used to model these flows with the FLOWGO model which is a thermo-rheological model. This model's performance was evaluated based on its ability to reproduce the total length and the internal channel geometry observed for these lava channels. FLOWGO was later on combined with VORIS (a probabilistic model) to assess the spatial distribution of lava flow hazard at Mount Cameroon. The result was the generation of lava flow hazard maps that delineated the SW flank of the volcano as having the highest probability of lava flow invasion over the entire volcano. The resulting maps would help local authorities in making the necessary decisions to deal with ongoing eruptions and to plan long-term land use policies.

Nyiragongo Volcano Eruption, 2002, as Constrained by InSAR data

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Session: AMR

On 17 January 2002, Nyiragongo volcano erupted along a 20 km long fracture network extending from the volcano to the city of Goma. The event was captured by InSAR data from the ERS-2 and RADARSAT-1 satellites acquired with three different beams. A combination of 3D numerical modeling and inversions is used to analyze these displacements. Using Akaike Information Criteria, we determine that a model with two subvertical dikes is the most likely explanation for the 2002 InSAR deformation signal. Both dikes have a trend parallel to the rift axis in the region. A first, shallow dike, 2 km high, is associated with the eruptive fissure, and a second, deeper dike, 6 km high and 40 km long, with its top located about 3 km below the city of Goma, extends for 20 km beneath the gas-rich Lake Kivu. This indicates that the interaction of magma and dissolved gas in the lake should be considered as a significant hazard for future eruptions. A likely scenario for the eruption is that magma supply to the deep dike started eleven months before the eruption, as indicated by LP events and tremor. A stress analysis indicates that this deep dike could have induced failure of the shallow magma reservoir and magma column beneath the permanent lava lake, followed by the injection of magma from the lake and shallow reservoir into the shallow eruptive dike. The deep dike induced the opening of the southern part of this shallow dike, to which magma from the deep dike was transmitted though a narrow dike. This model is consistent with the geochemical analysis, the lava rheology and the pre and post-eruptive seismicity. Since the dikes are parallel to the rift and have sub-vertical dips, the direction of both the 2002 eruption dikes, and the 1977 eruptive fissures, is probably controlled by the rifting process.

Multi-origin hazard study and assessment of associated risks in the Lefo Caldera of the Bamenda Volcano (Cameroon Volcanic Line)

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Session: HAZ

The Bamenda Volcano (BV) (2621m) is a stratovolcano situated in the Cameroon Volcanic Line (CVL) precisely between Mount Bambouto (2740m) and Mount Oku (3011m). It is characterized by numerous types of rocks that have been dated between 27.4 and 0.36 Myr (Kamgang et al., 2010). BV includes Mount Lefo (2534m) which is situated in the southern slopes and contains one elliptical caldera; precisely between 10°11' and 10°15' East and, 05°46' and 05°50' North. This caldera is propitious to farming and breeding activity. Despite these profitable assets, the Lefo caldera (LC) is an amphitheater of the occurrence of multi-origin hazard that have direct or indirect impacts on the biodiversity and human patrimony.

The most present hazards are that of meteorological origin. Numerous combined factors rule these hazards; such as steepest slopes, heavy rainfall (average of 400mm of rains in July, August and September), high velocity of wind current (more than 4.4m/s), loose state of pyroclastic materials, weathered state of volcanic products (trachytes and ignimbrites). These factors gave rise to the occurrence of the mass movements such as landslides which leaved around 17 gullies (average of 3m deep and 5m width each) on the caldera internal slopes and bottom and, rock falls which occur precisely on caldera northern and eastern rims, where prismatic trachytes and ignimbrites are found.

The hazard of anthropogenic origin is based on the destruction of the vegetal cover [mainly eucalyptus (average of 40m high)] by the population (around 300 people) for dealing, firewood and building issues. This behavior led to the loss of more than 75% of trees in the whole caldera. Moreover, during the breeding activity, the cattle cover the caldera throughout the day; this uneven the topography and destroy the meadow made up of grasses.

The hazard of volcanological origin is not yet present in LC; but the recent Lake Monoun and Nyos CO_2 eruptions (respectively in 1984 and 1986), the mount Cameroun eruptions in 1999 and 2000 as well as that of mount Oku Lake in 2011 which are close to the BV, constitute a subject of controversy toward the reactivation of the Cameroonian hotspot faults. Accordingly, the resumption of volcanic activities can intervene at any time in the LC as well as in the whole BV.

