a study because the dyke's gross geometry and composition have been determined through a substantial drilling program. Prior to the seismic field experiment, drill-core samples from the kimberlite and host rocks were used to measure P velocities and densities. These data were used to generate finite-difference and reflectivity synthetic seismograms in order to explore thin-bed resolution limitations, tuning effects and acquisition parameters. The seismic survey included two 2-d lines designed to obtain comparative datasets between different sources (explosives and vibroseis) and ground types (land and lake-ice). The explosive-source, land data yield a superb image of the thin dyke with high-amplitude reflections mapping the dyke topography to 1300 m depth. Weaker reflections indicate the dyke can be imaged to depths in excess of 1500 m. The vibroseis data detect the dyke only when sources and geophones are on land; they provide an image with nearly equivalent resolution. The dyke is not imaged beneath the ice by either source, due to reverberation and attenuation effects. The thickness of the thin intrusive layer is not directly resolved and 3-d structure makes the interpretation of fine-scale variations in reflectivity and continuity difficult. However, apparent correlations between variations in reflection characteristics and dyke properties (thickness, feathering, structure, and physical properties) suggest that seismic reflection data may be valuable for guiding drilling programs. The results demonstrate that, in the appropriate situation, seismic reflection methods have great potential for use in kimberlite exploration, subsurface mapping, and detailed imaging for mine development purposes.

S21C-08 0945h

Relating Pore Fabric Geometry to Acoustic Wave Velocity, Anisotropy and Fluid Flow in Porous Sandstone: A Laboratory Study Using Magnetic Ferrofluid.

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Pore fabric geometry is a key feature of sedimentary rocks. Anisotropy arising from pore fabric has been commonly studied in terms of acoustic-wave (seismic) anisotropy, fluid flow (permeability) anisotropy and magnetic anisotropy (Anisotropy of Magnetic Susceptibility - AMS). However, combined approaches are relatively few, and often concentrate on grain fabric AMS. Here, we present results from an experimental study in which the AMS technique is used to determine the average 3D void space geometry in porous rock saturated with a high susceptibility magnetic ferrofluid. Using this approach, we independently show that the acoustic wave anisotropy and permeability anisotropy are well described by knowledge of the pore fabric anisotropy. We also demonstrate that pressure produces marked changes in both permeability and acoustic wave velocity, and that pore fabric is a useful tool with which to explain such changes. Measurements were made on Crab Orchard sandstone (COS) and Bentheim sandstone (BHS), chosen specifically for their contrasting strong (COS) and weak (BHS) anisotropy. COS is fine-grained and exhibits layering on a mm scale. It has a high cement content, resulting in a porosity of 4.5%. By contrast, BHS comprises 95% quartz grains in an open structure, resulting in a porosity of 22%. AMS was determined by measuring the susceptibility of ferrofluid saturated samples in 15 different orientations. A least squares ellipsoidal fit was then applied to this data to calculate the principal directions. Comparative elastic wave velocity measurements were then made in 10 degree increments around the circumferences of sets of three orthogonal cores. An equivalent 3D velocity ellipsoid was then determined, allowing for direct comparison of the velocity and AMS data. The error in using an ellipsoidal fit, rather than a fourth rank tensor, is estimated as less than 1.5%; approximately equal to the error in velocity measurement. Finally, measurements of permeability anisotropy, together with simultaneous ultrasonic velocity measurements, were made in a servo-controlled permeameter at effective pressures from 5 to 90MPa. In general, the permeability of COS parallel to bedding is some 3 times higher than that normal to bedding; whereas the permeability of BHS exhibits no discernible anisotropy. We find a strong positive correlation between the principal directions given by pore space AMS, velocity anisotropy, and permeability anisotropy. P-wave velocity anisotropy on dry samples was 19% and 5% for COS and BHS, respectively. This compares with a pore fabric anisotropy of 3.8% (COS) and 1.4% (BHS). The permeability of COS decreases from 75 to 8 mDarcy as effective pressure is increased from 5 to 90 MPa, a corresponding increase in acoustic wave velocity is also observed. BHS has a considerably higher permeability (830 mDarcy), but this changes little as pressure is increased. Our results clearly demonstrate that the overall anisotropy in these sedimentary rocks is dominated by the average pore fabric shape and orientation. Hence, the analysis of this fabric provides a good indicator of the anisotropy of other related physical properties, such as mechanical strength.

S21D MCC: Level 1 Tuesday 0830h

Earthquake Location: Applications and Developments of New Techniques I Posters *(joint with NG)*

Presiding: **S Husen,** Swiss Seismological Service**; A O Konca,** California Institute of Technology

S21D-0319 0830h POSTER

The Rupture Characteristic of 1999 Izmit Sequence Using IRIS Data

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The standard source studies use teleseismic data (30° to 90°) to analyze earthquakes. Therefore, only a limited portion of the focal sphere is involved in source determinations. Furthermore, the locations and origin times of events remain incompatible with local determinations. Here, we attempt to resolve such issues by using IRIS data at all distances, leading to more accurate and detailed rupture properties and accurate relative locations. The 1999 Izmit earthquake sequence is chosen to test our method. The challenge of using data outside the conventional teleseismic distance range is that the arrival times and waveforms are affected more by the Earth structure. We overcome this difficulty by calibrating the path effects for the mainshock using the simpler aftershocks. Therefore, it is crucial to determine the source parameters of the aftershock. We constructed a Green's function library from a regionalized 1-D model and performed a grid search to establish the depth and fault parameters based on waveform matching for the Pnl waves between the synthetics and data, allowing the synthetics in each station to shift separately to account for the path effect. Our results show that the earthquake depth was around 7 km, rather than 19 km from local observatory (Kandilli) and 15 km from the Harvard's CMT solution. The best focal mechanism has a strike of 263°, a dip of 65°, and a rake of 180°, which is very close to the Harvard's CMT solution. The waveform fits of this aftershock is then used as a criterion to select useful source-station paths. A path with a cross-correlation value above 90% between data and synthetics is defined as a "good path" and can be used for studying the Izmit and Duzce earthquakes. We find that the stations in Central Europe and some of the Greek Islands are "good paths", while the stations in Northeast Africa and Italy cannot be used. The time shifts that give the best cross-correlation values are used to calibrate the picks of the Izmit and Duzce events. We realize that this is a very objective way to pick arrival times. However, our preliminary inversions using teleseismic data for Duzce and Izmit events show that handpicked P and S arrival times of the same station from two very close events are not always well correlated. Obviously, how we pick the arrival time governs the rupture pattern and rupture velocity. Therefore, our methodology brings a more objective approach to pick the travel times. To the end, we will invert for the source history of the Duzce and Izmit earthquakes with the regional data and compare with the inversion result using teleseismic data. Moreover, predictions of the teleseismic data, using the solution from the inversion using regional phases will be presented.

