Plate boundaries often coincide with the densely-populated margins of continents, and relatively large earthquakes occur at these boundaries. Much attention has been paid to seismic hazard assessment and earthquake preparedness in continental areas located along or near these boundaries. In contrast, a relatively small number of earthquakes, accounting for approximately 0.5% of the total global moment release (Johnston and Kanter, 1990), are not directly related to plate boundaries and are therefore termed intraplate earthquakes (Fig. 1). Though limited in number, their consequences can be disastrous, as is illustrated by a very recent example, the Mw = 7.7 earthquake of 26 January 2001 in Bhuj, India. As a result of this earthquake at least 20,000 lives were lost, more than 200,000 people were injured and nearly 400,000 houses destroyed (Rajendran et al. 2001). Whereas plate boundary earthquakes are well understood, the mechanisms that cause intraplate earthquakes are subject to considerable debate. In this paper we discuss some common features of intraplate earthquakes, and summarize hypotheses for the mechanisms that trigger these events. We conclude by describing new global datasets that may hold the key to understanding intraplate seismicity, and introduce some new research directions that we feel may be productive.

### S52F-0183 1330h POSTER

## Localized Weak Zones and Their Role in the Generation of Intraplate Seismic Zones: Effects of Weak Zone Geometry and Rheology

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It has been proposed that earthquake generation within intraplate seismic zones (e.g. the New Madrid Seismic Zone, NMSZ, in the south-central United States) may result from the transient relaxation of a lower crustal weak zone. As the weak zone relaxes, stress is transferred to the overlying seismogenic crust, potentially leading to a geologically short-lived burst of seismicity lasting 10,000's of years. The duration and number of earthquakes in this seismic sequence is dependent on weak zone geometry and rheology. Using finite element techniques which employ contact surfaces to model discrete faulting events, we investigate the relevant model parameter space as it effects the concentration of stress at the base of seismogenic fault. Faulting is modeled using discrete contact surfaces and failure is governed by a maximum shear stress criteria evaluated at each node on the fault surface. Investigated model parameters include weak zone geometry, weak zone rheology (Maxwell and Standard Linear Solid, SLS), earthquake stress drop, background tectonic stress, and maximum shear stress at failure. Of particular interest is the effect of model geometry and rheology. Wider weak zones transfer stress to areas potentially remote from fault leading to initially slower slip-rates. After complete relaxation, however, the cumulative moment is greater then for the narrow weak zone case. Prior models have considered only a Maxwell viscoelastic weak zone, which has no long-term elastic strength. This may not be a realistic intraplate material behavior. Thus, this study also considers a SLS weak zone which has a long-term elastic strength. This may be more realistic, though the long term elastic strength becomes an additional parameter which must be defined. Although the amount of stress available for transfer to the seismogenic zone is potentially decreased when a SLS is used, for certain parameters, 2-4 earthquakes still occur during the relaxation process. A number of different effective rheologies and geometries are considered and results have been compared to geologic observations in the NMSZ.

### S52F-0184 1330h POSTER

## Evaluation Of Seismic Gap To Candidate Regions For Coming Significant Earthquakes In Iran

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All historical background and instrumentally recorded earthquakes in present century indicates that Iranian Plateau is seismically active. However, the rate of activity is not uniformly distributed and changes from one place to another. For example, in Zagros structure zone, the seismic activity is high and relatively uniform, characterized by moderate earthquakes. On the other hand in Alborz mountain region the seismic activity does not indicate a regular pattern and the accumulated seismic energy is being released by relatively large and intensive earthquakes. In eastern Iran similar to Alborz, shows an irregular seismic activity pattern and several destructive earthquakes were recorded during this century. In this study taking into account both historical and present century recorded earthquakes data; we investigated the areas that show a kind of quiescent period which will increase the possibility of an occurring earthquake in these regions. This phenomenon if it is proved could be considered as a precursory and can be used as long-term prediction for the purpose of mitigation of disaster and saving human lives.

