

determine the ray parameter and backazimuth of these arrivals. Stacking in the tau-p domain has enabled us to image some arrivals which are not apparent on individual seismograms.

We are currently experimenting with a forward modeling approach along with a range of mineralogical models for subducted oceanic crust to develop insight into the waveform effects of various structures and to replicate the observed arrival times and amplitudes. Preliminary studies using a finite difference method to produce synthetic P-SV and SH seismograms have predicted arrival times for some phase conversions for intermediate depth events. The starting model used for this was based on the inferred thermal and mineralogical characteristics of the Tonga slab with an eight km thick low velocity crustal layer. We will present the results of further modeling for a range of events and an assessment of the match between observations and the arrivals predicted by different mineralogical models.

S52A-1075 1330h POSTER

Test of the Slab Stress Guide Hypothesis for the Vanuatu Wadati-Benioff Zone

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It has long been proposed that subducting slabs act as stress guides. Data from Wadati-Benioff zone earthquakes have been both supportive and conflicting with this hypothesis. Here we test this hypothesis using stress inversions of WBZ earthquakes for the Vanuatu arc. The strike of the slab of the Vanuatu arc changes by over 70° along strike, allowing us to separate the effect of slab geometry from plate tectonic parameters, such as convergence direction, which do not vary in this manner. Our results show various directions of σ_1 and σ_3 along the arc at several depth ranges. When we unbend the slab to put all data into the slab reference frame we get an excellent data collapse in which the inversion for the entire arc at each depth range provides a good solution. These indicate that σ_1 is slab normal and σ_3 is down dip in the top 60 km. In the ranges 61-120 and 121-180 km σ_1 is also slab normal but σ_3 defines a girdle pattern in the plane of the slab, suggesting bi-axial extension of the slab. These results strongly support the stress guide hypothesis, but the stress patterns in the deeper regions do not support the notion that the stresses are controlled by slab pull or subduction resistance. They suggest instead that they are controlled by a slab normal compressive force, most likely the sea anchor force, which results from the face-wise translation of the slab through the mantle

S52A-1076 1330h POSTER

Modelling the Anisotropic Structure Beneath Wellington, New Zealand

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In a previous study, frequency-dependent anisotropy was observed at the permanent broadband station SNZO, Wellington, New Zealand, which lies above the fore-arc region of the Hikurangi subduction zone. The oblique subduction of the Pacific plate beneath the Australian plate terminates just south of Wellington, and the major geologic features in the Wellington region follow the northeast-southwest trend of the trench. We have made splitting measurements using events recorded since the previous study, as well as going back and redoing measurements using unfiltered waveforms where possible. Thus we have nearly nine years of data in total, giving 67 useable SKS, ScS and S phases and therefore good azimuthal coverage. The measurements exhibit a dependence on the propagation and incoming polarisation directions, as well as frequency. The fast polarisations range between 2 deg and 103 deg, and the delay times range between 0.75 s and 3.05 s. The data were first inverted for a two layer anisotropic model with horizontal symmetry axes. This model fits the fast polarisations reasonably well but does not fit the delay times, and does not explain the frequency dependence which is observed. This suggests more complicated structure such as a dipping symmetry axis, which was also suggested by Savage (1998) in order to fit receiver functions at SNZO. We have investigated the velocity model sn116 proposed

by Savage (1998) for SNZO to see whether it fits our observed splitting measurements. We increased the thickness of the bottom anisotropic layer in order to model the large observed delay times. This model does not reproduce the large variation in fast polarisations which is observed, and does not fit the pattern of delay times, though it does produce a variation in delay time with back azimuth. The splitting measurements from this model do not exhibit any frequency dependence either. We plan to do detailed forward modelling and possibly nonlinear waveform inversion to try to obtain an anisotropic model for SNZO which fits the observed splitting measurements.

