

liquefaction-induced surface phenomenon by analyzing time series measurements collected by the MISR sensor on board the Terra platform. The analysis of MISR measurements in the near-infrared spectral domain reveals the spatial extent of the surface water and its persistence. This event reactivated ancient river channels in the Rann of Kachchh. Other regions further away from the epicenter have also been affected by the liquefaction process. Indeed, the presence of water along the Nagar Parkar fault a few days after the earthquake was unveiled by the analysis of the MISR multi-angle data taken in the red spectral domain. Our study expands and complements the observations from geographically limited ground investigations. It demonstrates that the liquefaction phenomenon has affected areas far away from the epicenter.

S72E MCC: 133 Sunday 1515h

Earthquake Source Studies II

Presiding: J L Hardebeck, University of California, San Diego; A Ferris, Boston University

S72E-01 1515h

Using S/P Amplitude Ratios to Improve Earthquake Focal Mechanisms: Two Examples from Southern California

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We test whether S/P amplitude ratios can be used to constrain the focal mechanisms of small earthquakes. We study S/P ratios for a cluster of aftershocks of the 1994 Northridge, California, earthquake. These events have highly similar waveforms, implying that they have very similar locations and mechanisms. The average S/P values at each station are qualitatively consistent with the average P-wave polarity mechanism for the set. However, there are considerable amplitude variations at most stations. This noise is usually a factor of 2-3, but can be up to a factor of 10.

We include the S/P ratios in the focal mechanism inversion, to test whether their use improves the solutions. We try one approach that minimizes the misfit, and another that incorporates the uncertainty in the S/P data into the solution. The first approach performs poorly, returning a set of mechanisms less similar than the P-polarity solutions. The second approach has little effect on well-constrained mechanisms, but significantly improves the lower-quality solutions. This demonstrates that S/P ratios can constrain focal mechanisms, but the noise must be accounted for in the inversion method.

Most earthquake sequences are recorded by only a few stations, and it is in these regions of sparse coverage that S/P amplitude ratios are potentially most useful. We simulate this situation using subsets of the stations, and compare the quality of the solutions with and without S/P data. When 8-12 stations are used, the mechanism improvement due to the S/P data is considerable.

A spatial cluster of aftershocks of the 2001 Anza, California, earthquake, demonstrates the value of S/P ratios in seismotectonics. The P polarities divide the events into two sets based on polarity differences at two stations, but the station distribution is too sparse to constrain how different the mechanisms may be. The observed S/P ratios for the events in the two groups span similar values, however, constraining the mechanisms to be similar, with nodal planes just to either side of the two stations. From the P-polarity data alone, there appear to be two distinct sets of mechanisms at this location. The inclusion of S/P ratios reveals that the mechanisms are actually very similar, although not identical.

S72E-02 1530h

b-value: What about focal mechanisms?

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In the past, we have shown that the *b*-value of the frequency-magnitude relationship varies over short distances between about 0.5 and 1.5 beneath volcanoes and along fault zones. This observation can be interpreted as due to heterogeneity in stress or in fault geometry. We have also identified statistically significant changes of *b*-value as a function of time. These occur less frequent and are less dramatic than the differences as a function of space. Here, we investigated the dependence of *b*-value on focal mechanism along and near the San Jacinto strike-slip fault in southern California. By broadly defining two types of mechanisms, strike-slip (with rake $0^\circ \pm 30^\circ$, or $180^\circ \pm 30^\circ$, and any strike and dip) and thrust (with rake $90^\circ \pm 30^\circ$, and any strike and dip) we extracted two separate catalogs with 13321 and 2485 events (all of southern California), respectively, for the period 1981 through 2001. Mapping a *b*-values cross-section for strike-slip events along the San Jacinto fault in volumes of radius 15 km (approximately 40 events) revealed that they vary between 0.6 and 1.3 as a function of space, having an average value of 1.1. The patches of anomalously low *b*-values along the fault that we had previously interpreted as asperities were also mapped by the strike-slip events, showing $b < 0.8$. Furthermore, when we map *b*-values with a catalog containing all events, we found that the patches of anomalously low *b*-values became more strongly defined as we narrow the width of the cross-section zone, taking into account only the events closer to the fault. This also indicates that the prevailing strike-slip events in the near vicinity of the fault contain information about asperities. However, the *b*-value variations in the catalog of thrust events did not follow this pattern. In the volumes near and in 'asperities', they showed values of $b > 1.2$, while the average value is $b = 1$. We conclude that within a seismogenic volume that produces earthquakes with a variety of focal mechanisms, *b*-values can vary as a function of mechanism. The observation that only strike-slip events map 'asperities' along the San Jacinto fault can be interpreted as showing that these events rupture along the major fault and contain information about the condition of the fault surface (resistant or non-resistant to faulting), whereas the thrust faults are smaller and occur off the well developed strike-slip fault. This case study suggests that hitherto untapped information about the conditions in seismogenic volumes may be unlocked by mapping *b*-values separately for populations of earthquakes with different focal mechanisms.