### S52F-0185 1330h POSTER

## Swarm Activity of Low Frequency Earthquakes beneath Ashio Region, Central Japan

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It is well known that the depths of almost all inland earthquakes are shallower than 15 km, and this cut-off depth can be interpreted as a brittle-ductile transition zone. However, a few earthquakes with depths ranging 20 km to 40 km have been observed. These anomalously deep events have lower dominant frequencies for both P and S waves than the corner frequencies expected from those magnitudes which based on ordinary earthquake source spectrum model. These events are termed Deep Low-Frequency earthquakes (DLF). Recently, a high sensitivity seismograph network (Hi-net) is installed by National Research Institute for Earth Science and Disaster Prevention (NIED), and we can obtain high-density high-gain seismic data in Japan. On 2002 March 11, we recognized swarm activity of DLF in Ashio region, central Japan. More than 140 DLF events were observed within only 4 hours. The first time we locate the hypocenters, it seemed that the hypocenters migrated westward about 2 km during this activity. This is very fast migration compared with previous study which reported that DLF hypocenters migrated toward west about 2 km during half a year. Then we obtain high resolution relative hypocenters of similar earthquakes (22 events) by cross spectral analysis method and double-difference earthquake location algorithm. Relocated DLF hypocenters didn't show remarkable migration. The distribution of DLF hypocenters like a vertical disk (with radius 700 m and thickness 200 m and the strike EW) which suggest some structure of lower crust. We analyzed some DLF events to get focal mechanisms by using a waveform inversion method. The result is that some of DLF focal mechanisms have almost the same P-axis directed west-southwest.

# S52G MCC: 3009 Friday 1340h

## African Superswell Province: From Core to Crust III *(joint with T, V)*

***Presiding:*** **G R Keller,** University of Texas at El Paso**; P Maguire,** University of Leicester

### S52G-01 1340h

## Deep Upwelling Beneath the Northeastern Afro-Arabian Continent?

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A large low shear-wave velocity anomaly is observed at upper-mantle depths beneath the northeastern Afro-Arabian continent, from the Turkana depression, South-West of Ethiopia, to the Red sea and South of Arabia. The question of connection between this anomaly and a source of material rising from the lower mantle is of major concern for understanding how a plume associated with the African superswell could interact with the upper mantle structure in the region. Thanks to the deployment of five broadband stations in Ethiopia and Yemen (INSU-RLBM), complementing several sets of broad-band stations in Arabia, Ethiopia and Djibouti (IRIS, Geoscope, PASSCAL) we address this question by using two broadband seismological tools: 1) higher-mode surface wave tomography and 2) receiver function technique. Higher-mode surface waves tomography shows a clear low shear-wave velocity anomaly down to 400 km depth beneath the Ethiopian plateau and the Afar depression. In a paper by Debayle et al. (2001), no continuity of this anomaly with a deeper low-velocity anomaly is observed beneath Ethiopia. Instead, a deeper low-velocity anomaly (down to 500-600 km depth) was observed farther north beneath the Red Sea and South of Arabia, suggesting a possible link with lower mantle material rising there. Applying a SVD receiver function technique to a set of broad-band records from Arabia to Ethiopia, including Yemen, we discuss the above suggestion by looking at the seismic discontinuities of the upper-mantle transition zone.

### S52G-02 1355h

## Plume, Lithospheric Interaction and Small-scale Convection Beneath Africa from Anisotropic Tomography and Geochemical Data

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A high resolution three-dimensional tomographic model beneath Africa has been derived by using seismic data provided by the French seismic experiment named "Horn of Africa" complemented by permanent (GEOSCOPE and IRIS networks) and temporary experiments in this region. By simultaneously inverting for seismic velocity and anisotropy of the upper 400km of the mantle, two kinds of mantle plumes are revealed. The first one, the Afar plume is coming from deeper than 400km (at least from the transition zone), and the second kind of plume is the consequence of the complex interaction between the asthenospheric mantle flow, the plume head and the lithosphere. If anisotropy direction is considered as a good marker of convective flow in the upper mantle, the flow in the asthenosphere (100-300km) is to first order, close to the almost South-North plate motion of the African plate except around the Afar hotspot where it is diverted and gives rise to secondary convection in the East-west direction with a wavelength around 1000-1500km. This small-scale convection can explain the existence of the Darfur, Tibesti, Hoggar and Cameroon hotspots and their geochemical signature different from the Afar hotspot. The origin of this second kind of hotspot is then confined to the asthenospheric upper mantle in the space left between african cratons.