S52A-1077 1330h POSTER

Inverting Telesismic P and SKS for Dip and Anisotropy in the Lithosphere

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The inversion of sets of single-station teleseismic receiver functions for lithospheric structure is difficult due to the non-linearity of the problem, which is greatly increased in the presence of dipping interfaces and layer anisotropy. Given an efficient ray-theoretical tool for forward-modelling teleseismic seismograms (Frederiksen and Bostock, 2000), we perform a directed Monte Carlo search technique using the neighborhood algorithm of Sambridge (1999), enabling us to search 20-30 parameters in a reasonable amount of computer time. Tests on synthetic data reveal inherent velocity-depth tradeoffs in typical data sets, due to the limited moveout present in teleseismic Ps; the azimuth of the anisotropic symmetry axis and the strike of a dipping interface prove to be well-resolved given adequate back-azimuthal coverage. We apply this technique to two single-station data sets. The first, from permanent station PGC, Vancouver Island, British Columbia, displays dipping low-velocity sediment layers in the mid-crust. The second, from a station at the northern end of the Tibetan plateau operating in 1991 and 1992, requires a sequence of thick crustal anisotropic layers to explain the observed pattern of receiver-function arrivals. In principle, the same modelling and inversion techniques are applicable to S waves of known polarization, though to date the lack of a means to remove the source function from an S signal has impeded the use of event collections analogous to receiver-function gathers. Given that the SKS phase is purely SV polarized upon entering the upper mantle, and that the SKP recording of the same event should exhibit the same source function, we investigate the possibility of deconvolving SKP from SKS. A deconvolved SKS signal (or SKS receiver function) should enable the detection of both multiple shear-wave splits from layered lithospheric anisotropy, and Sp conversions from interfaces; we investigate the potential of both phenomena from a neighbourhood-inversion standpoint.

S52B MCC: Hall C Friday 1330h Whole Lotta' Shakin' Goin' On: Earthquake Process Posters (joint with NG, G, T)

Presiding: K F Tiampo, University of Colorado; B Enescu, Kyoto University

S52B-1078 1330h POSTER

Nonlinear Modeling of Frictional Melting at Asperity Tips

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There is substantial interest in studying pseudotachylites (PT) as products of frictional melting because their study can provide information on the physical and chemical conditions at the earthquake source, including temperature, redox state, stress levels, the role of fluids in fault zone rheology, and the energy budget during seismic slip. PT are dark rocks found in fault zones, that typically contain two components: (a) a very fine grained matrix of recrystallized molten

rock showing various flow, shear and chill structures; and (b) embedded clastic material that are products of frictional wear and comminution of the host rock. Frictional melting is thought to initiate between opposing asperity tips during fault slip. While several studies have modeled the macroscopic generation of wear material as well as frictional melts in fault zones, few studies have modeled "microscopic", or asperity-scale mechanisms of frictional melting.

This study examines the influence of asperity-scale fault dynamics on asperity temperature distribution, and therefore, the potential for frictional melting to occur. Our model considers elastic and isotropic hemispherical asperities whose thermal properties are strongly temperature dependent. Asperity sizes have a fractal size distribution that scales with slip displacement. The model allows for both pure (homogeneous) asperities made up of a single material, or composite (heterogeneous) asperities made up of two different materials (e.g., quartz core surrounded by a feldspar shell). Fault slip is modeled as adiabatic, and the problem is reduced to 2-D conduction within a hemisphere, with a point heat flux pulse boundary condition at the asperity tip that scales with asperity size. The fully non-linear PDE (with linear and non-linear boundary conditions) is first linearized using the Newton-Kantorovich procedure, and then solved using the δ -form of Douglas & Gunn two level scheme. The general code written to implement this two-stage finite difference algorithm has been tested for both solution accuracy and convergence rate - second order convergence of grid functions in space and time; quadratic convergence of non-linear iterations - using over 30 linear and non-linear problems with well-known or pre-assigned solutions.

Preliminary results obtained from this numerical model for pure quartz asperities indicate that peak temperatures are attained slightly after asperity tip separation. As expected, these peak values are much larger than those predicted by the macroscopic, infinite, planar fault slip models. Also, independent of asperity size, the peak of the temperature distribution rarely reaches the asperity center, and temperatures there rarely attain levels required for melting. This implies that much of the melt in PT may be provided by the melting of the asperity tips, and that melting is highly localized. Further runs and analyses are being done to confirm these results, and to ultimately determine: (i) the dependence of maximum temperature and temperature distribution (in both space and time) of pure asperities on (a) asperity size, (b) asperity spacing and (c) fault zone characteristics (slip velocity, shear stress, and displacement); (ii) the temperature distribution, maximum temperature and melting potential in composite asperities; and (iii) influence of heat convection - from the asperity surface to the fluid surrounding the asperity (frictional melt, hot gases/vapor) - on these temperature distributions.

S52B-1079 1330h POSTER

A Numerical Investigation of the Relation between Coulomb Stress, Strength, and Earthquake Slip

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Research over the past 10 years has demonstrated a clear causal link between Coulomb stress perturbations and subsequent earthquakes, most strongly that aftershocks occur primarily in areas of positive Coulomb stress change and that positive stress perturbations can apparently advance the time-to-failure of future large earthquakes. There are a number of questions still unanswered, however; perhaps principle among them is the extent to which Coulomb stress perturbations are first order effects given that any particular fault will have both a heterogeneous loading history and, most likely, heterogeneous material properties.

