S72D MCC: 121 Sunday 1330h

Shake, Rattle, and Roll II: New Results in Earthquake Hazards *(joint with PA)*

***Presiding:* I A Beresnev,** Iowa State University**; C Goldfinger,** College of Oceanic and Atmospheric Sciences

S72D-01 1330h

Ground motion simulations for the Kocaeli and Chi-Chi earthquakes using a composite source model

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The Kocaeli, Turkey and Chi-Chi, Taiwan earthquakes were the two largest events in 1999. Both events were well recorded by dense strong motion arrays, especially the Chi-Chi earthquake. The wealth of ground motion data from these two earthquakes has provided us the opportunity to understand the source rupture processes of large earthquakes and their high-frequency radiation. I used the composite source model of Zeng et al. to study the earthquake sources and to predict the high frequency near-field strong ground motion. I first used the genetic algorithm to compute a joint GPS static deformation and strong motion waveform inversion for the Kocaeli and the Chi-Chi, earthquake to determine their composite source rupture processes. For both earthquakes, I have used a fault model with a curved fault plane based on the surface rupture data from field mapping. The total moment is 2.1×10^{-27} (dyne*cm) for the Kocaeli earthquake and 2.9×10^{-27} (dyne*cm) for the Chi-Chi earthquake. We found evidence of supershear for the Kocaeli earthquake fault rupture. For both events, the subevents of the composite sources show significant slow rupture or long rise time compared with other earthquakes we have previously studied. The slow subevent rupture velocities fit the low frequency observations, while higher subevent rupture velocities are required to fit the high frequency ground accelerations. This indicates that after the rupture front passes along the rupture plane, the fault continues slipping slowly and then stops abruptly.

S72D-02 1345h

ShakeMaps of the 1999 Chi-Chi Taiwan Earthquake Sequence

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ShakeMap was designed originally as a rapid tool to potray the extent and variation of ground shaking throughout southern California immediately following significant earthquakes (Wald et al., 1999a). Since its inception ShakeMap has been applied to earthquakes in western United States. ShakeMap relies primarily on observed ground motion shaking levels determined rapidly from free-field strong motion seismic instruments. Taiwan has one of the most complete instrumental strong motion networks in the world. Applications of the ShakeMap tool are highly feasible. As a beginning in this direction, we have made retroactively the ShakeMaps of the 1999 Chi-Chi earthquake sequence taking advantage of the unusually large amount of strong motion data both from the real-time system and free-field instruments. We first generate maps of instrumental intensity through relationships between recorded ground-motion parameters and expected shaking intensity values (Wald et al., 1999b). We then compare prominent features in the ShakeMaps of the main shock and several strong aftershocks. Finally, we attempt to correlate the ShakeMap with spatial patterns of building collapse rates from the main shock.

S72D-03 1400h

An Empirical Relationship between Liquefaction and Seismic Wave Energy - Lesson from the 1999 Chi-Chi Earthquake, Taiwan

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The 1999 Chi-Chi (Mw=7.5) earthquake in Taiwan caused widespread liquefaction and serious property damage. However, most liquefaction was located in specific areas, i.e., in the Yuanlin district on the Choshui River alluvial fan and in the Nantao district in a piggyback basin west of the ruptured Chelungpu fault. Most other parts of the alluvial fan did not suffer similar damage. In order to understand the different seismic response in the different areas to the Chi-Chi earthquake and to find an empirical relationship between the occurrence of liquefaction and the seismic wave characteristics, we examined a large number of digitized water-level records from 188 monitoring wells on the Choshui River alluvial fan, a large number of well logs and a large number of seismic records from a dense network of strong-motion seismic stations. Furthermore, we constructed the 3D structure of the basin beneath the alluvial fan in search of any structural characteristics of the basin that might be related to the occurrence of liquefaction. Two relationships have emerged from this search: (1) The occurrence of liquefaction appears to be strongly correlated with the occurrence of the maximums in seismic energy at frequencies of 0.5 1 Hz; and (2) the occurrence of liquefaction appears to be strongly correlated with rising water-level in the unconfined aquifer, but not with that in the confined aquifers. These relationships are testable in other parts of the world where earthquake-induced liquefaction occurred and where strong-motion records and water-level records are available. They suggest that (1) the sediment deformation in the area under seismic shaking may be more sensitive to frequencies of 0.5 1 Hz, and (2) the occurrence of liquefaction in the Chi-Chi earthquake may have been restricted to the uppermost unconfined aquifer. On the other hand, no specific structural or lithological characteristics of the basin was found to be directly correlated with the occurrence of liquefaction.