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### S52G-03 1415h

## Geochemical Overview of the East African Rift System

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Mafic volcanics of the East African Rift System (EARS) record a protracted history of continental extension that is linked to mantle plume activity. The modern EARS traverses two post-Miocene topographic domes separated by a region of polyphase extension in northern Kenya and southern Ethiopia. Basaltic magmatism commenced ~45 Ma in this highly extended region, while the onset of plume-related activity took place ~30 Ma with eruption of flood basalts in central Ethiopia. A spatial and temporal synthesis of EARS volcanic geochemistry shows progressive lithospheric removal (by erosion and melting) as the degree of rifting increases, with basalts in the most highly extended areas recording melting of depleted asthenosphere. Plume contributions are indicated locally in the northern half of the EARS, but are absent from the southern half. The geochemical signatures are compatible with a physical model in which the entire EARS is fed by a discontinuous plume emanating from the core-mantle boundary as the South African Superswell. Quaternary basaltic lavas erupted in the Afar triangle, Red Sea and Gulf of Aden define the geochemical signature attributed to the Afar plume ($^{87}Sr/^{86}Sr$ 0.7034-0.7037, $^{143}Nd/^{144}Nd$ 0.5129-0.5130; La/Nb 0.6-0.9; Nb/U 40-50). These suites commonly record mixing with ambient upper mantle having less radiogenic isotopes but generally overlapping incompatible trace element abundances. Within the Ethiopian dome both lithospheric and sub-lithoshperic contributions can be documented clearly; lithospheric contributions are manifest in more radiogenic isotope values ($^{87}Sr/^{86}Sr$ up to 0.7050) and distinctive trace element abundances (e.g., La/Nb <2.0, Nb/U > 10). The degree of lithospheric contribution is lowest within the active Main Ethiopian Rift and increases towards the southern margin of the dome. The estimated depth of melting (65-75 km) is consistent with geophysical observations of lithospheric thickness. In regions of prolonged volcanism the lithospheric contributions and estimated melting depths decrease through time, corresponding to a higher degree of rifting. In the Kenyan dome, including the western rift, the degree of extension is low and lithospheric melting is the dominant source for basaltic magmatism. Mafic lavas from these regions have generally lower MgO but higher contents of alkalis, P2O5 and many incompatible trace elements than are observed in the Ethiopian Rift. High values of $^{87}Sr/^{86}Sr$, $^{207}Pb/^{204}Pb$ and Zr/Hf relative to other parts of the EARS indicate melting of metasomatized lithosphere. Melting in this area occurs at depths up to 100+ km, consistent with the thick crustal section observed seismically. Between the topographic domes, basalts from the Turkana region record melting at shallow levels ($\sim$35 km) consistent with seismic evidence for nearly complete rifting of the crustal section. The geochemistry of these lavas is dominated by asthenospheric source materials, with only minor lithospheric involvement. Temporal evolution of EARS geochemistry reflects progressive rifting of the thick craton. This change is manifest within lavas that are interpreted as plume-derived, as Tb/Yb values decrease from 30 Ma through the present. The modern thermal anomaly associated with Afar volcanism does not appear to extend below the shallow mantle, but may reflect a large blob of deep mantle material that became stuck to Africa 30 Ma and has contributed to regional volcanism ever since. Relative contributions from this deep mantle source, shallow asthenosphere and lithosphere are controlled by the extent of rifting and cannot be predicted solely on the basis of surface topography.