Here we begin to investigate this issue in a complex 3-D fault network model that includes structural complexity but simplifies the stress interactions in order to keep it computationally tractable. Each fault in the model is represented by an individual cellular automaton, with nearest neighbor stress transfer rules formulated to produce realistic stress concentrations. Following every moderate to large event, tensorial stress perturbations due to the event are computed (using a boundary element method) at the locations of each cell not involved in the rupture and are resolved into the 3-D Coulomb stress change appropriate for the cell's orientation. Such stress perturbations may in turn trigger subsequent events.

This model has been used to examine the relation between Coulomb stress change and triggered slip by examining earthquake pairs under a range of stress and strength heterogeneity conditions. For each pair, we plot the distribution of Coulomb stress on the fault plane of the triggered event and compare this to the distribution of triggered slip. In general, we find a close correspondence when the background stress heterogeneity is small, but very little if any when the heterogeneity

ity is large. The latter result is consistent with observation (c.f. Nalbant et al., this meeting) and supports the ideas that earthquake rupture is a complex phenomenon in which heterogeneity plays a major role.

S52B-1080 1330h POSTER

Velocity Weakening and Velocity Strengthening Applied to Fracture Propagation: Insight From an Analogue Model

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Since more than 40 years the stick-slip behaviour has been considered a good falsifier of the seismic reactivation, for it takes into account the elastic and the frictional properties at the same time. The aim of this study is to show that fractures propagation follows a stick-slip behaviour when a dynamical instability occurs. This instability could be considered as a triggering factor of natural seismic releasing. This idea was inspired by the results of an analogue model where stable and unstable ruptures are performed by the detachment of an adhesive tape from a fixed PVC-plate, at constant traction velocity imposed. When the latter exceeds a threshold value the failure is alternately given by stages of slow-ruptures (stick-phase) and quasi-instantaneous ruptures (slip-phase), with different mechanical properties. Stick-slip behaviour is caused by a variation on the rate of fracture propagation velocity. Under the threshold value the rupture is continuous and follows a predictable evolution where no dynamical instability occurs. The dependence of stable and unstable behaviour from fracture propagation velocity can be analytically expressed by the Dieterich-Ruina and Ruina-Dieterich constitutive laws of friction. Their analysis considers the friction coefficient as a function of sliding velocity variation. We use the same mathematical formalism, with fracture velocity variation in substitution of sliding velocity variation. For this reason we suggest that the concepts of velocity weakening and velocity strengthening are valid, not only for sliding processes, but also for unstable and stable rupture processes.

S52B-1081 1330h POSTER

Dynamic Rupture Inversion with a Neighbourhood Algorithm

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Inverse methods have successfully been used to estimate kinematic parameters such as slip on the fault (e.g., Wald and Heaton, 1994), but, to our knowledge, not to estimate friction parameters or stress distributions directly. The main reason for the lack of such efforts is that efficient numerical methods for modeling spontaneous rupture in three dimensions, including the computation of the radiated waves, have only recently become available (e.g., Madariaga et al., 1998). For example, Peyrat et al. (2001) used such method to demonstrate that it is possible to estimate the initial dynamic conditions for the 1992 M7.3 Landers event using trial-and-error inversion of the observed accelerograms. The results by Peyrat et al. showed that the radiated waves are highly sensitive to the distribution of stress and friction parameters on the fault, an essential requirement for the inversion to work. Here, we attempt to carry the nonlinear inversion for the dynamic rupture to a new level using a systematic method. The nonlinear inversion is performed with the neighbourhood algorithm (NA) introduced by Sambridge (1999), a direct search method using simple geometrical concepts to explore the parameter space. We present examples of inversion using the NA algorithm to illustrate the performance of the method and demonstrate that it is possible to invert for realistic heterogeneous distributions of the dynamic parameters, e.g., initial stress, for historical earthquakes such as the Landers and the 2000, M6.6 Tottori, events. Our results from systematic nonlinear inversion show great promise for future estimation of the parameters controlling the dynamic rupture of large earthquakes.