S21D-0320 0830h POSTER

Cross-Correlation-Based Relocation of Intermediate-Depth Subduction Seismicity in Japan

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We present very high precision hypocenter relocations of intermediate-depth subduction earthquakes off the Ibaraki Prefecture of north-central Honshu, Japan and analyze their implications for subduction mechanics and the mechanism of intermediate-depth earthquakes. Our relocations are obtained using cross-correlation-derived differential arrival times and the double-difference algorithm of Waldhauser and Ellsworth (2000). Cross-correlation-based relocation of subduction seismicity substantially increases the location precision over relocations using only catalog phase picks and dramatically improves routine catalog locations. Our previous relocations in neighboring regions using the double difference method on catalog arrival times have shown a substantial increase in organization of seismicity, compared with the catalog locations. In particular, we observed a narrowing of the seismogenic zone at depth and a narrowing of each limb of the double seismic zone when viewed in cross-section. We have also observed unusual events that appear to be within the mantle wedge above the slab and substantial seismicity within the slab between the two planes of the double seismic zone. We chose the Ibaraki region for its high rate of slab seismicity, its relatively simple geometry, and for the presence of an intermediate-depth double seismic zone. We relocate nearly 5000 mostly intermediate-depth events occurring in this region between June 2002 and May 2003 using more than 100,000 waveforms from the JMA unified catalog. Many of these waveforms are from stations in Hinet, a recently installed national borehole network that provides particularly high-quality data.

S21D-0321 0830h POSTER

Earthquake Relocation and Error Estimate for Aftershocks of 2003 M 7.0 Northeastern Japan Earthquake

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We investigate the aftershock sequence of a M 7.0 earthquake that occurred on 26 May, 2003 in northeastern Japan, where the characteristic double seismic zone (DSZ) was first identified by Hasegawa in 1978. The preliminary locations(from Tohoku University) show that these aftershocks are distributed between 65km-80km depth, not along the upper plane of the DSZ, but cut cross the slab at a steep angle. Catalog data from 227 aftershocks and waveform data from 69 large aftershocks (M>3.8) are used to refine earthquakes location. After double-difference earthquake location (hypoDD), the aftershocks are found to distribute along plane with dip angle about 53 (degree), but with significant scatter (RMS deviation is about 1.524km).These aftershocks are right along the eastern coast of Japan, in an area with significant velocity heterogeneity. We test the ability of hypoDD to recover the correct locations using synthetic data without and with noise added. The synthetic data are created based on the real data with the same set of event-station observation but with varying geometry. First, all the aftershocks are projected onto a plane (strike angle = -10 (degree), dip angle =53.79 (degree)) to generate the synthetic events, and synthetic travel time are calculated with 3-D velocity model. Several variations are then created to estimate the relocation error, and examine the effects of initial source locations, Gaussian noise and correlated noise on the relocation results.The results show that hypoDD does well in recovering the correct locations (RMS$\simeq$224m) and the initial source locations have little effect on relocation if arrival time errors are small. The absolute relocation error mainly comes from model error (true model is 3-D, hypoDD model is 1-D), and Gaussian noise represents the noise well.

S21D-0322 0830h POSTER

Relative relocation of seismic events following the June 15, 1991 eruption of Mount Pinatubo

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The June 15, 1991 climactic eruption of Mount Pinatubo (Philippines) was followed by intense seismicity which remained at a high level for several months with thousands of recorded events. In contrast to the pre-eruptive seismicity which was focused in two groups below the summit area, post-eruptive events were widely distributed below and around the volcano. We located about 10,000 events among the triggered recordings available from July 1 to mid December 1991 and applied precise relative relocation methods to these events. The classification of these events indicates the presence of several large families of similar volcano-tectonic events. The precise relocation using cross-correlation delays delineates several planar features which could be interpreted as fault planes. These are mostly subvertical, with often a roughly east-west strike. The small number of stations available (6) limits the quality of the relocations. In an effort to test the robustness of our results we carried out several tests. Two of the major sources of error are poor delays caused by mis-alignments at one (or several) station(s) and large uncertainties for poorly constrained events. The one-by-one elimination of a station in the relocation process provides a first way to test the influence of each station on the shapes defined by relocated events. A Monte Carlo simulation assuming Gaussian errors on takeoff and azimuth angles and on delays provides error ellipses for each relocation. Despite relatively large uncertainties (commonly about 100-200 m in horizontal and 200-500 m in vertical), the values for the better constrained events are smaller than the extent of the relocated clusters. These tests indicate that reliable features can be detected with the small Pinatubo network, and we expect that similar success can be attained for other cases with sparse network geometries.