### S52G-04 1435h

## Magma Genesis during Continental Rifting: Isotopic Constraints from Quaternary lavas of the Main Ethiopian Rift

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The East African Rift System (EARS) provides an unparalleled opportunity to study the links between tectonic activity and magma genesis in a plume-driven continental rift setting. As an example, the geochemistry of primitive EARS lavas offers detailed information about the interplay between lithospheric and sub-lithospheric magma sources in the continental rifting process. In order to test for geographical control on this process in the active Main Ethiopian Rift, we have studied magnesian basalts from five Quaternary volcanic centers in the Main Ethiopian Rift (MER: Fantale, Kone, Boseti, Gedemsa, and Tulu Moye), which lie immediately south of the highly extended Afar region. Incompatible element ratios (e.g., Zr/Nb, La/Nb) and isotopic data (Sr,Nd) of these MER lavas trend towards primitive earth values, signaling incorporation of both enriched and depleted mantle components. There are, however, lithospheric or crustal overprints in the more evolved basaltic samples (those with MgO < 6 wt. %), as have been found in the southern portion of the study area (1). Both isotopic and incompatible trace elemental signatures of the more primitive samples support the notion of increased lithospheric involvement in the generation of basaltic magmas with increasing distance from the Afar region. This phenomenon of lithospheric erosion during the onset of continental rifting has been observed in other temporally controlled suites in the EARS (e.g., (2),(3)) as well as other sites of continental rifting (e.g., (4)). High precision Pb isotopic analyses currently underway on the Quaternary MER samples will provide a more detailed picture of the number of source contributions and the nature of the mixing and transport processes significant in the genesis of MER lavas. (1) Trua et al., Chem Geol, 155, 201-231, 1999. (2) Furman and Graham, Lithos, 48, 237-262, 1999. (3) Furman et al., J Pet, in press (4) DePaolo and Daley, Chem. Geol. 169, 157-185, 2000.

### S52G-05 1450h INVITED

## Understanding the Transition From Continental to Oceanic Rifting in the Northern Ethiopian Rift the EAGLE Project

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A consortium of UK (Leeds, Leicester, Royal Holloway, Edinburgh,), US (Stanford, UTEP, Penn State,) and Ethiopian (Addis Ababa) universities are exploring the kinematics and dynamics of continental breakup through the Ethiopia Afar Geoscientific Lithospheric Experiment (EAGLE), which aims to probe the crust and upper mantle structure between the Main Ethiopian (continental) and Afar (ocean spreading) rifts. EAGLE is a multi-disciplinary study centered around a set of passive and controlled-source seismic experiments, and incorporates additional magnetotelluric, gravity, GPS and petrological studies. The initial Phase I seismic experiment consisted of a deployment of 30 broadband seismometers for a period of 16 months (Oct. 2001 to Jan. 2003) over a 250 km x 250 km area of the rift valley and its uplifted flanks. P- and S-wave tompography from teleseismic traveltime residuals, SKS splitting analyses and receiver functions provide images of crust and deep earth structure. The Phase II seismic experiment consisted of a further 50 broadband instruments for a period of 4 months over a 200 km x 100 km area encompassing 4 magmatic segments in the Main Ethiopian Rift. These recordings have furthered our understanding of the location of active seismicity, fault plane mechanisms and segmentation of rift crustal structure. Phase III consisted of the deployment of a further 1100 seismic instruments during a controlled source seismic project involving 20 shots being fired into one 450 km cross-rift profile (Profile 1), one 450 km axial profile (Profile 2), and a dense 2D array of instruments in a 150 km diameter circle around the profiles intersection (Profile 3), all centered on the magmatically active Nazret region. The crust and upper mantle velocity models derived provide estimates of total crustal thinning across the rift, assess the role of basement in the location of major faults and magmatic segments, and determine whether significant underplating takes place. An 18 sounding magnetotelluric profile along the cross rift profile I provides additional constraints on the nature and distribution of crustal heterogeneity, and images melt accumulation zones. New gravity and geodetic information have also been acquired.

