the IT region the 21/10/1995, Mw 7.1, H 165 Km, Rebollar et al., 1999); 7) The events with a thrust fps are aligned in a NNE-SSW and a NW-SE bands, these two bands intersect each other at Cuauthemoc, the P axis of the events with H< 40 Km have the same direction than the Cocos plate, the P axis of the events with H between 40 and 100 Km are subhorizontal, and for the events with H> 100 Km their P axis increase their inclination angle; 8) Several shallow events H< 30 Km with normal and thrust fps were also detected, these events were associated to surficial intraplate activity in the region (Ramirez, 2000); 9) We consider that the N-S and NE-SW stress directions mentioned above are due to the Cocos plate subduction in the IT region, and that the NW-SE stress direction is probably associated to the interaction of the Chiapas Batholit and the left lateral fault system of southeast Mexico with the Cocos plate, we also think that the compresive stresses in the N-S and NW-SE directions acting in the same IT zone where the E-W tension stresses are also present, bring the equilibrium in this part of the IT; 10) The source parameters of the 44 events are: $1.2 \leq \mathrm{Mw} \leq 2.8$, $10.3 \leq \log_{10}\mathrm{Mo} \leq 12.7$, $5.6 \leq fc \leq 13.2$ Hz, $0.1 \leq \Delta\sigma \leq 4.6$ bars, $0.1 \leq r \leq 0.3$ Km.

S71D MCC: 133 Sunday 0830h

Plumes, Hot Spots, and Calderas I

(joint with G, GP, OS, T, V, DI)

Presiding: **R B Smith,** University of Utah**; M Wilson,** Leeds University

S71D-01 0830h INVITED

Hotspot Motion and Shape of Plume Conduits as Inferred From Global Mantle Flow Models

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Mantle plumes are frequently inferred as cause of hotspots, however alternative explanations exist as well. Different models of hotspot origin can be tested by comparing how well they are able to explain existing observations, or predict expected observations associated with hotspots. As a contribution to such a comparison, we use here a model of plumes distorted by global mantle flow to compute hotspot motion and conduit shape. Both can be compared to observations: For the hotspot motion, paleomagnetic results may indicate hotspot latitude in the past. For both Hawaii and Kerguelen hotspot, suitable results exist, and indicate a more northerly location in the past. A southward motion of roughly the right magnitude is also a robust feature of our model results. In combination with plate motion models, it is also possible to compute geometry and age progression of hotspot tracks and compare these to observations. In this context, our models yield a motion of the Easter hotspot towards Hawaii and Louisville hotspots at a speed of several cm per yr, hence a predicted age progression along the Easter hotspot track on the Nazca plate that is measurably faster than for assuming fixed hotspots. For the Yellowstone hotspot, our models tend to yield westward motion, beginning with several cm per year and slowing down with time, hence an age progression on the North American plate measurably faster than for a fixed hotspot. Conduit shapes can be compared to seismological results (areas of transition zone thinning, tomography). For Iceland, a robust prediction of our model is a conduit coming up from the south; this prediction has been confirmed by seismological results that indicate thinner transition zone to the south of Iceland. For a Yellowstone plume, a conduit coming up from the west is predicted. Not all hotspots may be underlain by deep mantle plumes, and the comparison of our predictions with observations may help to assess which hotspots are more likely candidates for a deep mantle origin.

S71D-02 0850h INVITED

The General Theory of Plate Tectonics; No Role for Lower Mantle Components, Thermals or Other ad hoc Adjustments