S72E-03 1545h

Systematic Determination of Earthquake Fault Planes From Directivity Analysis of Long-Period Spectra

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Earthquake focal mechanisms resolve two possible fault planes. If the earthquake has a predominantly unilateral rupture, the pulse width will vary depending on the azimuth from the rupture direction, allowing the actual slip plane to be determined from a directivity analysis. We have developed a method to estimate the amount of pulse broadening from the spectrum and apply it to a long-period database of all large earthquakes between 1988 and 2000. We have 2031 events with good signal-to-noise ratios at ≥ 15 stations. We select vertical-component *P* waves at epicentral distances of 30° - 98° . We compute the spectra from a 64-s-long window around each *P* wave arrival. Each spectrum is the product of source, receiver, and propagation response functions as well as local source- and receiver-side effects. We correct each spectrum for the known instrument response and a source model with an ω^{-2} falloff at high frequencies. Since there are multiple receivers for each source and multiple sources for each receiver, we can approximate the source- and receiver-side terms by stacking the appropriate *P* log spectra. The resulting source-specific response functions include any remaining source spectrum and the effect of near-source attenuation in the upper mantle; the receiver stacks include the site response and near-receiver *Q* structure. We remove the appropriate source- and receiver-side stacks for each path, leaving effects from directivity and lateral variations in attenuation. We find that the directivity effects dominate and we estimate pulse broadening from the slope of the log spectrum. Next, we plot these measurements on the focal sphere along with the Harvard CMT solution. To determine the preferred slip plane for each earthquake, we measure the angle between the slip vector for each plane and the take-off vector to each station. For the two possible slip planes, we fit a cosine curve to the pulse broadening measurements. In $\sim 20\%$ of the cases, one of the two slip planes produces a much better fit to the data and can be identified as the true fault plane. We find particularly good fits for earthquakes occurring in the Andreanof segment of the Aleutian subduction zone. Of the 22 thrust events in the area, 16 are clearly better fit by the shallow dipping plane, in agreement with an analysis of an M_W 7.9 event in the

area [Tanioka and Gonzalez, 1998], while the remainder are inconclusive. We also compare our results with the known slip planes of recent earthquakes, such as the 1994 Landers, 1999 Hector Mine, 1999 Izmit, and 1999 Düzce events.

S72E-04 1600h

Different cluster relocation techniques and their applications to mid-oceanic earthquakes

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We examine and apply three multi-event relocation (cluster analysis) techniques: double difference (DD), hypocentral decomposition (HDC), and joint hypocenter determination based on master events constrained by seafloor bathymetry (JHDME) to mid-oceanic earthquakes. We compare them with single event relocation method coupled with three dimensional (3D) model-based station corrections (SER3D), in terms of event clustering against background bathymetry, location errors, root mean square (RMS) of the residuals and relocation vectors. We find that using virtually the same dataset, JHDME fits the data best and yields lower residual RMS than the other methods. Absolute locations cluster better for HDC and JHDME against the bathymetric features. In one of our experiments, HDC hypocentroid change little and this reduces HDC to JHDME in which only one master event is fixed. Because DD fits relative travel times, the absolute residual RMSs are relatively larger, relocation vectors are smaller and final locations scatter more. But the error ellipses for DD are smallest. SER3D uses more available phases for each event but no other inter-event constraint than model-based station corrections and usually generates smaller relocation vectors than the other methods, except DD. For the cluster on the Romanche Fracture Zone (RFZ), all methods leave several events off the main transform. But the cluster 'collapses' more toward the linear RFZ bathymetric low for HDC and JHDME. For the cluster in the Gulf of Aden, distribution of the relocated events is more consistent with the geometry of closely spaced ridges and transforms. We introduce a measure for the mid-oceanic earthquake clustering based on the concept of Voronoi cells but adapted to the linear bathymetry features. This measurement is set up to be a function of the volume of each Voronoi cell around an earthquake weighted by the minimum distance between the earthquake and any possible ridge/transform to which the earthquake is assumed to be related. This applies to large ridges or transform faults as well as really closely-spaced ridge and transform system as in Gulf of Aden. Preliminary results show that such measure is at its minimum by using JHDME.