S52B-1082 1330h POSTER

Ground Motion Simulation Based on 3D Shear Dynamic Rupture Model Using Finite-Difference Method with Variable Grid Spacing

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Compared with the kinematic models the dynamic source models are based on physical, and therefore more realistic seismic source properties. With the development of efficient numerical techniques these models are being used in studies of the seismic source and near-fault strong ground motion simulations as well. Several numerical techniques have been applied in simulations of the rupture processes of the fault. However, a few efforts are devoted to the simulation of ground motion and wave propagation based on dynamic fault models and large scale structures. The use of three-dimensional finite-difference methods (3D-FD) with uniform grid formulation in this type of analyses requires relatively large computer memory. The 3D-FD computation requirements are reduced considerably if the grid spacing is made variable (e.g., Pitarka, 1999). In this study we used the numerical technique of Pitarka (1999) to simulate the spontaneous dynamic rupture propagation on a planar fault. The accuracy of the model was tested through simulation of different problems of spontaneous rupture propagation in a fault embedded in an elastic medium presented in the specialized literature. These numerical tests demonstrate that the proposed nonuniform staggered-grid finite-difference model is efficient for the simulation of dynamic rupture problems. Then, we simulated the ground motion caused by the dynamic rupture propagation of the 2000 Tottori (Japan) earthquake. The simple slip-weakening model, in the form given by Andrews (1976), was used as the friction law on the pre-existing fault for the shear rupture propagation. The dynamic parameters, such as stress drop, strength excess and critical slip, were recovered from the results of waveform inversion. The results presented in this paper show that the 3D-FD method is efficient at calculating near-source long period ground motion using dynamic models.

- Andrews, D.J. (1976), Rupture Velocity of Plane-Strain Shear cracks, *J. Geophys. Res.*, 81, 5679-5687.
- Pitarka, A. (1999), 3D Elastic Finite-Difference Modeling of Seismic Motion Using Staggered Grid with Nonuniform Spacing, *BSSA*, 89, 54-68.

S52B-1083 1330h POSTER

Dynamic Source Parameters in the Characterized Source Model

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Somerville et al. (1999) characterized source slip models inverted from strong motion records for mainly California events. They introduced a criterion to extract rectangular-shaped asperities that an asperity consists of fault elements with final slips larger than 1.5 times of the average over an entire fault. They found that total area of asperities follows a scaling relation to seismic moment. Recent events such as the 2000 Tottori-ken Seibu (Mw6.6), Japan, the 1999 Chichi (Mw7.6), Taiwan, and Kocaeli (Mw7.4), Turkey, and some moderate-size crustal earthquakes in Japan were shown to follow the relation (Miyakoshi et al., 2000, Miyake et al., 2001).

Irikura and Miyake (2001) proposed characterized source model based on this scaling relation in a RECIPE for strong motion prediction. The availability of the characterized source models has been proved through the strong motion simulation in near-source area in the broadband frequency band for the 1995 Kobe (Kamae and Irikura, 1997) and for the 1997

Kagoshima-ken Hokuseibu (Miyake et al., 1999) earthquakes. However, in those simulations, they estimated stress drops only for the asperities by forward simulation of the high frequency contents of the records. When constructing a characterized source model for strong motion prediction in the broadband frequency band, we need rules to set stress parameters.

Bouchon (1997) proposed a mapping method of a spatio-temporal shear-stress distribution on the fault plane from a spatio-temporal slip distribution. We examined dynamic source parameters such as stress drops, Dc (critical distance), and Gc (surface fracture energy), by his method for the 1999 Chichi, and the 2000 Tottori-ken Seibu earthquakes (e.g. Zhang et al., 2001). Dynamic parameters averaged over on- and off-asperity areas are estimated from a viewpoint of characterized source model. For the both events, average effective stress values of on-asperity areas, that were estimated to about 15MPa, coincide with the ones that were used for forward ground motion modeling (e.g. Ikeda et al., 2002, Kamae and Irikura, 2001). Average effective stress value in off-asperity area was estimated about 3MPa. Those values both in on- and off-asperity area obtained here can be used for the characterized source model.