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Plate tectonics introduces chemical,thermal,viscosity,melting and density inhomogeneities into the mantle and stress inhomogeneity into the plates.Idealized models often assume uniform mantle, rigid homogeneous plates ,non-passive mantle, and ad hoc explanations for island chains, melting anomalies and continental breakup. Plates, however, drive and break themselves and organize the underlying mantle, in common with other cooled-from-above systems.Pressure, often ignored in simulations, suppresses thermal expansion and the Rayleigh number making the deep mantle a sluggish system with gigantic features, consistent with tomography,and isolating it from the upper mantle and plate tectonics (except by conduction and gravity).Large scale chemical stratification is therefore likely. Plate tectonics, with adjectives such as rigid, homogeneous, isothermal, fixed, subsolidus, reservoir, steady-state etc. dropped, is a much more powerful concept than generally believed. Cracks, rifts, dikes, incipient plate boundaries, melting anomalies and variations in melt volume and chemistry are natural parts of the general theory of plate tectonics. The long-sought alternative theory to deep mantle plumes may just be a less restricted view of plate tectonics. It appears to be the adjectives, assumptions and other baggage that are the problem. Many of the geochemical paradoxes associated with deep plumes and primordial views of the mantle can be traced to the reservoir concept where deep seismic boundaries are assumed to delineate reservoirs. The mantle is heterogeneous, as it should be from plate tectonic considerations (recycling, inefficient melt and gas extraction, history).This suggests that sampling theory and dispersed components may explain the diversity of basalts. The central limit theorem (CLT) predicts that large scale averagers, such as ridges, should have less variance and less extreme values than xenoliths,inclusions,seamounts or OIB, as observed. Homogeneity is achieved by partial melting, averaging and magma chamber processes, not by large scale convection. This idea is tested with Os and He isotopes, which are as different from each other and from the standard isotopes as possible. The conclusion is that both MORB and OIB are products of a heterogeneous upper mantle, sampled in different ways (volume of mantle averaged, degree of melting, magma chamber processes). The CLT plus mass balance calculations obviate the need for an undegassed reservoir or lower mantle components . High 3He/4He components can be ubiquitous in the shallow mantle but only expressed in OIB, off-axis seamounts and other volcanic systems sampling small mantle volumes, or at the onset of volcanism.

S71D-03 0910h INVITED

Tomographic Constraints on Plume Imaging

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Recently emotions are running high in the earth science community on the debate whether or not plumes/plume-like structures are existing.
Much of the seismological evidence for the existence of plumes stems from the tomographic imaging of structures interpreted to be hot spot related or plume-like. In this paper we shall review some of the recent results of tomographic imaging of plumes of different scales as well as discuss some tomographic constraints on plume imaging, such as
the general limitations of tomographic imaging of deep structures,
the issue of resolution and
the influence of different methodologies and/or colour-coding on the images and their interpretation.

S71D-04 0930h

Detection of Mantle Plumes Under Hotspots

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The mantle plume hypothesis is now widely accepted to explain hotspot volcanoes, but direct evidence for actual plumes is weak, and seismic images are available for only a few hotspots. In this work, whole-mantle tomographic images under 45 major hotspots on Earth are presented. Slow anomalies are revealed in the mantle under almost all the hotspots. Plume-like, continuous slow anomalies in the entire mantle are clearly visible under Hawaii, Iceland, Jan Mayen, Cobb, Eifel, Louisville, Canary, Cape Verde, Kerguelen, Tibesti, Tahiti and other five hotspots in the South Pacific, suggesting that mantle plumes under those hotspots originate from the core-mantle boundary. The slow anomalies under those hotspots usually do not show a vertical pillar shape, which suggests that plumes are not fixed in the mantle but can be deflected by the mantle flow. As a consequence, hotspots are not fixed but can wander on the Earth's surface, as evidenced by recent paleomagnetic and numeric modeling studies. In many cases, slow anomalies under the hotspots are complex around the transition zone. A thin low-velocity layer is visible right beneath the 660 km discontinuity under some hotspots, which reflects ponding of plume material in the top part of the lower mantle. Under a few other hotspots, slow anomalies spread laterally just above the 660 km discontinuity. The variety of behaviors of the slow anomalies under hotspots reflects strong lateral variations in temperature and viscosity of the mantle, which controls the generation and ascending of mantle plumes as well as the flow pattern of mantle convection.

S71D-05 1005h INVITED

Proof of plumes, or richness of plate tectonics?

