Different offset range of data was analyzed and migrated using reverse-time pre-stack depth migration algorithms. The results show that long-offset data provides improved illumination of the vertical impedance boundaries.

S21F-0406 0830h POSTER

Shallow Seismic Trapping Structure in the San Jacinto Fault Zone, California

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We analyze a waveform data set generated by 385 events and recorded by linear seismic arrays across the Clark Valley and Coyote Creek faults in the trifurcation area of the San Jacinto fault zone (FZ). The goal is to obtain structural information from a comprehensive analysis of FZ trapped waves in the data. A previous work based on selected waveforms suggested a low-velocity waveguide continuous to a depth of at least 18 km (Li and Vernon, JGR, 2001). If so, events located clearly outside the FZ proper should not generate any FZ trapped waves. On the other hand, a shallow FZ waveguide can produce (Fohrmann et al., PAGEOPH, 2003) trapped waves for events clearly off the fault. Our analysis of trapped waves in the larger considered data set is compatible with the existence of shallow non continuous waveguide layers along both the Clark Valley and Coyote Creek faults. Ben-Zion et al. (GJI, 2003) found in the context of the North Anatolian fault that many events off the fault produce FZ trapped waves and suggested that a better term for such data may be FZ related site effects. Within a distance of roughly 90 km, a subset of 159 events including many off the fault are suitably recorded by the arrays for analysis. A spectral ratio method is used to calculate the concentration of seismic energy within the FZ stations, producing a systematic measure of the quality of trapped waves or FZ related site effects. We find that FZ site effects are observed at FZ stations for the majority of the earthquakes, with the generating events located at various distances from the fault trace and various angles and distances from the receivers. The distribution of the events implies that the trapping structures are not continuous along the strike of either fault branch and do not extend bellow the depth of the shallowest events (e.g., 5 km). A travel time analysis of the difference between the direct S and trapped wave group arrivals shows no systematic increase with hypocentral distance or event depth, compatible with shallow discontinuous waveguide structures. Synthetic waveform fits to the data generated using the 2D analytical solution of Ben-Zion & Aki (BSSA, 1990) indicate propagation distances within the low velocity FZ layer of around 5km, supporting the other analyses. We obtain good fits to the data produced for the Coyote Creek fault using a model consisting of a single low velocity layer in a half space. However, on the Clark Valley fault the waveguide appears to be weaker and the synthetic waveform fits are not as good. A feature of all the waveform modeling for both the arrays is that the waveguide center is located to the NE of the surface trace.

S21G MCC: 3011 Tuesday 1020h

Coda the Destroyer: Rupture Kinematics and Dynamics I *(joint with T)*

Presiding: **D Lavallee,** Institute for Crustal Studies**; A M Rubin,** Princeton University

S21G-01 1020h

Dynamic Heterogeneities Versus Fixed Heterogeneities in Earthquake Models

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A debate has raged over whether fixed material and geometrical heterogeneities or alternatively dynamic stress heterogeneities arising through frictional instabilities dominate earthquake complexity. It may also be that both types of heterogeneities interact and are important. This work makes a first step in examining this interaction, combining two previously separate lines of research. One line examined friction which have attractors (the subset of phase space the system evolves towards in the long run) on homogeneous faults which are simple, and then added fixed heterogeneities to the faults to obtain complex attractors. Another line examined frictions which produced complex attractors on homogeneous faults. Here, we examine frictions which produce complex attractors on homogeneous faults, and study them on heterogeneous faults, in order to study the interaction of dynamic stress heterogeneities and fixed fault heterogeneities. We consider two types of fixed heterogeneities: an additive noise and a multiplicative noise to the frictional strength of the fault. Because of the linearity of the bulk elastodynamics, the attractor is unaffected by additive fixed noise in the strength of the fault: adding an arbitrary function of space, fixed in time, to the friction leaves the resulting attractor unchanged. In contrast, multiplicative fixed noise multiplying the friction can have a profound effect on the resulting attractor. In the small multiplicative noise amplitude limit, the frictional weakening attractor is little perturbed; at finite amplitudes, fixed heterogeneities substantially alter the attractor. We see, as one consequence, a shift toward longer length events at larger amplitudes. Fixed heterogeneities are seen to reduce the irregularities created by the frictional instability we study, but by no means destroy them. We quantify this by examining a measure of variability of importance to hazard, the coefficient of variation of large event recurrence times. The coefficient of variation is seen to remain substantial even for large fixed heterogeneities. For friction which weakens with time, so the underlying uniform fault attractor is simple, fixed heterogeneities increase irregularity. For all frictions examined, at low fixed heterogeneity the stress concentrations left over by the ends of the large events dominate where most of the small events occur, while at higher heterogeneity the stress irregularities left over by fixed fault heterogeneities begin to dominate where the small events occur. This may be the strongest signature of fixed heterogeneities, and should be examined further in the Earth. Finally, in what may have important implications for more sophisticated estimates of earthquake hazard, we see a correlation of locations with lower strength drop having higher variation in large event repeat times.