S72D-04 1415h

Array Observations for Long-period Basin Ground Motions in the Taipei Region During the M 7.1 Eastern Taiwan Offshore Earthquake of 31 March 2002

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The time history and spatial variation of the long-period (2-10 sec) ground motions recorded in the Taipei basin during the magnitude 7.1, 31 March 2002, eastern Taiwan offshore earthquake is presented. The two-dimensional (2D) ground motions of this event were reconstructed from 89 free-field strong motion records spanned over an area of 40 x 40 km square in northern Taiwan. The reconstructed 2D snapshots provide the visualization for seismic wave propagations inside the basin. The observed basin ground motions show complex waveforms, extended durations and multiple propagation directions of later phases. The dominant basin ground motions are identified to shake in its radial directions after the S-wave arrivals. Within the analyzed period band (2-10 sec), results of this study show the seismic wave amplifications in basin area with respect to its surrounding hard rock sites and major amplification occurred on the eastern edge and the western portion of the basin. We interpret these later phases to be surface waves, which are generated by body wave interacting with the thickening margin of the basin. The snapshots of ground motions reconstructed in this study may provide a well constrain in further 3D numerical simulation for the basin response and the basin velocity structure, and to predict ground motions of the further large earthquakes.

S72D-05 1430h

Recent CSMIP/CALTRANS Downhole Array Data and their Application in Site Specific Analysis

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The California Strong Motion Instrumentation Program (CSMIP) operates 13 downhole geotechnical arrays throughout the state of California, 8 of them instrumented with the support and cooperation of California Department of Transportation (Caltrans). More than 60 low amplitude recordings from earthquakes with $2.4<M<7.1$ were recorded at these arrays.

The strongest acceleration of 0.5g was recorded at the La Cienega array in Los Angeles area during the M4.2 earthquake of 9/9/2001. This is a relatively small event with the epicentral distance of 2.7 km and depth of 7.9 km (almost vertical wave incidence). This case presents an opportunity to trace the incident and reflected phases of shear wave recorded at different elevations of the array. The structure of shallow ground layers is evaluated based on those phases and shows good agreement with the downhole profile of US Geological Survey and Caltrans. At the La Cienega site the shear wave velocity increases gradually from 163 m/s at the ground surface to 653 m/s at depth of 250 m. Due to vertical propagation of waves, the one dimensional wave propagation program SHAKE91 can be used to model ground motion in the layers. The earthquake ground motion at depth of 252 m is considered as the input, and the ground motion is computed at the surface, and at depths of 18 m and 100 m using SHAKE91 program. The recorded motion at the depth of 252 m consists of the two main phases: incident wave and reflected wave from the ground surface. The incident wave is used as an input ground motion in order to prevent coupling effect. Output motions are in good agreement with the actual recordings at the ground surface, 18 m and 100 m depths.

The earthquake ground motion recorded at geotechnical arrays show that the incident and reflected phases of P- waves overlap in some cases (because of higher P-wave velocity the arrival time of reflected phase cannot be visually identified) and additional analysis is necessary to distinguish the arrival times of those phases. As an example of such case, low amplitude 0.03 g ground motion of the M5.3 earthquake of 6/17/2002 recorded at the Eureka geotechnical array at the epicentral distance of 37 km is considered. Correlation analysis of the vertical component ground motion at the surface and lower elevations provides clear picture of P- wave propagation in the array.

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S72D-06 1445h

Properties of Vertical Ground Motions

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A typical engineering approach to developing site-specific design vertical ground motions starts with rock-outcrop horizontal motions, converts them into the vertical component using an empirical V/H ratio, and propagates the resulting motion through the soil column as a vertically incident P-wave. In the absence of data on strain-dependent soil properties in compressional deformation, strain-compatible shear-wave properties from the horizontal-component analyses are utilized. This approach makes two assumptions: (1) that the vertical motions are primarily composed of compressional waves, and (2) that strain-dependent material properties in shear deformation can be extrapolated to compressional deformation. Our study

deals with the empirical validation of both assumptions. First, we investigated the ratio of SV- to P-wave spectra of the vertical component of ground motions from significant recent events in California to find which wave type predominantly contributed to the vertical motions, in the frequency range of 0.5 to 25 Hz. The results indicate that shear waves dominate the vertical motions at frequencies up to approximately 10 Hz, above which the contribution of compressional deformation is about as strong or greater. Second, using the data from the KiK-net borehole arrays in Japan, we estimated the nonlinearity in compressional deformation by studying P-wave amplification at variable amplitude levels. Frequency shifts and in some instances reduced amplification are found as the amplitude of compressional strain increases. A tentative curve of constrained-modulus reduction is similar to the existing shear-modulus reduction curves.