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Large volcanic provinces are traditionally attributed to plumes of hot material rising from the core-mantle boundary. However, with ever-improving quantity and quality of data, there is growing awareness that the most fundamental predictions of the plume model are often not confirmed by observation. At well-studied areas such as Iceland and Yellowstone, multiple predictions of plume theory may be tested. Evidence for high, plume-like temperatures is absent in petrology and heat flow. At Iceland, and most other hotspots, there is no hotspot track. Volcanism there has always coincided with the mid-Atlantic ridge, and has not migrated as predicted by models of relative hotspot fixity. The mantle low-velocity anomaly extends no deeper than the mantle transition zone. At Yellowstone, superimposed on widespread basaltic volcanism, there is a time-progressive track of silicic volcanism that has an orientation consistent with the fixed-hotspot reference frame. However, there, the mantle seismic low-velocity anomaly clearly does not extend deeper than 200 km, arguing against a downward-continuous plume. In both regions, high maximum values of helium isotope ratios are observed, generally assumed to indicate plume-transported, lower-mantle material. Other observations, however, are incompatible with either Iceland or Yellowstone being the products of deep mantle plumes, suggesting that voluminous melt, time-progressive volcanic tracks, high helium isotope ratios and OIB geochemistry may result from shallow processes. Such observations may thus not be used as conclusive evidence for plumes elsewhere. Alternative theories can explain the holistic observations at volcanic provinces with less special pleading and fewer coincidences than the plume model. Excess melt may be produced by variations in fertility, e.g., remelting recycled oceanic crust in old subduction zones and sutures. This is predicted to generate much greater volumes of melt than passive upwelling, and can also explain OIB geochemistry. Local EDGE convection, and melt focusing at the juxtaposition of thick cratons and thin, young crust, also predict anomalous melt volumes and can explain volcanic margins. High helium-isotope ratios may be preserved by storage of ancient helium in low U, Th rocks, e.g., the mantle lithosphere, and time progressive magmatism may result from the propagation of cracks where intraplate extensional strain gradients exist. Large volcanic provinces clearly have various genesis mechanisms, and cannot all be attributed to one cause. Alternative theories must be critically discussed as part of the work of data interpretation and should take precedence over plume models where they are more consistent with the observations as a whole.

S71D-06 1025h

Effects of Variable Melt Productivity and Active Mantle Upwelling on Trace-Element and Isotopic Composition of Hotspot Magmas

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We examine the effects of variable melt productivity and upwelling rate on the composition of magmas generated by mantle plumes. Melting of peridotite with relatively high concentrations of highly incompatible elements and volatiles is expected to begin at greater depths than for more depleted peridotite. The deepest melting is expected to occur at a minimal rate of melt production per increment of decompression (i.e. melt productivity) and to liberate melts with maximum concentrations of incompatible elements. In addition, the rate of upwelling, and thus decompression melting, in a buoyant mantle plume is expected to be relatively high at the base of the melting zone. As melting proceeds, melt productivity increases substantially, incompatible element concentrations decrease, and mantle decompression rate decreases. Together these effects predict pooled melts with greater concentrations of incompatible elements compared to models that do not include a deep zone of low melt productivity and active mantle upwelling. We consider these effects on the mixing of melts derived from a heterogeneous mantle source in which an incompatible-element-enriched component begins melting deeper, in an expanded zone of low melt productivity, and a more depleted component begins melting shallower, in a smaller zone of low productivity. We also assume the enriched component has relatively high ^{87}Sr/^{86}Sr and low ^{143}Nd/^{144}Nd.