### S52G-06 1510h

## Initiation and Along-Axis Segmentation of Seaward-Dipping Volcanic Sequences Captured in Afar

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The Afar triple junction zone provides a unique opportunity to examine the early development of magmatic margins, as respective limbs of the triple junction capture different stages of the breakup process. Initial rifting in the southernmost Red Sea occurred concurrent with, or soon after flood basaltic magmatism at 31 Ma in the Ethiopia-Yemen plume province, whereas the northern part of the Main Ethiopian rift initiated after 12 Ma. Both rift systems initiated with the development of high-angle border fault systems bounding broad basins, but 8-10 My after rifting we see riftward migration of strain from the western border fault to narrow zones of increasingly more basaltic magmatism. These localised zones of faulting and volcanism (magmatic segments) show a segmentation independent of the border fault segmentation. The much older, more evolved magmatic segments in the southern Red Sea, where not onlapped by Pliocene-Recent sedimentary strata, dip steeply riftward and define a regional eastward flexure into transitional oceanic crust, as indicated by gravity models constrained by seismic refraction and receiver function data. The southern Red Sea magmatic segments have been abandoned in Pliocene-Recent triple junction reorganisations, whereas the process of seaward-dipping volcanic sequence emplacement is ongoing in the seismically and volcanically active Main Ethiopian rift. Field, remote sensing, gravity, and seismicity data from the Main Ethiopian and southern Red Sea rifts indicate that seaward-dipping volcanic sequences initiate in moderately stretched continental crust above a narrow zone of dike-intrusion. Our comparison of active and ancient magmatic segments show that they are the precursors to seaward-dipping volcanic sequences analogous to those seen on passive continental margins, and provides insights into the initiation of along-axis segmentation of seafloor-spreading centers.

### S52G-07 1525h

## Faults, Fissures and Flexures: Upward Propagating Normal Faults in the Koka Magmatic Segment, Main Ethiopian Rift System.

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Where do normal faults nucleate? The intra-rift structural fabric of the Main Ethiopian Rift System (MER) provides constraints on normal fault growth models, with a recent interpretation arguing for nucleation in the near-surface consequent on the downward propagation of surface fissures. Examples of genetically related fissures and normal faults occur within the Koka Magmatic Segment near its southern termination against the Asela Border Fault. Considerable along-strike variations in displacement are evident, resulting in flexure of the rift floor. Ramps, breached ramps, hanging wall anticlines and footwall synclines indicate that normal faults have grown by segment linkage. Fault spacing, throw, and back tilting decrease toward the intra-rift axial zone, which comprises subparallel grabens separated by narrow, occasionally synclinal, horsts. Fissures on the order of 1 to several meters wide occur within these grabens and have similar length scales to primary segment lengths revealed by linkage structures along the normal faults. Commonly, fissures are located at the top of narrow monoclinal flexures trending parallel to the axial graben. Where a throw (< 1-2m) occurs across the fissure, the associated flexure is more subdued. Monoclinal flexures continue for some distance (generally < a few 10s of meters) beyond the lateral tips of the associated fissure, though their curvature reduces significantly. Partially filled fissures of similar width occur at the foot of steep normal fault scarps with throws of > 20m. Thus, there appears to be an evolution from small-offset fissure to large-offset fault. The top-down fault nucleation model invokes fault drag as a consequence of higher friction at the fissure-fault transformation depth to explain the observed surface flexure. However, examples of monoclines without fissures or with small poorly connected fissures occur both along the graben floor and within hanging walls of large normal fault splays, suggesting that in some cases flexure development precedes fissure development. This may arise as a consequence of upward propagation of a blind normal fault nucleated at depth, which induces warping and associated fissuring in cover materials; or alternatively, as a consequence of localised sub-surface mass transport into or out of the axial zone.

# S52H MCC: 3011 Friday 1340h

## Collateral Damage: Earthquake Source Characteristics I *(joint with T)*

***Presiding:*** **S Baher,** U.S. Geological Survey**; J Ampuero,** Princeton University

### S52H-01 1340h

## Systematic Determination of Earthquake Rupture Directivity and Fault Planes From Analysis of Long-Period P-Wave Spectra

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If an earthquake has a primarily unilateral rupture, the pulse width observed on seismograms will vary depending on the angle between the rupture direction and the takeoff vector to the station. We have developed a method to estimate the amount of pulse broadening from the spectrum and apply it to a long-period