S21D-0323 0830h POSTER

Precise Hypocenter Relocation of Microearthquakes in the Torfajökull Volcanic System, Iceland

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The Torfajökull volcanic system is one of about 30 active volcanoes comprising the neovolcanic zones of Iceland. It is located at the rift-transform junction between the Eastern Volcanic Zone and the South Iceland Seismic Zone. The central volcanic part of the system is the largest silicic centre in Iceland with a caldera of about 12 km diameter. It's high-temperature geothermal system is one of the most powerful in Iceland. Torfajökull is the source of persistent seismicity, where both high- and low-frequency earthquakes occur. To study the microseismicity of the volcanic area in detail a temporary array of 20 broad-band seismic stations was deployed between May and November 2002. These temporary stations were embedded in the permanent South Iceland Lowland (SIL) network, and data from nine adjacent SIL-stations were included in the study. A 'minimum one-dimensional velocity model' with station corrections was computed for earthquake relocation by inverting manually picked P- and S- wave arrival times from events occurring in the Torfajökull volcanic centre, beneath Myrdalsjökull glacier south of the temporary array, and in the South Iceland Seismic Zone in the west. High-frequency earthquakes from the Torfajökull volcanic centre were then relocated using the program NonLinLoc, which calculates a non-linear, probabilistic solution to the earthquake location problem. From several hundred earthquakes in the Torfajökull area, 122 were well locatable (gap < 180 degrees, more than 10 observations). Subsequently, we correlated the waveforms of this subdataset (around 2000 obseravtions) to define linked events, calculated the relative travel time difference between event pairs, and solved for the hypocentral separation between these events with HypoDD. The resulting high-resolution pattern shows a tighter clustering in epicenter and focal depth when compared to original locations. All earthquakes are located beneath the caldera with hypocenters between 1 and 6 km depth and most earthquakes lie within the geothermal system. The deeper earthquakes occur directly underneath the western caldera rim and seismic activity shallows towards the center of the caldera. No seismic activity has been observed in the fissure swarms to the north-east and southwest of the volcanic centre.

S21D-0324 0830h POSTER

3D Velocity and Hypocentre Distribution About a Cone-Volcano: Mt Taranaki, New Zealand

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Mt Taranaki is a 2518 m andesite cone-volcano (last eruption AD1755) within an oil-bearing sedimentary basin approximately 50 km west of the deepest part of the Benioff zone beneath the North Island of New Zealand. It is the most recent of a series of volcanoes that have erupted in the Taranaki region in the last 1.7 million years. Although a permanent six-station seismic network monitors Mt Taranaki for signs of unrest, little is known of the structure at the depths earthquakes occur and magma maybe stored. This information is vital for interpreting precursors to any future eruption. For nine months in 2001-2002, a temporary network of 75 three-component, broadband (0.03 - 50 Hz) seismographs (area c. 100 km by 100 km) was used to collect data to image crustal structure and accurately locate earthquakes in the Taranaki region. Three hundred and eighty-nine earthquakes were located using more than 15,000 phase picks (55% P and 45% S). A joint inversion for 1D Vp, Vs and hypocentres was undertaken using Velest followed by a 3D inversion for Vp, Vp/Vs ratio and hypocentres using Simul2000. The base of the seismogenic zone increases gradually from a depth of 20 km immediately west of Mt Taranaki to 35 km deep 100 km to the east, corresponding to a previously observed increase in crustal thickness. The area close to Mt Taranaki is anomalous in that there are few earthquakes and all are shallower than 10 km. Within the upper 5-10 km of the crust Vp is closely related to surface geology, being high beneath Mt Taranaki, low beneath the surrounding sedimentary basin, and very high to the east of the basin. We present the Vp and Vp/Vs structure and hypocentre distribution of the Taranaki region and discuss features that can be attributed to volcanism at Mt Taranaki and older volcanic centres.

S21D-0325 0830h POSTER

Comprehensive Waveform Cross-correlation of Southern California Seismograms: Part 1. Refined Hypocenters Obtained Using the Double-difference Method and Tectonic Implications

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We present preliminary results applying waveform cross-correlation to southern California seismograms for over 380,000 events between 1984 and 2002. Waveforms recorded by the SCSN are first extracted from the SCEDC data center in 50 s windows that include both P and S waves. The resulting online waveform archive uses about 0.5 TB on a RAID system. The traces are then re-sampled to a uniform 100 Hz sample rate and band-pass filtered to between 1 and 10 Hz. Next, we apply time domain waveform cross-correlation for P and S waves between each event and 100 neighboring events (identified from the catalog based on a 3-D velocity model of Hauksson (2000). We identify and save differential times from the peaks in the cross-correlation functions and use a spline interpolation method to achieve a nominal timing precision of 0.001 s. These differential times, together with existing P and S phase picks, are input to the double-difference program of Waldhauser and Ellsworth (2000). We define a grid across southern California and locate hypocenters near each grid node. Because some events may be located many times as hypocenters are calculated near successive grid-points, we assign a weight to each hypocenter and calculate a weighted average hypo-center for each earthquake. The new HypoDD hypocenters show improved clustering both horizontally and vertically, creating a more focused picture of the previously identified, spatially complex distributions of seismicity. In many cases, the late Quaternary faults, such as the Elsinore and Hollywood-Santa Monica faults appear to bracket the seismicity distributions; in other cases, the faults trace the median within a symmetric distribution of hypocenters. The depth distribution of the seismicity shows sudden changes across some of the major strike-slip faults, while regions of dip-slip faulting are often bound by dipping surfaces that are clearly defined by the deepest hypocenters. The seismicity around the southern San Andreas fault shows clear alignment along the Carrizo Plain segment while both the Mojave and Coachella Valley segments are dominated by off-fault hypocenters. A prominent horizontal boundary striking a few degrees north of west with a prominent depth change in the seismicity cuts across Banning Pass towards San Bernardino. Earthquake swarms in the Salton Sea at the south end of the San Andreas fault suggest the presence of two north-northwest striking seismic zones at the south end of the San Andreas fault. The seismicity along the San Jacinto fault forms sharp alignments that in most cases are adjacent to, but not coincident with, the mapped surface traces that are either parallel to the traces or form high angles to them. In the Los Angeles basin, the major aftershock sequences appear as densely focused clusters within a cloud of scattered background seismicity. The seismicity along the Newport-Inglewood fault forms a sharp alignment to the north and a diffuse distribution to the south, where the 1933 Long Beach earthquake occurred. Similarly, several clusters as well as scattered background seismicity extending from east to west across the basin illuminate the blind thrusts beneath the north edge of the basin. The major aftershock sequences such as 1992 Landers, 1994 Northridge, and 1999 Hector Mine form clusters, with distinct internal structures, illuminating secondary faults and a heterogeneous main fault rupture surface. Some of these alignments suggest that high angle cross-faults were activated by the mainshock.