S21G-02 1035h

Dynamic Rupture Processes on Fault Models under Stress Fields Estimated from Active Fault Information: The 1995 Kobe, Japan, Earthquake

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We tested our 3-D finite-difference dynamic rupture model by comparing the rupture process of the 1995 Kobe earthquake estimated from waveform inversions. In our model, the stress fields are estimated from geomorphological and geological studies of active faults. Surface rupture of the Kobe earthquake appeared only on the fault southwest of the rupture initiation (Hokudan segment). The waveform inversion results indicate that large moment releases occurred in the entire Hokudan segment and deep part of the Rokko-san segment, northeast of the epicenter. We tested many fault models, by varying the location of discontinuity, because the geometry of the segment boundary is located beneath Akashi strait and not well known. In our 3-D finite-difference model, we modeled the variation of fault strike and dip angles by introducing heterogeneity of the initial stress field. We assumed hydrostatic condition, and also assumed several patterns of stress drop distribution along the fault dip (in the depth direction). We used observed surface slip, both horizontal and vertical, as the constraints of model. When the two segments are discontinuous and stress drop is zero in the top 8 km of the Rokko-san segment, our dynamic modeling produces rupture area similar to the Kobe earthquake. The rupture propagates smoothly on the Hokudan segment. The rupture on the Rokko-san segment, however, is delayed for 8 seconds, which is inconsistent with the waveform inversion results. In order to rupture the Rokko-san segment first, the two segments must be continuous or the Rokko-san segment must have some discontinuous subfaults. In such cases, however, surface slip is 0.5 m or larger on the Rokko-san segment regardless of the stress drop distribution, hence, the surface ruptures are expected to appear. We need to consider more heterogeneous stress drop distribution to reproduce the observed rupture process.

S21G-03 1050h

Evidence for Self-Similar, Triangular Slip Distributions on Earthquake Faults, and Implications on Fault and Earthquake Mechanics