S72E-05 1615h

Complex Rupture Process of the November 14, 2001, Kunlun Earthquake and Its Tectonic Significance

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The November 14, 2001, Kunlun earthquake ($M_w = 7.8$) occurred in northeastern Tibet along the western segment of the left-lateral Kunlun strike-slip fault system and produced a surface rupture of ~ 400 km. The rupture process of this event is examined by using the teleseismic body-wave data collected by IRIS-DMC stations. The Harvard centroid moment tensor (CMT) solution indicates an oblique strike-slip mechanism with the fault plane dipping 61° to the south and a location 200 km east of the rupture initiation given by the PDE location. The P-wave first motion polarities (FMP) indicate a pure strike-slip mechanism suggesting a change in fault dip after rupture initiation. We invert P-waveforms for the spatial and temporal development of the mainshock using a finite fault source for the two fixed focal mechanisms (CMT and FMP). The CMT solution provides the best fit to the overall waveforms and results in a total seismic moment of 4.3×10^{20} Nm ($M_w = 7.7$). Inversion results indicate that the rupture propagated unilaterally towards the east with an average rupture velocity of about 3.3 km/s and released most of the energy along an energetic asperity located 200-250 km east of the hypocenter. This major subevent, with a seismic moment of

$\sim 2.3 \times 10^{20}$ Nm, has a rupture length of ~ 65 km and assuming a rupture width of 15 km, has an average slip of ~ 8 m with a stress drop of ~ 90 bars. Most of the aftershocks cluster next to the dominant asperity, near the eastern bifurcation of the Kunlun fault. For such a large event, few moderate sized aftershocks were recorded and all of them have thrust or normal focal mechanisms rather than strike-slip. This suggests a high degree of complexity for the mainshock. Correlation of the rupture characteristics with other earthquakes, the amount of radiated seismic energy, and the mainshock to largest aftershock energy ratio support an interplate earthquake classification for this event.

S72E-06 1630h

Detection and location of slow seismic sources using surface waves

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The vast majority of earthquakes follow a remarkably simple scaling relationship such that the source duration is proportional to the cube root of the seismic moment. Only a very small number of slow seismic events of significant size ($M_W > 5$) deviating from this relationship have been identified. The dearth of slow events may in part be a consequence of the traditional practice of detecting, locating, and assigning magnitudes to earthquakes using high-frequency seismograms. Systematic analysis of longer-period seismic waves may lead to the identification of previously undetected slow events. The recently discovered continuous excitation of the Earth's fundamental normal modes generates a noise threshold that prevents single-station detection of surface waves from smaller events at long periods. To extract a buried long-period signal in the seismograms, a stacking technique is required. We have developed a method of surface-wave cross correlation and stacking to search for seismic events using near-real-time data from the GSN. Given a test location, seismograms are corrected for propagation effects to each station in the network. The envelopes of the resulting waveforms are stacked and cross correlated with a model wavelet to determine whether an event has been detected. For a detection, maximizing the cross correlation as a function of latitude and longitude leads to the determination of an origin time and location. Regular shallow earthquakes of $M_W > 5$ are commonly located to within ~ 50 km using the new surface-wave method. Off-line application of the technique to GSN data from July and August of 2000 leads to the detection of numerous slow earthquakes with $M_W = 4.5-5.7$ associated with the caldera collapse on Miyake Island, Japan; these events were not identified by traditional short-period techniques, and do not appear in global earthquake catalogs. A magmatic mechanism has been proposed for the source process of these events, but a tectonic explanation in terms of complex slip on a circular caldera fault is a viable alternative.