S21D-0326 0830h POSTER

Comprehensive waveform cross-correlation of southern California seismograms: Part 2. Event locations obtained using cluster analysis

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We obtain precise relative locations for over 340,000 southern California earthquakes between 1984 and 2002 by applying the source-specific station term (SSST) method to existing P and S phase picks and a differential location method to about 100,000 events within similar event clusters identified using waveform cross-correlation. To simplify the computation, we first divide southern California into five polygons, such that there are $\sim$100,000 events or less in each region. Polygon boundaries are chosen to lie in regions of sparse seismicity. The entire catalog is first relocated using existing phase picks and the SSST method of Richards-Dinger and Shearer (2000). Next, we apply cluster analysis to the waveform cross-correlation output (see accompanying Hauksson et al. abstract for details) in order to identify similar event clusters. Because we do not compute cross-correlation between all possible event pairs, some modifications to standard cluster analysis algorithms were necessary to achieve a suitable method. We relocate earthquakes within each similar event cluster using the differential times alone, keeping the cluster centroid fixed to its initial SSST location. We estimate standard errors for the relative locations from the internal consistency of differential locations between individual event pairs; these errors are often as small as tens of meters. In many cases the relocated events within each similar event cluster align in planar features suggestive of faults. We observe a surprising number of conjugate faults at small scales that strike nearly perpendicular to the main seismicity trends. In general, the fine-scale details of the seismicity reveal a great deal of structural complexity in southern California fault systems.

S21D-0327 0830h POSTER

Earthquake Relative Relocation Near the Mendocino Triple Junction

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We relocate 30664 events recorded from the Northern California Seismic Network (NCSN) between 1977 and 2002 near the Mendocino Triple Junction. Although absolute earthquake locations depend on the three–dimensional velocity structure of the Earth, relative event locations within seismicity clusters can be accurately improved through the use of source-specific station terms and waveform cross correlation. The Mendocino Triple Junction (MTJ) is formed where the Pacific, North American, and Juan de Fuca/Gorda plates interact. The area is one of the most seismically active regions in California. Active source seismic tomography of the MTJ 1993-94 PASSCAL wide–angle seismic experiment revealed a smooth three-dimensional velocity model of the area. Dividing the study area into clusters of similar seismicity, we relocate the regional earthquakes using local 1D velocity models extracted from the smooth 3D model. Using the appropriate velocity model for each region, P and S travel time tables are computed and compared with the picked arrivals from the NCSN. Source specific station terms (SSST) are obtained for each receiver–event pair as the weighted median of the residuals at the given station from a number of nearby events. An iterative approach that gradually reduces the number of nearby events ensures that events that belong to relatively small clusters are responsible for the final station corrections. The relative locations of ∼5000 events are further improved with waveform cross correlation of closely spaced events with similar waveforms. Results reveal a significant improvement in the relative locations of events, both laterally and in depth, within different seismicity clusters. Although the absolute location of each cluster is not fixed, events within the clusters tend to concentrate around known and apparent fault lines. The improved event locations give new insights into seismic areas within the North American plate, including the region north of Clear Lake, and offshore areas within the Gorda plate and the subduction zone.

URL: http://igpp.ucsd.edu/~christos/

S21D-0328 0830h POSTER

Applying Massive Waveform Cross Correlation and Double-Difference Location to Northern California and China

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In recent years substantial advances in earthquake location have realized one to two orders of magnitude improvement over seismically broad areas due to the complementary benefits of waveform cross correlation and double-difference (DD) relative location in reducing both measurement and velocity model errors respectively. We report on results from applying these techniques on a massive scale to locally recorded seismic data across all of Northern California and to regional and teleseismic data in China. We are in the process of performing 2.5 billion correlation measurements on 280,000 events in Northern California from 1984 to present. The waveforms comprise the entire digital archive at the NCEDC recorded by 900 short period vertical component stations totaling 225 GB of data. We use a correlation detector instead of a correlation function to allow lags greater than 1/2 of the window length (typically 1 to 2 s) to be searched. At station JST, which includes 35,000 events from Bay area faults such as the Hayward, the Calaveras, and the San Andreas faults, 40% of the events have at least one other event with cross correlation coefficients (CC) greater than 0.9 (62% for CC > 0.8, 77% for CC > 0.7). These percentages of similar events are surprisingly high, but they include known areas of repeating events on the Calaveras and San Andreas Faults. For a station in Long Valley Caldera recording 72,000 events, the distribution is 18% for CC > 0.9, 43% for CC > 0.8, and 67% for CC > 0.7. A station including 20,000 events in the different tectonic settings of Mendocino Triple Junction and Geysers Geothermal Fields has 16% of the events with CC > 0.9 with at least one other event, 32% have CC > 0.8, and 49% have CC > 0.7. The lower numbers of correlated events observed at the latter two stations most likely reflect the different faulting processes that take place in these areas, compared to the (mostly) strike-slip events recorded at JST. To improve the accuracy of inter-event distances from which we determine pairs of events for correlation measurements we have relocated about 240,000 events using the double-difference method together with about 5 million NCSN P-phase picks. The mean shift between routine NCSN locations and DD relocations is about 300 and 500 m in the horizontal and vertical directions, respectively. The relocated seismicity shows a substantially increased level of detail across most of the Northern California region, which can be significantly enhanced by incorporating the cross correlation differential time measurements, once they are available. In China, we applied cross correlation methods to seismograms recorded at regional and teleseismic distances from ∼14,000 earthquakes and explosions, to measure relative arrival times to an accuracy of ∼0.01 s, obtaining location precision around a few 100 m — approximately a hundredfold improvement over current methods. From the results it is discovered about 10% of earthquakes in and near China, reported for the period 1985 to 2000 with $M \geq 3$, are repeat events generating essentially the same signals from sources each of which cannot be more than about 1 km from another event.