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The objective of our work is to characterize slip distributions for earthquake faults. We have compiled three types of data available in the literature: 1) Surface measurements of slip performed by geological mapping after earthquakes; 2) "total" earthquake slip distributions deduced from published finite-source rupture models (Mai, 2002); 3) Source time functions of large earthquakes known to have propagated unilaterally. Overall, the data sets include about 100 earthquakes of various magnitudes (5.5-8.1) and kinematics. Both surface and total slip profiles are broadly similar in overall shape (along both strike and dip), being roughly triangular and asymmetric regardless of magnitude and kinematics. This suggests that distribution of slip on an earthquake fault is not random, and that seismic slip distributions are self-similar overall. The observation of triangular, self-similar seismic slip distributions together with roughly constant stress drops during earthquakes, cannot be accounted for by the available mechanical models. Earthquakes with such an asymmetric triangular slip profile initiate close to one fault tip and mainly propagate unilaterally along-strike toward the other end of the fault. Most hypocenters locate at or close to where total slip is higher along-strike, but some initiate at or close to where total slip is minimum (fault taper). However, no earthquake is observed to initiate where total slip is minimum both along-strike and -dip. This demonstrates that earthquakes cannot initiate without any "stress concentrator" or barrier capable of sustaining high stresses and strain. As a matter of fact, earthquakes seem to accumulate less total slip (per length or width) along either strike or dip when their hypocenter is close to the fault taper along strike or dip, respectively. The triangular, self-similar seismic slip distributions resemble those recently found on long-term cumulative normal faults (0.1-60 km-long; 0.01-1 Ma-old) and rift systems (10-1000 km-long; 0.1-10 Ma-old). This further suggests that features created in tens of seconds and in tens of thousands years or millions years may share some common mechanical explanations. We suggest that the observation of triangular, self-similar slip profiles can be mechanically understood if some form of off-fault inelastic deformation is included. We use an elastic (static) modeling to show that large triangular zones of off-fault damage can explain the observed triangular, self-similar slip profiles provided damage is anisotropic and in the form of cracks and/or secondary faults subparallel or slightly oblique to the main fault. This suggests that on-fault processes may be insufficient to explain the dynamics of earthquake ruptures, with wide ranging implications for understanding earthquake processes.

S

S21G-04 1105h

Effect of a Material Contrast on a Dynamic Rupture: 3-D

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We use numerical simulations of spontaneously propagating ruptures to examine the effect of a material contrast on earthquake dynamics. We specifically study the case of a lateral contrast whereby the fault is the boundary between two different rock-types. This scenario was previously studied in two-dimensions by Harris and Day [BSSA, 1997], and Andrews and Ben-Zion [JGR, 1997], in addition to subsequent 2-D studies, but it has not been known if the two-dimensional results are applicable to the real three-dimensional world. The addition of the third dimension implies a transition from pure mode II (i.e., plane-strain) to mixed-mode crack dynamics, which is more complicated since in mode II the shear and normal stresses are coupled whereas in mode III (i.e., anti-plane strain) they

are not coupled. We use a slip-weakening fracture criterion and examine the effect on an earthquake rupture of material contrasts of up to 50 percent across the fault zone. We find a surprisingly good agreement between our earlier 2-D results, and our 3-D results for along-strike propagation. We find that the analytical solution presented in Harris and Day [BSSA, 1997] does an excellent job at predicting the bilateral, along-strike rupture velocities for the three-dimensional situation. In contrast, the along-dip propagation behaves much as expected for a purely mode-III rupture, with the rupture velocities up-dip and down-dip showing the expected symmetries.

S21G-05 1120h

Importance of Intermediate Principal Stress Magnitude in Dynamic Rupture Propagation in 3D

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Dynamic rupture process along non-planar faults has been progressively studied by several groups, but there are few studies that take into account the possibility that slip directions (rake) may change along the different segments. This may actually happen; for example, rupture started on an inverse fault and propagated far along several strike-slip faults during the 2002 Denali, Alaska, earthquake. We apply a 3D boundary integral equation method (BIEM) and numerically study dynamic rupture propagation along a few fault segments subjected to a uniform tectonic regime but with different strikes and dips. Their different geometry implies different rakes for each segment. Furthermore, not only the magnitude but also the direction of the dynamic stress perturbation is calculated since it may not be the same as that of the initial stress regime. Thus, compared to previous models, the occurrence of dynamic rupture jumps depends on the relative segment geometry, the relative value of the dynamic and static friction coefficients, but most importantly, on the relative value of the intermediate principal stresses.