Beneath young/thin lithosphere, the effects of a deep low-productivity zone and active upwelling are minimized; thus magmas are only moderately enriched in incompatible elements and are isotopically similar to the depleted source component. Beneath lithosphere of greater age, where melting stops deeper, the effects of the deep low-productivity zone and active upwelling become increasingly important. Predicted magma compositions become increasingly enriched in incompatible elements and isotopically more similar to the enriched source component. These predictions are consistent with the observations of relatively low ^{87}Sr/^{86}Sr, high ^{143}Nd/^{144}Nd and a smaller total range of isotopic variability at hotspots near mid-ocean ridges compared to intraplate hotspots, and with observations along the Hawaiian-Emperor Chain. We do not require mixing with depleted upper mantle to explain the compositions of near-ridge hotspots. More broadly, compared to models that ignore a deep low-productivity zone and active upwelling, our models can account for many geochemical differences among hotspots, and between hotspots and mid-ocean ridges, with a smaller range of mantle source composition.

S71D-07 1040h

Why Don't Hotspots Move?

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Seismological observations suggest that the lowermost mantle contains superposed thermal and (intrinsically denser) compositional boundary layers that are laterally heterogeneous. Moreover, characteristic ”ultra low seismic velocities” may imply that the dense layer contains metals or partial melt, and thus it is reasonable to expect the dense layer to have a relatively low viscosity.

We use analog experiments to investigate the mechanical and thermal interaction between flow into plumes ascending from a thermal boundary layer at the base of the Earth's mantle and an underlying dense, low viscosity chemical boundary layer. Our experimental observations and theoretical scaling analyses show that the dense layer may be deformed by the flow of thermal boundary layer fluid into ascending plumes. The amount of deformation of the dense layer depends on the stabilizing density difference and the viscosity differences between the dense layer, the thermal boundary layer, and ambient mantle, respectively, and has two important effects on the convection. First, the dynamic coupling between resultant topography and motions driven by lateral temperature variations stabilizes the pattern of flow. In particular, plumes become fixed spatially when hot, buoyant fluid is able to ascend along the sloping interface with the low viscosity fluid more easily than rising vertically into the overlying fluid . We find that smaller relief on the dense layer is needed to stabilize the flow when the viscosity ratio is large. Second, the entrainment of dense, low viscosity fluid establishes structurally robust cylindrical conduits that remain intact for time scales much longer than the time for plume rise.

When our results are applied to the Earth we find that the presence of a dense layer at the base of D” causes mantle plumes to become fixed in space. Moreover, the entrainment of low viscosity fluid from the dense layer enables plumes to persist for hundreds of millions of years and influences their composition. Our results may resolve a basic conundrum in mantle dynamics that hotspots remain approximately fixed in space relative to each other for time scales much larger than the time for a plume to rise through the depth of the mantle.

S71D-08 1055h

Spots yes, hot barely or not

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A change in ideas about the origin of midplate hotspot swells has been the recognition that the elevated topography does not reflect significant excess heating of the shallow portions of the lithosphere. Initial models of individual swells like that at Hawaii [Crough, 1978] and and broad South Pacific superswell [McNutt and Judge, 1990] implied that the lithosphere was thinned dramatically, such that temperatures within its upper parts were raised by hundreds of degrees. Although analyses of heat flow data were interpreted as showing the expected elevated heat flow, subsequent analysis showed that the assumed-high swell heat flow was at most only slightly higher than that of oceanic lithosphere of comparable age elsewhere [Stein and Stein, AGU Geophysical Monograph 77, 1993]. This analysis, which has been confirmed by subsequent studies, precludes the possibility that swell lithosphere at shallow depths is significantly hotter than elsewhere for comparable age, as assumed in the thinning and reheating models, in accord with the observation that neither the maximum depth of earthquakes at Hawaii [Wiens and Stein, 1983] or the velocity structure along the Hawaiian swell shown by surface wave dispersion [Woods and Okal, 1996] differ from those observed for lithosphere of comparable age elsewhere. Although the simplest interpretation of these data is that lithospheric temperatures at swells have not been elevated significantly, because these data types are sensitive to temperatures in the upper lithosphere, they are consistent with models which predict some heating of the lower lithosphere so long as it occurs at depths great enough that the additional heat has not had time to be conducted upward and raise temperatures in the shallow lithosphere.