S21D-0329 0830h POSTER

Single-earthquake Location Using 3-D Vp and Vs Model - Applications in the Central USA and Taiwan Regions

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Traditional local earthquake location using a horizontally layered homogeneous velocity model is always limited in its resolution and reliability due to the existence of frequently overlooked 3- dimensional complexity of the real earth. Simultaneous earthquake relocation during a traditional 3-D seismic tomography has only applied to a limited set of selected earthquakes that more than 50% of earthquakes in a catalog are basically ignored. A new earthquake location program has been developed to locate every local earthquake using the best available 3-D Vp and Vs model for a region. Many modern seismic networks have provided excellent spatial coverage of seismic stations to record high-resolution earthquake data to allow the determination of high-resolution 3-D Vp and Vs velocity model for the region. Once Vp and Vs information for all 3-D grid points are available, travel time from each grid point to all seismic stations can be calculated using any available 3-D ray tracing techniques and be stored in computer files for later usage. Travel times from a trial hypocenter to the recording stations can be interpolated simply from those of the adjacent 8 grid points available in computer files without the very time consuming 3-D ray tracing. Iterations continue until the hypocenter adjustments are less than the given criteria and the travel time residual, or the difference between the observed and the calculated travel times, is a minimum. Therefore, any earthquake, no matter how small or how big it is, will be efficiently and reliably located using the 3-D velocity model. This new location program has been applied to the New Madrid seismic zone of the central USA and in various seismic zones in Taiwan region. Preliminary results in these two regions indicate that earthquake hypocenters can be reliably relocated in spite of the very significant lateral structural variations. This location program can also be applied in routine earthquake location for any seismic network in the future as long as a reliable 3-D Vp and Vs velocity model is available.

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S21D-0330 0830h POSTER

Regional Travel-Time Uncertainty and Seismic Location Improvement Using 3-Dimensional *a priori* Velocity Models

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We assess the ability of 3-D velocity models to better predict regional seismic travel times, relative to 1-D models, as well as quantify the travel time uncertainties. Accurate travel time prediction and uncertainty characterization is essential for properly identifying regional seismic phases and computing seismic event locations with representative error ellipses. To accomplish this we use an *a priori,* 3-D velocity model of Western Eurasia developed at LLNL [*Pasyanos et al.,* 2003] and a dataset of *P* and *Pn* phase picks from a catalog of calibration events which meet strict network criteria as investigated by *Bondar et al.,* [2003]. We evaluate the predictive power of the model by computing the median residuals between the observed arrivals and those predicted by 3-D finite difference computations. Statistical assessment of prediction accuracy is made in a non-stationary framework. We conclude that 1-D velocity models are not able to accurately characterize travel time uncertainties; not even radially symmetric models will work. Also, statistical estimates of uncertainty must be made in a region-specific framework (*i.e.,* 3-D). These results demonstrate quantitatively that 3-D velocity models accomplish two goals: improving travel-time prediction (by reducing overall variance of residuals), and reducing the dimensionality of the uncertainties by accounting for the non-stationary component. We also investigate improvement in seismic location using an adaptive station correction approach which combines both model predictions and empirical data. We find that no individual Earth model provides optimal travel-time prediction everywhere. We have, therefore, geographically merged travel-time predictions from a variety of different models and empirical observations to form a travel-time model (correction surface) for each station. Our approach combines the extrapolative advantages of model-based corrections and the interpolative/geostatistical advantages of kriging [*Schultz et al.,* 1998] to produce hybrid travel-time predictions and uncertainty models. For ease of use, model-based and empirical corrections are combined to produce one travel-time correction surface (per seismic station) and uncertainty model that is applied on top of the *iasp91* global Earth model in our location algorithm. Such 3-D models and uncertainty characterizations help to achieve location accuracy and computation of representative location error ellipses in a regional monitoring environment, particularly for small events not recorded teleseismically. *This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48, Contribution UCRL-JC-155079-ABS.*

S21D-0331 0830h POSTER

ASSESSMENT OF REGIONAL-NETWORK SEISMIC LOCATION ACCURATY USING RELATIVE AND MASTER-EVENT TECHNIQUES AND A NEVADA TEST SITE DATASET

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We use a set of Nevada Test Site (NTS) nuclear explosions and the Grid Search Multiple Event Location (GMEL) algorithm to test location accuracy achieved using master-event techniques. Arrivals from seventy-four nuclear tests recorded at 64 regional stations comprise the test dataset. Baseline relative location accuracy is established for 4 velocity models. We find that location and known travel-time prediction accuracy (derived from known hypocenters) are highly correlated, but root-mean-squared, a posteriori travel-time residuals (after relocation) are not a reliable indicator of either location or travel-time prediction accuracy. Unlike most master-event algorithms, GMEL accommodates any number of master events, allowing us to test the improvement achieved with more than one calibration event. For each of the 4 models, we test master-event location accuracy by successively relocating events relative to 1, 5, 10, 37, and 67 fixed hypocenters. In the case where 1 event is fixed we successively relocate relative to each of the 74 events. For tests with more than one master event, we randomly select the desired number of events in 74 instances. We find that, on average, one master event improves location by 58%. Using 5 and 10 master events improves location accuracy by 66% and 68%, respectively. Using 67 master events adds a meager 4% improvement over 10 constrained events. From these tests we conclude that although calibration using one master event is highly desirable, calibration from one event is susceptible to picking and other random errors that confound the goal of estimated travel-time-prediction bias. Using more than one master event helps to further mitigate extraneous random errors and results in more accurate determination of prediction bias. We find that between 5 and 10 calibration (master) events within one spatial correlation length is an optimal number. More than 10 events are not needed and calibration with fewer than 5 events may not provide sufficient averaging of random errors. This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48

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S21D-0332 0830h POSTER

Relative Constraints on Correction Surfaces for More Effective use of Low-Order Ground Truth

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We are developing a technique for applying relative constraints among travel time correction surfaces for stations within a network, whose goal is to improve the usefulness of lower order ground truth events within a catalog. Using the NCEDC catalog to develop and test our method, we demonstrate that for well-picked events the traveltime residual differences for events colinear with a given station pair vary slowly with little scatter for source-receiver separations involving local Pg phases. For the NCEDC catalog we observe that the consistency of residual relationships is good for events whose alignment with a station pair is neither parallel, nor in close proximity, to a major fault. Such fault-parallel station and event geometries lead to nodal arrivals and large pick and/or traveltime inconsistencies, which are manifested as large fluctuations in the residual differentials. Mislocation of earthquakes results in a geometrically-dependent uncertainty in the residual diffentials. As a first step we have modeled relative traveltime perturbations in a three-dimensional extension of the USGS 1-D Coast Range crustal model. For events placed in a dense grid within the model, we build a spatially-varying function of uncertainty in traveltime differentials caused by perturbations of each source within a 3-D Gaussian distribution about its "true" location. The resulting pattern of uncertainties suggests that the colinear residual relationships may be expanded to cover a significant azimuth range, allowing us to constrain correction surfaces over broad regions despite minor mislocatoins in the hypocenters upon which they are based. This in turn can improve locations for low-order ground truth events by suplying station correction constraints where they were previously unavailable or poorly defined. By including GT0 events in the procedure, we hope to establish absolute constraints on these surfaces.