S21G-06 1135h

Numerical Models of Stopping Ruptures on a Bimaterial Interface

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Using a cross-correlation earthquake relocation technique, Rubin and Gillard (2000) and Rubin (2002) found that the nearest aftershocks of microearthquakes on the San Andreas fault were much more likely (by a ratio of nearly 3:1) to occur to the NW of the mainshock than to the SE. They attributed this asymmetry to the material contrast across the fault and the resulting dynamical reduction in normal stress near the rupture front propagating to the SE (the front moving in the direction of slip of the more compliant medium). Specifically, it was hypothesized that regions of the fault far enough from failure to resist this extra dynamical "kick" would be that much farther from failure once those dynamical stresses decayed. However, analytical (steady-state) models of propagating slip on a bimaterial interface (Weertman, 1980) show that, as with the static stress field, normal stress changes occur only behind the rupture front. The proposed explanation works most simply if the region ahead of the SE rupture front experiences a transient stress favorable for slip. In principal this stress transient could be associated with either rupture growth or arrest. To investigate this further, we ran 2-D numerical models of slip on a bimaterial interface with slip-weakening friction, using the code of Cochard and Rice (2000). The ruptures spontaneously accelerate to the generalized Rayleigh wave speed of the medium, when such exists. During this growth phase, large tensile stresses are indeed restricted to regions of large slip velocity behind the SE-propagating rupture front. Ahead of the rupture front the normal stresses are smaller and compressive. If the rupture front is stopped abruptly, the short-wavelength tensile stress pulse continues to propagate at roughly the same velocity. The above comments also apply in an anti-symmetric sense to the NW rupture front, although there the slip speeds and normal stress changes are lower. If the rupture is stopped by a more gradual reduction in the loading stress, the moving tensile pulse can spawn a decaying slip pulse at the SE front but not the NW. If this slip pulse marks the furthest extent of slip, the resulting static stress field is quite asymmetric even for a symmetric initial stress, lying on the failure envelope at the NW end of the rupture but well below it at the SE end. These results are at least permissive of the explanation proposed by Rubin and Gillard. For weaker slip pulses (due to any of a number of factors contributing to smaller maximum slip speeds), the furthest extent of slip near the SE rupture front can be driven by the stopping phase arriving from the NW end of the crack. Under such conditions the final stress field is more symmetric. We will be running models using heterogeneous stress fields to explore these questions further, and hope to use rate-and-state friction to investigate the observed temporal decay of the aftershock asymmetry.

S22A MCC: Level 1 Tuesday 1330h

Mechanical Strength of the Continental Lithosphere III Posters

(joint with T, V)

Presiding: **J C White,** University of New Brunswick**; C W Holyoke,** Brown University

S22A-0407 1330h POSTER

Constraining the Vertical Coherence of Deformation in Central Asia Using GPS, Geologic, and Shear-Wave Splitting Data

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First-order constraints on the depth dependence of lithospheric strength are provided by the degree of vertical coherence between crustal and mantle deformation. We evaluate the level of vertical coherence for the Tibetan Plateau, and off-plateau region of Yunan, by comparing the strain-rate field that has been calculated for the surface, and the mantle field inferred from mantle anisotropy. A continuous surface strain-rate field is determined from GPS observations and Quaternary fault-slip rates that are interpolated using continuous bi-cubic spline polynomials. Point estimates of the mantle finite-strain field are inferred from measurements of the shear wave splitting fast polarization directions, ϕ , of core phases, which are assumed to denote the orientation of shear in the lithospheric mantle under transpressional deformation. We evaluate the surface field at the locations of splitting measurements, and calculate a surface-derived prediction of ϕ , ϕ_s, assuming that the finite-strain shear orientation corresponds to the no-length change orientation. We then use the difference angle $\Delta\phi_s = \phi - \phi_s$ as a measure of vertical coherence. On the Tibetan plateau, vertical coherence is remarkably high under left-lateral shear; the RMS value of $\Delta\phi_s$ is less than 10°, which approximately corresponds to the expected uncertainty in the splitting measurements. In contrast, $\Delta\phi_s$ is very large for the off-plateau region for either right (52°) or left lateral (43°) shear, signifying the absence of vertical coherence. We calculate the mantle strain-rate field assuming that the Indian plate, Tarim Basin, south China Block, Ordos block, and Sunda block, represent rigid lithospheric blocks. GPS measurements are used to define the rotations of these bounding blocks, and we solve for a continuous strain rate field in the deforming interior region. We calculate predicted values of ϕ, ϕ_m, where splitting measurements are available. The most dramatic change, compared to surface field, is that in Yunan, $\Delta\phi_m$ is less than 10°, suggesting that boundary conditions alone are enough to predict mantle deformation field off the plateau. For Tibet, the fit is degraded, compared to predictions from the surface field, with $\Delta\phi_m = 22^\circ$, suggesting a need for a second mantle deformational driving force, namely a contribution from body forces. Indeed previous dynamic modeling of Tibet shows that the surface deformation field (and hence the mantle field) requires a significant body-force contribution. Given that the crust and mantle have distinct strain-rate and velocity fields, at least in certain regions, we next seek to quantify the horizontal shear in the decoupling zone between the two. For this purpose, we determine a mantle velocity field consistent with the splitting observations by again applying the GPS-inferred rotations of the rigid blocks, and also impose the shear wave splitting measurements as directions of no length change in the inversion. With continuous surface and mantle velocity fields we can then calculate a differential velocity field between the crustal and mantle layers. By assuming different thicknesses and viscosity values for the decoupling zone, we calculate the shear strains and resulting shear tractions. These stresses are then compared to the observed surface deformation to place bounds on viscosity values within the decoupling zone.