S71D-09 1110h

A Third Type of Hotspot: Volcanism Produced by Horizontal Flow in the Asthenosphere Combined With a Variation in Lithosphere Thickness

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There is a north-south straight line marked by four small leucite-rich eruptions in eastern Australia whose direction and age progression agree perfectly with the direction and rate of the nearby Tasmantid seamount chain. The voluminous basalts of this region are near the coast of Australia, more than 100 km from the leucite-eruptions which have more congruence with the shape of the Australian coastline than with any plate motion direction. Remarkably these coastal basalts have the identical age progression of the leucitite eruptions (Duncan and McDougall, Intraplate Volcanism in Eastern Australia and New Zealand, 1989). We show that the ascent of a rising plume beneath Australia could be halted at the lid of deep continental lithosphere (at a depth where only tiny amounts of the enriched leucite-melt phase are formed). A few of the leucite magmas make it to the surface, but the bulk of the upward flow of the plume is deflected, traveling horizontally beneath the continental lithosphere towards the Tasman Sea. Where the lithosphere markedly thins (from continental to oceanic thickness), the sublithosphere flow experiences a decrease in pressure and the resulting pressure-release melting produces the extensive volcanism along the entire eastern coast. The location of the volcanism at a given time is given by the site of variation in plate thickness and is not precisely at the point above the ascending plume.

The same mechanism can be applied to a unique volcanism along the coast of eastern Asia bordered by back-arc basins. Some asthenosphere on the back-arc side of the trenches off Asia is dragged down/entrained by the down-going slab. This lost volume of asthenosphere is replenished by horizontal flow of asthenosphere from beneath the continent of Asia. At the transition of the lithosphere from continental thickness to oceanic thickness, the material flowing from the continent rises, and the associated pressure-release produces scattered volcanism form Vietnam to north of Korea. This volcanism has no causal relation to hotspots, but the deep melting at the base of the lithosphere produces a low-percent-melt, alkalic-enriched chemical composition very similar to the composition of true hotspot volcanism.

S71D-10 1125h INVITED

Structure and Physics of the Eifel Plume, Europe

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Volcanic eruptions occurred in the Eifel mountains, Central Europa since Mesozoic time. Two new volcanic fields evolved in the last 600 ka with the last eruptions only 11-12 ka B.P. Coincident uplift (up to 250 m in 600 ka) occurred in the region. To study the deep structure of the Eifel region 10 European institutions shared their facilities to operate a network with 84 permanent and 158 mobile stations including 32 broadband instruments during an 8 months field experiment. The network had a 500 km by 500 km aperture and the mobile stations were deployed between Nov 1997 and June 1998. Here we present images obtained from teleseismic tomography and their geodynamic interpretation. The P-wave model contains a column-like low-velocity anomaly (LVA, -1% to -3%) in the upper mantle underneath the Eifel volcanic fields reaching down to at least 400 km depth. The S-wave model has a prominent LVA of up to -5% in the upper 100 km of the mantle. At 200 ± 50 km depth there is no clear S-wave velocity anomaly. Below the S-wave velocity reduction is about -1%, and it extends at least to the transition zone. Teleseismic P-wave attenuation shows a strong absorption anomaly in the lithosphere and a weaker anomaly in the mantle. The lithospheric anomaly is interpreted as scattering attenuation at a magmatic intrusion zone. In the asthenosphere temperature-induced solid-state anelastic attenuation is assumed. The P- and S-velocity anomalies in the lithosphere and upper asthenosphere can be explained by an increase of temperature by about 100-150 K plus 1% melt. In the lower asthenosphere, above the transition zone, the excess temperature of the plume is at least 70 K, because the velocity anomalies are underestimated.

URL: http://www.uni-geophys.gwdg.de/~eifel

S71D-11 1140h INVITED

The Geodynamic Setting of Tertiary-Quaternary Intra-plate Magmatism in Europe: Is There a Link With the Iceland Plume System?