S21D-0333 0830h POSTER

A Comparison of Multiple-Event Location Methods

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Multiple-event location methods solve jointly for the location parameters (hypocenters and origin times) of seismic events in a cluster and travel-time corrections at the stations recording the events. This paper reports some preliminary comparisons of five such methods that have been developed over the years: hypocentral decomposition (HDC), double differencing (DD), progressive multiple-event location (PMEL), joint hypocenter determination (JHD), and a recently developed algorithm based on grid search (GMEL). We have applied each method to two adjacent earthquake clusters in Turkey: 33 events from the 17 Aug 1999 Izmit earthquake sequence and 41 events from the 12 Nov 1999 Duzce sequence. Previously, Engdahl and Bergman (2001) had applied HDC to these clusters using Pn and teleseismic P arrival times from NEIC and ground-truth (local network) locations for a few of the events. Their data set comprised approximately 3500 arrivals at 640 stations for the Izmit cluster and 3200 arrivals at 600 stations for Duzce. We applied the other multiple-event location methods to the same set of phase picks, using the same phase identifications and fixed event depths that were used in the HDC analysis. While the five algorithms are quite different in their computational approach, our initial results indicate that the methods yield quite similar relative event locations when they are applied with the same data and assumptions. However, they resolve the trade-off between the centroid location of a cluster and station corrections differently, and they also differ in how they use ground-truth information to constrain this trade-off and obtain absolute event locations. The locations relative to the cluster centroids generally agreed within 5 km, but was on the order of 10 km in some instances. This may have to do with the different schemes for weighting data used by the different methods, which cannot always be equalized between methods. To test this hypothesis, we applied GMEL with two different weighting schemes and found discrepancies between relative locations as large as 10 km. Conversely, when GMEL was applied with the same station-variable weighting scheme that was used in the HDC analysis, the relative locations agreed within 2 km for all but a few events and within 5 km for all the events.

S21D-0334 0830h POSTER

Investigating Alternative Location Methods at the ISC

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The International Seismological Centre is replacing the software it uses to calculate hypocentres, which it does using arrival times from all over the world. The new program will initialy use the same algorithms as now but can also be used to test ways of improving solutions using modern methods. Here, we investigate using travel times from three dimensional earth models instead of from the Jeffreys-Bullen tables currently used. Travel times were calculated for every combination of station and source area using velocity models and ray tracing and the resulting source specific station times were stored and used in tables. Travel times for regional phases (delta less than 16 degrees) were calculated using a model for the upper mantle developed at the University of Colorado (Ritzwoller et al. 2002). Travel times for teleseismic phases (delta greater than 20 degrees) were calculated using a mantle model developed at Harvard University (Antolik et al. 2003). As a test we calculated residuals for arrivals in the ISC bulletin for large nuclear explosions in Nevada and Kazhakstan. In general, the new travel time tables reduced residuals with respect to these known source times and locations and when we tried free solutions for these events the results were closer to the truth than when using existing ISC methods. Although initial indications are that solutions would improve using these methods the ISC would face many challenges if it were to adopt them for routine hypocentre computation. From a scientific perspective the models may lack sufficient resolution in regions without many earthquakes or local stations. From a technical perspective station specific tables become awkwardly large when calculated for many hundreds of stations at several depths and for various phases.

S21D-0335 0830h POSTER

Hypocenter Determination To Issue The Earthquake And Tsunami Information From LISS And JISNET Data By Using the Grid-Search Method

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Matsushiro Seismological Observatory, Japan Meteorological Agency developed the real-time conversation processing system for the improvement in hypocenter determination accuracy and speeding up of a far coast tsunami earthquake by using the data of LISS (Live Internet Seismic Server) ,USGS. The processing displays a waveform as real time at the time of the occurrence of an earthquake, it can perform time-axis expansion, expansion and reduction of an amplitude axis, rearrangement of a channel, comparison with the theoretical travel time, and the phase detection etc. . The grid-search method for having devised for calculation time shortening is used for hypocenter calculation. In the first calculation, the latitude and longitude are fixed to an interval 5 degrees, focal depth is fixed to 30km and the origin time is fixed to an interval of 60 seconds. Next, the search range and a grid interval are made small covering 17 stages, finally, 0.01 degrees hypocenter accuracy search for latitude and longitude, 1 km for the depth searches and 0.1 second for the origin time. The process time is required about 5 seconds, using a personal computer in calculation. The hypocenters are determined within the limits of few 10km in general as compared with the hypocenters of USGS. Next, we applied this technique to the JISNET(Japan and Indonesia broad-band seismometer network) data installed in Indonesia, in order to investigate an earth internal structure, and we evaluated the hypocenter determination accuracy about the event generated in and around the Indonesia of it about the earthquake beyond M6.5 considered to be necessity for a big earthquake or a tsunami information announcement, it turns out that the hypocenter information is searched for in sufficient accuracy. However, the data using satellite communication etc. needs to be real-time for the utilization. In this case, a total of 23 JISNET stations and at least eight points of the optimal arrangement are enough. If the extensive real-time data will be sent to LISS of USGS, the hypocenter determination accuracy using these data will improve if the extensive real-time data will be sent to LISS of USGS, and it will lead not only to this region but to improvement for the far coast tsunami information in the Pacific rim. In near future, we will develop the automatic hypocenter determination system from the high sensitivity seismic array real-time data in Japan by using this technique.