The results of this study suggest that vertical motions can be modeled as non-vertically propagating SV-waves. This could be implemented through conventional one-dimensional horizontal-component modeling using SHAKE and the application of empirical depth-dependent V/H correction factors to account for the inclined propagation path. At high frequencies, vertical motions may have to be modeled as near-vertically propagating P-waves, with strain-dependent properties specifically developed for compressional deformation.

S72D-07 1520h

Origins of Turbidites Along the Northern California Margin: Earthquakes on the Northern San Andreas Fault?

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During June and July, 2002, we collected 60 cores from channel and canyon systems draining the northern California margin. The objective of this project is to test the hypothesis that many of the turbidites deposited in these channels resulted from turbid flows triggered by earthquakes on the northern San Andreas fault. Previous work on the Cascadia margin has shown that turbidites there were most likely the exclusive result of earthquake triggering of turbid flows. Along the north coast of California, the northern segment of the San Andreas lies close to the coast or just offshore between San Francisco and Point Delgada. Favorable physiography of both fault and channel systems suggested that the northern San Andreas might be a good locality to test the methods and hypotheses previously applied to Cascadia. Unlike Cascadia, the Northern California margin does not appear to have a regional stratigraphic datum, thus results will depend mostly on AMS 14C dating of individual events. Preliminary mineralogic data however, suggest an earthquake origin for at least some of the events examined thus far. We have been able to distinguish three mineralogic provenances in the cores, well linked to the onshore source geology. Channels from separate provenances come together at confluences, below which we see mixed provenance. Rather than separate events from each provenance, we see either doublets, with no intervening time between them, or bimodal coarse fractions in the turbidites, each peak representing a separate provenance. Since the coarse fractions of turbidites settle out in minutes to hours, the couplets and bimodal distributions indicate little or no time passage during deposition. Synchronous deposition in turn suggests a synchronous timing of the triggering of the source events. Few, if any, triggering events other than earthquakes can satisfy the very short time requirements for synchronous initiation of turbid flows separated by large distances along the margin. Our preliminary investigations suggest that at least some of the events observed in our initial look at these cores are probably earthquake triggered.

S72D-08 1535h

The Brawley Seismic Zone, Imperial Valley, Southern California

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High precision hypocenter patterns define the fault structures of the Brawley seismic zone (BSZ) and nearby faults. The BSZ is divided into four segments: (1) The north segment, between the east shore of the Salton Sea and the northeast-striking Elmore Ranch fault. The north segment represents a continuation of the San Andreas fault striking N25°W (with a 20 degree bend from the San Andreas to the north), with a sub-parallel fault just west of the San Andreas continuation. (2) The Salton Sea geothermal area, near the south shore of the Salton Sea. The Salton Sea geothermal area lies over a small northeast-striking spreading center. Seismicity in the geothermal area is unusually shallow, and is triggered by geothermal power production activities. (3) The central segment, between the Salton Sea geothermal area and the northeast-striking fault defined by aftershocks of the 1979 Imperial Valley earthquake. This segment comprises an extensional transform fault, with seismicity driven by magmatic dikes. (4) The southern segment, south of the 1979 aftershock-defined fault to the north end of the Imperial fault. The extensional transform fault continues in the segment, and it includes the stepover of the transform fault to the Imperial fault.

Seismicity along the southernmost San Andreas fault zone (just north of the BSZ) does not occur on the principle strand of the San Andreas fault, but occurs on steeply northeast dipping faults a few km to the east. Major northeast-striking faults running from the BSZ to the San Jacinto fault zone are localized by basement heterogeneities along the Salton trough margin and within the trough metasediments.

S72D-09 1550h

Seismicity Variations Perpendicular to Strike-slip Faults in Southern California

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We have examined the variations in frequency-magnitude statistics of strike-slip faults in Southern California as a function of distance perpendicular to the fault planes. We first estimated the location uncertainties by comparing the differences in 261,000 hypocenters common to three catalogs: the raw Southern California Seismic Network (SCSN) catalog, Hauksson's [2000] relocated catalog, and Richards-Dinger & Shearer's [2000] relocated catalog. Subcatalogs were constructed for 10 nearly vertical strike-slip fault segments by selecting hypocenters up to 20 km on either side of the segment traces. From the intercatalog variations, we find that the uncertainties in the relative event locations perpendicular to the fault planes are about the same for all three catalogs (a surprising result). They vary with position in the network but have a mean value on the order of 1 km.