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Despite recent improvements in our understanding of the nature of mantle convection we still have few constraints on the geometry of the thermal (and chemical anomalies) widely referred to as mantle plumes. Several different scale lengths of convective instability are probable, with hot upwellings originating from thermal boundary layers in the Earths mantle such as the 660 km discontinuity or the core-mantle boundary.

Paleocene-Recent volcanism within western and central Europe, which is spatially and temporally linked to the development of a major intra-continental rift system and to domal uplift of Variscan basement massifs, has been attributed to the diapiric upwelling of small-scale, finger-like, convective instabilities from the base of the upper mantle. Evidence for this model comes from the French Massif Central and the Eifel province of northern Germany where both local and global seismic tomographic studies indicate the existence of localised zones of mantle upwelling from the base of the upper mantle, 100-300 km across and 100-200 degrees Centigrade hotter than ambient mantle. Global seismic tomographic studies also suggest the existence of a zone of low seismic velocities at depths of 900 to 1400 km in the lower mantle, extending from Iceland to the Eifel volcanic province of northern Germany, the Massif Central of France, the Hoggar massif in northern Africa and the Canary Islands. This raises the intriguing possibility that the diapiric upper mantle upwellings inferred to have triggered the Tertiary-Quaternary volcanic activity within Europe may be linked dynamically to the upwelling of the Iceland mantle plume.

The spectrum of primitive mafic magma compositions within the European volcanic province ranges from melilite nephelinites and melilitites, through basanites and alkali basalts to subalkaline tholeiites; these are considered to be the products of variable degrees of partial melting of a relatively homogeneous HIMU-like reservoir within the upper mantle, the European Asthenospheric Reservoir or EAR. Variations in the trace element and Sr-Nd-Pb isotopic characteristics of magmas are consistent with mixing of partial melts from both lithospheric and asthenospheric mantle sources. A component geochemically similar to the EAR also exists within the Icelandic plume system; this is preferentially sampled by relatively rare, small degree, partial melts (nephelinites and alkali basalts). Thus both geophysical and geochemical data can be used to support a geodynamic link between the Paleocene-Recent activity of the Icelandic mantle plume system and the magmatism much further to the south in western and central Europe.

S71D-12 1155h INVITED

Constraining the Iceland Low-velocity Anomaly to Test Causal Hypotheses

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For several decades the mantle plume hypothesis has been the most prevalent model cited as the cause of the geophysical and geochemical anomalies around Iceland. Recently the hypothesis has come under increasing pressure as various workers argue that the apparent anomalies are not particularly anomalous, and alternative models, operating entirely within the upper mantle, are presented as the causal mechanism.

Seismic tomography provides the only method of ”imaging” 3D mantle structure in situ, and three seismograph networks have been deployed across Iceland to collect the necessary data. Several velocity images of the Icelandic mantle using traveltime delays recorded by these regional networks have been published; all use ray-theoretical tomographic inversion techniques. To first-order they are consistent, showing a low velocity anomaly with a horizontal width of a few hundred kilometers, and extending from the surface to the maximum depth of resolution around $\sim$400 km. However, small variations in the structure imaged, and inherent distortions associated with the inversion techniques, have provided for a range of interpretations.

Here we present constraints on the geometry and amplitude of the low-velocity anomaly beneath Iceland. They are the results of tests using both ray-theoretical and full 3D wave propagation methods designed to test the extent to which the anomaly can be bent and squeezed. Ray-theoretical tests to squeeze the low-velocity anomaly both horizontally and vertically show that low-velocities are required to at least 350 km depth. They also suggest that the traveltime dataset could be satisfied by a narrow low velocity column, 100 km in diameter. Using the Spectral Element Method (SEM) we calculate synthetic waveforms and traveltime delays for stations across Iceland given various anomaly geometries. The SEM delay maps show a much broader delay footprint than ray-theoretical calculations would predict, implying that the Iceland anomaly could be about half the width of the ray-theoretical tomography results. However, the amplitude of the delays is also significantly reduced for narrow anomalies. We conclude that the Iceland low-velocity anomaly must extent to at least 350 km depth, is 100 to 200 km wide and does not extend laterally along the North Atlantic Ridge.