S21D-0336 0830h POSTER

Relative Location of Multiple Events Using Empirical Green Functions

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Some events of the earthquake swarms occurring in NW-Bohemia, Czech Republic, display complex waveforms indicating a complicated rupture process. The method of empirical Green function deconvolution has shown that relative source time functions of these ML=2..3 earthquakes consist of several single events whose origin times and perhaps also other source parameters may differ. To find the parameters of individual single events, which build up the multiple event, a new method of modeling the waveforms of complex events with the use of empirical Green functions was designed. The waveform of a complex event is considered as a sum of waveforms of several single events with different moments, origin times and hypocenter coordinates. To construct a waveform of each single event composing the multiple event a source-time function of a triangular shape and a waveform of a near small event as an empirical Green function is used. Assuming similar focal mechanisms of the sub-events and of the "Green event", the method searches for coordinates and origin times of the sub-events and for their relative seismic moments. The relative position and timing of the sub-events give insight into the process of rupture propagation of swarm events yielding constraints for the rupture velocity, which helps to test the causal relation of the sub-events. Application of the method to the waveforms of the year 2000 swarm has shown that it is possible to distinguish hypocenters of sub-events whose relative distance exceeds 50m. The comparison of the relative position of the sub-events with their focal mechanisms indicated if they correspond to an interrupted rupture growth or likely belong to parallel cracks.

S21D-0337 0830h POSTER

Three-Dimensional Source-Scanning Algorithm: Imaging Seismic Sources of Earthquake or Non-earthquake Origins

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A scanning algorithm is developed to image the seismic source of earthquake or non-earthquake origin in a 3-D heterogeneous media. For a given time segment, the scanning process first calculates the theoretical arrival times from one grid point inside the velocity model to all seismic stations. This is efficiently done by retrieving the pre-calculated travel time tables stored online. The corresponding amplitudes at all stations are stacked to give the "brightness" of that point, and this calculation is systematically repeated for all grid points to image the snapshot of seismic sources in the region at that particular time. The scanning then proceeds to

the next time segment. In reality, we conduct a preliminary scan at a time interval of 5 s with a spatial resolution of 1 km to identify coherent seismic events. The scanning is subsequently done at shorter time intervals (down to 0.1 s) to locate the brightest spot. The two biggest advantages of this algorithm are (1) it is completely free from human picking errors and thus is perfect for automatic analysis, and (2) it maps out the geometric configuration of the finite source rather than just outputs a single point in the model space. Control tests using synthetic waveform data indicate that this algorithm is robust even under a high level of background noise. We apply this algorithm to a local earthquake (Mw 4.3) in the northern Cascadia subduction zone. The scanned image shows a vertical rupture plane striking E-W, consistent with one of the nodal planes determined from moment-tensor inversion of regional broadband waveforms. The point with the maximum brightness is remarkably close to the hypocenters determined by conventional earthquake location methods. Application of this algorithm to the tremor activity of the latest Episodic Tremor and Slip (ETS) event beneath the southern Vancouver Island indicates that the ETS tremors have east-dipping sources located in the vicinity of the inferred plate interface.

S21D-0338 0830h POSTER

Using Waveform Cross-correlation to Detect and Identify Regional Seismic Phases Based on a Reference Event Set

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It is widely observed that earthquakes and mining blasts occurring very close to each other can share very similar waveforms. An adaptive waveform cross-correlation automated phase detection method based on a reference event set of waveforms and picks has been developed and applied to process daily seismicity in New Mexico. This method can produce robust initial seismic phase estimates while greatly improving the handling of false triggers due to telemetry or other transient noise. 72 well-picked earthquakes and mining explosions in New Mexico during 1997-2003 were collected as an initial reference event set covering most historically active source regions. Each waveform in the reference event set has a high signal to noise ratio and accurately-picked P and S phases. All waveforms are converted to analytic time series envelopes before processing in order to increase the signal to noise ratio. If a new earthquake or mining blast occurs, it has a high probability of occurring close to a reference event. New event waveforms are compared to reference waveforms across all available stations using envelope cross-correlation. If the cross-correlation coefficient is sufficiently large, the phases of the most similar waveform in the reference set are assigned to the lag-aligned unknown waveform as initial picks for subsequent refinement. If cross-correlation coefficients are low, the new waveforms are either from a noise event or possibly from a seismic event occurring in a new source region. New source region events can readily be added to the reference event set following identification and picking. The NMT-SC network real-time data acquisition system, using the EarthWorm STA/LTA pick_ew/binde_rew modules, identifies hundreds of events per month, and most of them are noise transients. We have recently integrated this waveform cross-correlation phase detection and classification method into the Earthworm data flow and into Matseis (a Matlab-based analysis package developed at Sandia National Laboratories). The method makes adaptive use of evolving earthquake catalogues of waveforms and phases, improves the handling of false triggers, and increases the accuracy of initial P and S phases picking and automatic location and event classification.