We used maximum-likelihood to test the significance of frequency-magnitude variations as a function of the perpendicular distance from the fault plane, and reached two principal conclusions: (1) the upper magnitude cutoff decreases with distance from the fault plane, and (2) for small events (M$<$2.5), the slope of the frequency-magnitude curve increases with distance from the fault plane. The first simply reflects the strain localization on the fault plane. We interpret the second as a depletion of small earthquakes in the damage zone of the main fault. Two disjunct hypotheses that could explain this depletion are (a) catalog bias associated with near-fault attenuation, and (b) a decrease in slip-weakening distance (and thus minimum cutoff magnitude) with distance from the fault plane.

S72D-10 1605h

Las Vegas Basin Seismic Response Project: Overview and Site Response

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This presentation provides an introduction to a multi-institutional effort to characterize the seismic response of the Las Vegas Basin (LVB) to seismic ground motion. Las Vegas lies on top of a deep sedimentary basin (maximum depth 5-km) formed by extensional tectonics in the southern Basin and Range Province. The potential for large earthquakes in the region expose Las Vegas to seismic risk. Seismologists and engineers at LLNL, University of Nevada Reno (UNR) and University of Nevada Las Vegas (UNLV) are evaluating the response of the basin to seismic ground motion and its effect on structures. Recordings of earthquakes and historical nuclear explosions at the Nevada Test Site (NTS) are being used to evaluate the seismic response of the basin. Geotechnical investigations of specific sites are being performed to understand the relationship between ground motions and shallow seismic structure. In particular the presence of thick deposits of unconsolidated alluvial fill and strengthening effects of carbonate cementation. Seismic refraction studies are developing refinements to the basin depth model reported by Langenheim et al. (2001) based on gravity and seismic reflection. These results are being integrated into a community geophysical model of the region for use in finite-difference wave propagation calculations.

Preliminary results of seismic site response show that ground motions in the basin can be amplified by factors of 20 or more relative to sites on Las Vegas Valley's periphery. Site response is strongly correlated with basin depth. However, because the earthquake and explosion events studied sample similar paths from NTS to LVB, we cannot entirely eliminate propagation effects as a possible cause of the amplifications.

S72D-11 1620h

Local Magnitude Determination Using the P-arrival

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Local earthquake magnitude, M_L, is usually determined using peak ground motion observations made relatively late in the seismic wavetrain. Here we present a technique for estimation of earthquake magnitude using the P-arrival only, M_P. Such rapid magnitude determination makes it possible to estimate ground motion parameters prior to significant ground shaking (even at the epicenter for deeper earthquakes), making it ideal for earthquake early warning in southern California.

Using 53 historical earthquakes in southern California, ranging in magnitude from 3.0 to 7.3 and including Landers, Northridge and Hector Mine, we test the accuracy of the method by comparing M_P to M_L as determined by TriNet. For earthquakes with magnitudes $<$ 5.0 the best M_P estimates require only 2 sec of broadband data. For larger events, low-passing the data at 3 Hz provides the best estimates of M_P, which are possible with 4 sec of data. Using data from all available broadband seismic stations within 100 km of all 53 earthquakes the rms error in M_P is 0.5 magnitude units.

To test the speed with which a magnitude estimate could be provided in southern California we select a subset of earthquakes occurring beneath the more dense portions of TriNet. The subset consists of 28 events with magnitudes ranging from 3.0 to 5.1. Of these 28 test events, magnitude estimates are available at the same time as the S-arrival at the epicenter for 12 of them with an rms error of 0.76 magnitude units. Three seconds later estimates are available for 26 events with an rms error of 0.48. The algorithms developed, named ElarmS, provide a basis for earthquake early warning in southern California and are currently being tested with the TriNet realtime system.

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

S72D-12 1635h

Monitoring Earthquake Liquefaction Processes Using MISR/Terra Satellite Data

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The devastating Gujarat earthquake which hit the province of Gujarat in India on January 26, 2001, provoked an extensive liquefaction process. This presentation reports on the spatio-temporal distribution of this

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 $\geq$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 ~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.

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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. Such 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. Priliminary results show that such measure is at its minimum by using JHDME.

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

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The November 14, 2001, Kunlun earthquake (Mw = 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 (Mw = 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

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