URL: http://www.geology.wisc.edu/~rallen

S71E MCC: 121 Sunday 0830h

Radiated Energy and Apparent Stress: Constant or Nonconstant Scaling? I

Presiding: **K M Mayeda,** Lawrence Livermore National Laboratory**; R Abercrombie,** Boston University

S71E-01 0830h INVITED

Earthquake Apparent Stress Scaling

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There is currently a disagreement within the geophysical community on the way earthquake energy scales with magnitude. One set of recent papers finds evidence that energy release per seismic moment (apparent stress) is constant (e.g. Choy and Boatwright, 1995; McGarr, 1999; Ide and Beroza, 2001). Another set of recent papers finds the apparent stress increases with magnitude (e.g. Kanamori et al., 1993 Abercrombie, 1995; Mayeda and Walter, 1996; Izutani and Kanamori, 2001). The resolution of this issue is complicated by the difficulty of accurately accounting for and determining the seismic energy radiated by earthquakes over a wide range of event sizes in a consistent manner. We have just started a project to reexamine this issue by analyzing aftershock sequences in the Western U.S. and Turkey using two different techniques. First we examine the observed regional S-wave spectra by fitting with a parametric model (Walter and Taylor, 2002) with and without variable stress drop scaling. Because the aftershock sequences have common stations and paths we can examine the S-wave spectra of events by size to determine what type of apparent stress scaling, if any, is most consistent with the data. Second we use regional coda envelope techniques (e.g. Mayeda and Walter, 1996; Mayeda et al, 2002) on the same events to directly measure energy and moment. The coda techniques corrects for path and site effects using an empirical Green function technique and independent calibration with surface wave derived moments. Our hope is that by carefully analyzing a very large number of events in a consistent manner using two different techniques we can start to resolve this apparent stress scaling issue.

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S71E-02 0850h INVITED

Are Large and Small Earthquakes Dynamically Different?

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Large and small earthquakes are generally believed to be similar because of the “constant-static-stress-drop ($\Delta\sigma_S$)” scaling relation. Here, we address this question in light of other seismological parameters. First, is $\Delta\sigma_S$ really scale independent, as is generally believed? The estimate of $\Delta\sigma_S$ depends critically on the length scale of the source, $\tilde{L}$. For large events, $\tilde{L}$ is usually well determined, and the estimates of $\Delta\sigma_S$ is probably reliable. For small earthquakes, however, $\tilde{L}$ is not determined directly, but is inferred from the corner frequency or duration of an earthquake, with the implicit assumption that rupture speed, V, is comparable to S wave speed, β. Although V is close to β for large earthquakes, V is not known for small earthquakes. If V is smaller (or larger) for small earthquakes, then $\Delta\sigma_S$ can be larger (or smaller) than generally believed. The fast rupture speed for large earthquakes is in striking contrast with the slow rupture speed, $V \leq 0.4\ \beta$, measured for laboratory samples. The ratio, $\tilde{e}$, of radiated energy, E_R, to seismic moment, M_0 (this ratio multiplied by rigidity, μ, is traditionally called “apparent stress”) exhibits large variations among different data sets. Estimates of $\tilde{e}$, especially for small earthquakes, are subject to large uncertainties mainly because of the difficulty in estimating E_R accurately. Some variations are attributed to inaccurate estimates of E_R, but existing data still seem to suggest that small earthquakes have generally smaller $\tilde{e}$ than large earthquakes. However, the ratio, $\tilde{e}$, alone does not necessarily represent the dynamical property of earthquakes. A better parameter is the fracture energy, E_G, or the radiation efficiency, $\eta_R = E_R/(E_R + E_G) = 2\tilde{e}/(\Delta\sigma_S/\mu)$. For large earthquakes, η_R and E_G can be estimated fairly accurately from macroscopic source parameters such as E_R, M_0, and $\Delta\sigma_S$. The values of η_R estimated for most large earthquakes are larger than 0.3, which means that the fracture energy, E_G, is smaller than, or comparable to E_R. This is consistent with the observed high rupture speed, V. For small earthquakes, if V is smaller than that for large earthquakes, then $\Delta\sigma_S$ is larger, and η_R is smaller, even if $\tilde{e}$ is about the same between large and small earthquakes. In this case, the slower rupture speed V is consistent with the smaller η_R. These results, together with the various lubrication mechanisms that may work at large fault slip and slip velocity, suggest that large earthquake ruptures are more likely to run away. Also, the dynamics of faulting can be significantly different between large and small earthquakes, which means that ground motions of large earthquakes cannot be estimated from those of small earthquakes by direct extrapolation. However, this question is far from being resolved, and more precise determinations of rupture speed, source dimension and radiated energy, are required to resolve it.