S21D-0339 0830h POSTER

Automatic picker of P & S first arrivals and robust event locator

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We report on further development of automatic all distances location procedure designed for a regional network. The procedure generalizes the previous "local" (R < 500 km) and "regional" (500 < R < 2000 km) routines and comprises: a) preliminary data processing (filtering and de-spiking), b) phase identificatio n, c) P, S first arrival picking, d) preliminary location and e) robust grid-search optimization procedure. Innovations concern phase identification, automa tic picking and teleseismic location. A platform free flexible Java interface was recently created, allowing easy parameter tuning and on/off switching to t he full-scale manual picking mode. Identification of the regional P and S phase is provided by choosing between the two largest peaks in the envelope curve. For automatic on-time estimation we utilize now ratio of two STAs, calculated in two consecutive and equal time windows (instead of previously used Akike Information Criterion). "Teleseismic " location is split in two stages: preliminary and final one. The preliminary part estimates azimuth and apparent velocity by fitting a plane wave to the P automatic pickings. The apparent velocity criterion is used to decide about strategy of the following computations: teleseismic or regional. The preliminary estimates of azimuth and apparent velocity provide starting value for the final teleseismic and regional location. Apparent velocity is used to get first a pproximation distance to the source on the basis of the P, Pn, Pg travel-timetables. The distance estimate together with the preliminary azimuth estimate provides first approximations of the source latitude and longitude via sine and cosine theorems formulated for the spherical triangle. Final location is based on robust grid-search optimization procedure, weighting the number of pickings that simultaneously fit the model travel times. The grid covers initial location and becomes finer while approaching true hypocenter. The target function is a sum of the bell-shaped characteristic functions, used to emphasize true pickings and eliminate outliers. The final solution is a grid point that provides maximum to the target function. The procedure was applied to a list of ML > 4 earthquakes recorded by the Israel Seismic Network (ISN) in the 1999-2002 time period. Most of them are badly constrained relative the network. However, the results of location with average normalized error relative bulletin solutions e=dr/R of 5% were obtained, in each of the distance ranges. The first version of the procedure was incorporated in the national Early Warning System in 2001. Recently, we started to send automatic Early Warn ing reports, to the EMSC Real Time Bulletin. Initially reported some teleseismic location discrepancies have been eliminated by introduction of station corrections.

S21D-0340 0830h POSTER

How to pick depth phases

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Determining accurate hypocenter depth is scientifically challenging and is important because it is a useful discriminant between nuclear explosions and earthquakes. Shallow events (depths < 50 km or so) are especially difficult to determine with accuracy if only teleseismic P arrivals are used. Depth phases, pP and sP can help greatly in that aspect. The effect of using depth phases is like adding a station directly above the hypocenter. Depth phases, however, are used infrequently by institutes monitoring global seismicity such as USGS, IDC, and USNDC. The problem may be due to a lack of clear guidance for depth phase picking for the seismic analysts. The purpose of this paper is to review theoretical properties of depth phases and illustrate with examples how to pick depth phases. With Gaussian beam modeling, it is found that the focal mechanism orientation plays a major role in deciding if a station is going to see depth phases or not. Based on the relative location (azimuth and distance) of the stations to the source and focal mechanism orientation, a station may see just P, or just P and pP, or P, pP, and sP, or just P and sP. Without the focal mechanism being available at the time of picking for location, the identification of depth phases becomes tricky. Many researchers have tried special data processing, such as cepstral analysis, on single station data to identify depth phases. Our study shows that depth phases are best identified with data from an entire network data under scrutiny. The paper will also address issues of double explosions designed to mimic depth phases and multiple earthquakes separated by a very short time interval.

S21D-0341 0830h POSTER

Relative propagation parameters and source locations of similar events using seismic antennas

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We introduce a method to accurately determine the relative propagation parameters (apparent slowness and propagation azimuth) of events with similar waveforms recorded on seismic antennas. This relative slowness estimate (RelSE) method is based on precise measurements of the differences among arrival times of different earthquakes to the receivers of the antenna. Delays are determined using interpolations of the cross-correlations of the seismograms. Given the resemblance of waveforms, this method allows for an accuracy higher than the sampling rate. We apply the RelSE method to a multiplet composed of sixteen similar earthquakes recorded during the 1999 seismic crisis at Deception Island volcano, Antarctica. Relative apparent slowness vectors are determined for the P-wave onset. Results show that the slowness vectors are closely distributed in a narrow, north-south trending band on the apparent slowness space centered at about 0.27 s/km and 245°N. We estimate the source locations of these events using the S-P delays and an inverse ray-tracing procedure through a velocity model. The obtained solutions define two plane structures that can be regarded as the fractures originating the recorded earthquakes. We conclude that the RelSE method, combined with other source location techniques, may be very useful for the analysis of microearthquake series recorded on seismic antennas. Furthermore, it is well suited for the analysis of long-period seismicity in the field of volcano seismology.

S21E MCC: Level 1 Tuesday 0830h

Theories of Earth's Interior V Posters

(joint with T, V)

Presiding: **F J Simons,** Princeton University**; D D Jackson,** University of California, Los Angeles

S21E-0342 0830h POSTER

Next-generation marine instruments to join plume debate

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Whether hot spot volcanism is the consequence of plate tectonics or has a deep origin in a mantle plume is debated. G. Foulger (Geol. Soc. London Lett. Online, accessed 9/3/2003), writes that *carefully truncated cross sections, with color scales cranked up, give noisy images the illusion of strong anomalies traversing the mantle.* **Don Anderson**, the *big daddy of non-plume hypotheses* (R. Kent, Geol. Soc. London Lett. Online, accessed 9/3/2003) has written that *the resolution of regional tomography experiments must be improved in order to successfully determine whether (...) the deep mantle is the controlling factor in the formation of proposed hot spots* (Keller et al., GRL 27 (24), 2000). In particular for Iceland, at issue is the inherently limited aperture of any land-based seismometer array on the island: *(...) the resolution of such images could be increased (...) by using ocean bottom seismometers (...) (ibidem).* These problems are not unique to the plume debate. Coverage, resolution and robustness of models of the wave speed distribution in the interior of the Earth obtained by seismic tomographic inversions are limited by the areal distribution of seismic stations. Two thirds of Earth's surface are virtually inaccessible to passive-source seismometry, save indeed for expensive ocean-bottom seismometers or moored hydrophones. Elsewhere at this meeting, Montelli *et al.* describe how an improved theoretical treatment of the generation and survival of travel-time anomalies and sophisticated parameterization techniques yield unprecedented resolution of the seismic expression of a variety of "plumes" coming from all depths within the mantle. On the other hand, the improved resolution required to settling the debate on the depth to the seismic origin of various hot spots will also result from the collection of previously inaccessable data. Here, we show our progress in the development of an independent hydro-acoustical recording device mounted on SOLO floats. Our instrument is able to maintain a constant water column depth below the sound channel and will surface only periodically for position determination and satellite data communication. Using these low-cost, non-recovered floating sensors, the aperture of arrays mounted on oceanic islands can be increased manifold. Furthermore, adding such instruments to poorly instrumented areas will improve the resolution of deep

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