S22A-0408 1330h POSTER

Convergence in a Model Viscous Lower Crust and its Surface Topographic Expression

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A 2-D analytic solution for the displacement of the upper surface of a viscous layer moving past a rigid body illustrates that such a system can produce measurable signals at the Earth's surface. This problem is best-known in the case of a rigid indenter intruding into a viscous fluid, often used to describe the case of rigid Indian lithosphere intruding into a fluid layer beneath Tibet. Similar geometry and distribution of mechanical properties may exist in other regions of convergent tectonics. In these cases, the indenter excites vertical velocity in the fluid, which drives displacement of the upper boundary at amplitudes and wavelengths related to the length scales of the fluid layer and the indenter. These displacements decay over time, but persist sufficiently to be expressed in real landscapes, such that observations of characteristic topography may serve as direct tests for the presence of flow in the lower crust. In particular, this model may be applied in cases such as Tibet where additional independent evidence for a channel of low viscosity exists in the distribution of seismic moment release or in observations of rheology from seismic wave velocities.

S22A-0409 1330h POSTER

Stress Magnitudes in Asia and North America: Implications for Strength Profiles

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We present dynamic models that incorporate lithospheric gravitational potential energy (GPE), coupling with deeper mantle circulation, and stress field boundary conditions. Our integrated modeling approach allows us to quantify the degree of coupling between the lithosphere and the mantle in western North America and throughout southern and central Asia. Although both regions undergo active continental deformation in broad diffuse zones, the relative roles of the forces contributing to the deformation of each region differ. In order to quantify the forces responsible for the continental deformation we estimate the contributions of lithospheric GPE, stresses associated with plate motions, and basal tractions resulting from mantle-lithosphere coupling. Internal density distributions inferred using seismic tomography and history of subduction drive our mantle circulation model that is constrained to match the geoid, topography, and plate motions. Our lithospheric models are solutions to equations for a thin sheet, with basal traction contributions, and allow us to solve for both the vertically averaged magnitudes and styles of the total deviatoric stress field that drives continental deformation. Initially we determine a kinematic strain rate and velocity field model based on interpolation of GPS velocity vectors and Quaternary strain rates. Results to date are consistent with significant coupling between lithosphere and deeper mantle circulation throughout deforming Asia. On the other hand, our results require a significant decoupling between deeper mantle circulation and the lithosphere in western North America. The magnitudes of vertically averaged deviatoric stress range from 5-40 MPa in Asia, and 5-20 MPa in western North America. We next use the magnitudes of the vertical averages of stress to investigate how strength