S72E-07 1645h

Teleseismic Analysis of the 2001 Kunlun Earthquake and the Comparison with Field Observations

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A largest class inland-earthquake occurred on Nov. 14, 2001 in the Central Kunlun mountain area. About 400 km long surface rupture with strike-slip was observed along the pre-existing Kunlun fault. To investigate the source rupture process, we retrieved body wave records at teleseismic distances from IRIS-DMC. The observed records are highly complex, indicating a multiple shock nature. Thus, we first carried out the iterative deconvolution to derive discrete subevents with variable mechanisms. The derived mechanisms were nearly pure strike-slips and remained almost unchanged during the source process. Thus, we next modeled the source process by faulting on a fixed fault plane to estimate the spatio-temporal distribution of the moment release. Then the initial break and the rupture front velocity were determined by a grid search manner.

The results indicate that a rupture propagated mainly to the east in a unilateral manner. The mechanism for the total source is a nearly pure strike-slip: (strike, dip, rake)=(96, 86, 1). The total length amounts to 360 km: 330 km to the east and 30 km to the west from the relocated epicenter: (36.01N, 91.10E). There are two distinct slip areas (asperities). The largest dislocation is 6.6 m at about 220 km east

of the epicenter. The overall pattern of moment-release distribution is very well consistent with that observed in the field. The total seismic moment is 6.6e20 Nm (Mw 7.8). The averaged stress drop is 1.4 MPa, while the local stress drop on the asperity is about 7 MPa, indicating that relatively narrow regions possess a strong coupling which prevented aseismic slip there. The rupture front velocity is 3.4 km/s, as large as the S wave velocity. This may suggest that faulting on the asperity was triggered by S wave arrival from the initial break rather than a rupture propagation.

S11A MCC: Hall C Monday 0830h

Plumes, Hot Spots, and Calderas III Posters (joint with G, GP, OS, T, V, DI)

Presiding: G R Foulger, University of Durham; G Waite, University of Utah

S11A-1098 0830h POSTER

Interaction of the lithosphere with mantle plume material

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Mantle plumes impinge on the base of the lithosphere and produce primary hotspots above the plume and secondary hotspots where buoyant plume material flows along the base of the lithosphere. Variations in lithospheric thickness associated with plate age form an upside-down drainage pattern. Secondary hotspots occur from pressure-release melting above flowing material between plumes and ridge-axes and above ponded material at ridge axes. However, when viewed in detail, this process is not straightforward. One might expect prominent secondary hotspots where plume material cascades over the lithospheric relief associated with fracture zones. Instead, volcanic edifices do not occur preferentially in these locations on old crust. This lack of correlation results because even weak stagnant-lid convection (5-10 mW m⁻²) causes the step in lithospheric thickness to prograde to the old side of the fracture zone over time. A second phenomenon is that hotspot tracks appear to jump from off-axis chains to on-axis hotspots. An example is the gap between the New England and Corner seamounts. These features result from the intraplate membrane stress on the ascent of dikes toward the surface. The thickness of off-axis ponded material, which tends to put the off-axis lithosphere into membrane tension, decreases when a hotspot approaches the axis. The thickness of plume material ponded at the axis increases, tending to put the off-axis region near the plume into membrane compression. The net effect is that intraplate compression shuts down the off-axis hotspot by inhibiting dikes at about the time that the on-axis hotspot becomes active.

S11A-1099 0830h POSTER

Plumes do not Exist: Plate Circulation is Confined to Upper Mantle

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Plumes from deep mantle are widely conjectured to define an absolute reference frame, inaugurate rifting, drive plates, and profoundly modify oceans and continents. Mantle properties and composition are assumed to be whatever enables plumes. Nevertheless, purported critical evidence for plume speculation is false, and all data are better interpreted without plumes. Plume fantasies are made ever more complex and ad hoc to evade contradictory data, and have no predictive value because plumes do not exist. All plume conjecture derives from Hawaii and the guess that the Emperor-Hawaii inflection records a 60-degree change in Pacific plate direction at 45 Ma. Paleomagnetic latitudes and smooth Pacific spreading patterns disprove any such change. Rationales for other fixed plumes collapse when tested, and hypotheses of jumping, splitting, and gyrating plumes are specious. Thermal and physical properties of Hawaiian lithosphere falsify plume predictions. Purported tomographic support elsewhere represents artifacts and misleading presentations. Asthenosphere is everywhere near solidus temperature, so melt needs a tensional setting for egress but not local heat. Gradational and inconsistent contrasts between MORB and OIB are as required by depth-varying melt generation and behavior in contrasted settings and do not indicate systematically unlike sources. MORB melts rise, with minimal reaction, through hot asthenosphere, whereas OIB melts react with cool lithosphere, and lose mass, by crystallizing refractories and retaining and assimilating fusibles.