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How Good are our Source Parameter Estimates for Small Earthquakes?

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Measuring reliable and accurate source parameters for small earthquakes (M<3) is a long term goal for seismologists. Small earthquakes are important as they bridge the gap between laboratory measurements of stick-slip sliding and large damaging earthquakes. They also provide insights into the nucleation process of unstable slip. Unfortunately, uncertainties in such parameters as the stress drop and radiated energy of small earthquakes are as large as an order of magnitude. This is a consequence of the high frequency radiation (> 100 Hz) needed to resolve the source process. High frequency energy is severely attenuated and distorted along the ray path. The best records of small earthquakes are from deep (> 1km) boreholes and mines, where the waves are recorded before passing through the near-surface rocks. Abercrombie (1995) and Prejean & Ellsworth (2001) used such deep recordings to investigate source scaling and discovered that the radiated energy is a significantly smaller fraction of the total energy than for larger earthquakes. Richardson & Jordan (2002) obtained a similar result from seismograms recorded in deep mines. Ide & Beroza (2001) investigated the effect of limited recording bandwidth in such studies and found that there was evidence of selection bias. Recalculating the source parameters of earthquakes recorded in the Cajon Pass borehole, correcting for the limited bandwidth, does not remove the scale dependence. Ide *etal.* (2002) used empirical Greens function methods to improve source parameter estimates, and found that even deep borehole recording is not a guarantee of negligible site effects. Another problem is that the lack of multiple recordings of small earthquakes means that very simple source models have to be used to calculate source parameters. The rupture velocity must also be assumed. There are still significant differences (nearly a factor of 10 in stress drop) between the predictions of even the simple models commonly in use. Here I assess the uncertainties in available estimates of source parameters for small earthquakes and consider the implications that they have for earthquake rupture dynamics and nucleation.

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Progress Towards More Reliable Seismic Energy Estimates

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The radiated seismic energy density of an earthquake is peaked around the corner frequency of the earthquake. Since earthquake corner frequencies vary with earthquake size, seismic energy is distributed over a wide range of frequencies. It can be difficult to discern the nature of scaling of seismic energy because seismic energy estimates must account for the wave propagation effects this same wide range of frequencies. Despite the difficulties, studies in recent years have shown that many of the discrepancies between, for example, regional and teleseismic energy estimates for the same earthquake can be resolved if propagation effects are properly accounted for. In some instances, simply accounting for site response has resolved large discrepencies between estimates based on regional versus teleseismic data. In others, accounting for propagation effects empirically, either by empirical Green's function deconvolution or by spectral ratio analysis, has greatly reduced previous discrepancies in radiated energy.

Improved energy estimates should more clearly illuminate the nature of the scaling of energy with seismic moment. For example, Ide and Beroza [Does apparent stress vary with earthquake size?, Geophys. Res. Lett., 3349-3352, 2001] suggested that the scaling of radiated energy of microearthquakes reported in some studies might be an artifact of magnitude-dependent biases in the analysis. Better energy estimates should also help shed light on a related issue of whether observed large