The assessment of risks in the LC was based on the average income of breeding activity and house investment. The calculation revealed that, the economy of the LC represents about US$527,472.527. In order to reduce the level of looses in this zone, hazard and risks maps are provided in this paper as well as some recommendations.

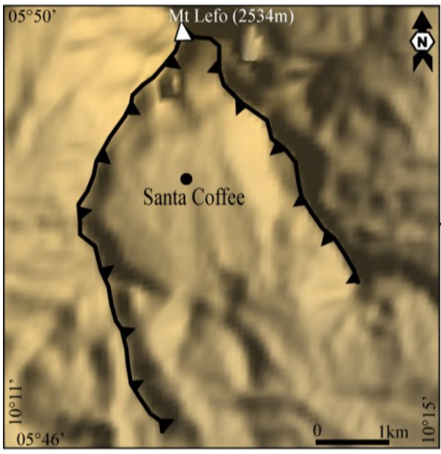

Fig. 2: Digital Elevation Model of LC

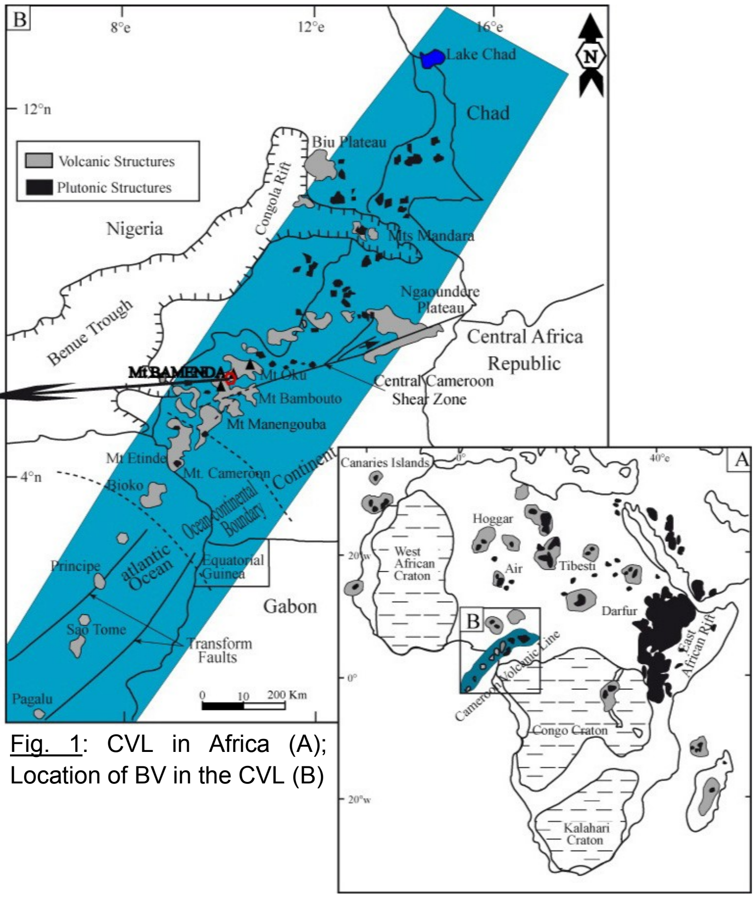

Fig. 1: CVL in Africa (A); Location of BV in the CVL (B)

The Magmatic Rifting and Active Volcanism Conference, 2012

The 2010 Eyafjallajökull eruption demonstrated that active volcanism on magmatic rifts can have a considerable impact on society, even well beyond its immediate location. In the past decade, new findings from active magmatic rifts on the continents, rifted margins and mid-ocean ridges have shown the importance of magmatism in governing the style of continental rifting and seafloor spreading. The meeting is being held to mark the end of the 5-year Afar Rift Consortium project and brings together people investigating the causes and impact of magmatic rifting and active volcanism in a variety of tectonic settings to share their latest findings. The meeting includes contributions that encompass processes occurring from the deep mantle to the surface.

The Afar Rift Consortium

The Afar Rift Consortium is a major project funded by the UK Natural Environment Research Council (NERC). The consortium is made up of scientists from the Universities of Leeds, Bristol, Oxford, Edinburgh, and Cambridge, and the British Geological Survey, with partners in Ethiopia, France and the US. Since 2007, it has been conducting a major series of geophysical, geological and geochemical surveys in the unique natural laboratory of the Afar Rift. The aim has been to understand how plate rupture and crustal growth is achieved through the processes of lithospheric thinning and magma intrusion.

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