The unfractionated lower mantle of plume conjecture is contrary to cosmologic and thermodynamic data, for mantle below 660 km is more refractory than that above.

Subduction, due to density inversion by top-down cooling that forms oceanic lithosphere, drives plate tectonics and upper-mantle circulation. It organizes plate motions and lithosphere stress, which controls plate boundaries and volcanic chains. Hinge rollback is the key to kinematics. Arcs advance and collide, fast-spreading Pacific shrinks, etc. A fore-arc basin atop an overriding plate shows that hinge and non-shortening plate front there track together: velocities of rollback and advance are equal. Convergence velocity commonly also equals rollback velocity but often is greater. Slabs sinking broadside push upper mantle back under incoming plates and force rapid Pacific spreading, whereas overriding plates flow forward with retreating hinges. Backarc basins open behind island arcs migrating with hinges. Slabs settle on uncrossable 660-km discontinuity. (Contrary tomographic claims reflect sampling and smearing artifacts, notably due to along-slab ray-paths.) Plates advance over sunken slabs and mantle displaced rearward by them, and ridges spread where advancing plates pull away. Ridges migrate over asthenosphere, producing geophysical and bathymetric asymmetry, and tap fresh asthenosphere into which slab material is recycled upward. Sluggish deep-mantle circulation is decoupled from rapid upper-mantle circulation, so plate motions can be referenced to semistable lower mantle. Global plate motions make kinematic sense if Antarctica, almost ringed by departing ridges and varying little in Cenozoic paleomagnetic position, is stationary: hinges roll back, ridges migrate, and directions and velocities of plate rotations accord with subduction, including sliding and crowding of oceanic lithosphere toward free edges, as the dominant drive. (The invalid hotspot and no-net-rotation frames minimize motions of hinges and ridges, and their plate motions lack kinematic sense.) Northern Eurasia also is almost stationary, Africa rotates very slowly counterclockwise toward Aegean and Zagros, Pacific plate races toward surface-exit subduction systems, etc.

S11A-1100 0830h POSTER

Shear-Wave Anisotropy at the Yellowstone Hotspot

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Several features of the 800-km long Yellowstone-Snake River Plain volcanic system can be explained by the steady motion of the North American lithosphere over a hotspot source, often thought to originate from a mantle plume. A 10 m geoid high centered on Yellowstone, a series of progressively older calderas that track the southwestern motion of the North America Plate, and a parabolic pattern of high topography, seismicity, and active faulting around the eastern Snake River Plain are consistent with a model in which buoyant plume material flattens against the moving lithosphere. We examine the upper mantle strain field in the Yellowstone region using shear-wave splitting measurements of teleseismic core phases (SKS, SKKS, and PKS). The teleseismic data were recorded at six permanent USNSN stations and a temporary array of 47 IRIS-PASSCAL seismographs deployed in a 300 km by 500 km area centered on Yellowstone.

The shear-wave splitting fast polarization directions are dominantly aligned parallel to the direction of North America Plate motion. While the fast polarization directions are not as coherent as those observed farther down the Snake River Plain to the southwest, there is no clear evidence for the divergent mantle flow commonly expected to be produced as a plume interacts with the lithosphere. It is possible that near the plume top, the overturn of material from the plume-plate interaction would not align olivine, and thus produce a region of no anisotropy. However, the largest split times of more than 2 sec are observed at the stations located within the present-day Yellowstone caldera, implying no cornerflow. The average delay time at stations outside the caldera is 0.9 sec. The splitting data are consistent with deformation from shearing by the North America Plate. In addition, upper mantle flow velocity may be parallel to the direction of plate motion as indicated by some global-scale models. There may also be significant lithospheric anisotropy related to several large-scale Precambrian tectonic features which trend northeast-southwest roughly parallel to the direction of plate motion and fast shear-wave polarization.