S52B-1084 1330h POSTER

Earthquake Recurrence Models: New Constraints From a 3-D Paleoseismic Investigation Across the San Andreas Fault

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How repeatable are consecutive ruptures of a fault? The answer to this fundamentally important question in earthquake science will depend largely on the recovery of reliable records of serial fault rupture. Unfortunately, high-quality records are extremely rare. Our recent 3D excavations at a site along the San Andreas fault reveal a record of several repeated offsets at a single location. At this site along the Carrizo segment of the San Andreas fault, small channels cross the fault at a high angle. Upstream from the fault, a solitary source channel cuts a Pleistocene alluvial fan. On the downstream side, several small channels are offset laterally from the source channel and have been sequentially abandoned. This configuration has enabled us to determine the slip associated with the past several ruptures. We opened a latticework of trenches across the offset channels on both sides of the fault. The trenches downstream from the fault show several single channels, partially filled by fluvial and colluvial debris. The trenches across the upstream part of the channel exposed a set of nested channels. The elevations, shapes, stratigraphy and ages of these nested channels allow us to correlate them with particular, singular channels across the fault, downstream. These excavations allow us to locate accurately the offset channel pairs and determine the amounts of motion. The dextral slips associated with the latest 6 events are, from youngest to oldest, 7.9 ± 0.1 m, 7.45 ± 0.25 m, 5.35 ± 0.27 m, 1.53 ± 0.4 m, 7.7 ± 0.6 m, and >5.3 m (7.7 m?). The magnitudes of most of these ruptures are between 7 and 8m. Curiously, the combined magnitude of the 3rd and 4th events back is also in this range. Unfortunately, age constraints for these events are not very tight. Nonetheless, this work provides a new opportunity to re-examine various earthquake recurrence models. It appears that at this locality the San Andreas fault has a predilection to slip 7 to 8 meters per event.

S52B-1085 1330h POSTER

Differences in Ground Motion and Fault Rupture Characteristics between Surface and Subsurface Rupture Earthquakes

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We have studied differences in ground motion and fault rupture characteristics between surface rupture earthquakes and subsurface rupture earthquakes. We found the ground motion caused by subsurface rupture in the period range around one second is larger than the average for all earthquakes, e.g. as represented by the empirical ground motion model of Abrahamson and Silva (1997). On the other hand, ground motion from earthquakes that rupture the surface is smaller in the same period range. This phenomenon is considered to be caused by differences in fault rupture process between the two types of earthquakes.

Somerville et al. (1999) proposed scaling characteristics of crustal earthquakes. We divided the original data used by Somerville et al. (1999) into two types of earthquakes, and found that the rupture area of subsurface rupture earthquakes is clearly smaller than that of surface rupture earthquakes having the same seismic moment [Kagawa et al.(2001)]. We also found that the large slips of surface rupture earthquakes are concentrated into the depth shallower than several km, i.e. their asperities are shallow. Meanwhile, slips of subsurface rupture earthquakes are spread over the depth deeper than 5 km, i.e. asperities are deep. Furthermore, slip velocities of shallow asperities are almost half that of deep asperities.

To test whether these differences in source characteristics can explain the observed differences in ground motions between the two types of earthquake, we assumed standard fault rupture models for surface and subsurface earthquakes. We calculated strong ground motion by a hybrid method [Kamae and Irikura (1992), Bouchon (1981)] in the near fault region. The simulated ground motions in the period range around one second have the same characteristics as those of the observed ground motions. We consider that the difference in ground motion between two types of earthquakes is caused by the difference of magnitude-area scaling, depth of asperities and their slip velocities.

[REFERENCES] Abrahamson and Silva (1997), SRL, 68, 94-127. Bouchon (1981), BSSA, 71, 959-971. Kagawa et al.(2001), AGU Fall Meeting, . Kamae and Irikura (1992), 11WCEE, 801-806. Somerville et al. (1999), SRL, 70, 59-80.

S52B-1086 1330h POSTER

Initial Rupture Process of Microearthquakes Revealed by High-sampling Waveform Data

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The investigation of the initial rupture process is an important key to understand a growing process of earthquakes. Some previous works on a slow initial phase [Iio, 1992; 1995] or a nucleation phase [Ellsworth and Beroza, 1995] reported that a feature of the phase might be causally related to the eventual size of an earthquake. However, it has been still controversial because such a feature of the phase is apparently caused by the path effect and/or artificial effects.

In order to quantify the initial rupture process of microearthquakes, we should apply source models that are physically acceptable to high quality waveform data. For this purpose, we installed a trigger recording system with a sampling frequency of 10 kHz at the base of a deep borehole (1673m) at the Nojima Fault, which was ruptured during the 1995 Hyogo-ken Nanbu earthquake, central Japan. We observed more than 300 events around the borehole for two years, from June 2000 to August 2002. Rejecting poor quality data, we analyze waveform data of 25 events, whose seismic moment ranges from 1.0×10^{10} Nm to 7.1×10^{11} Nm.

We use two source models in this study. One is a circular crack model with an accelerating rupture velocity [Sato and Kanamori, 1999], which generates a slow initial phase of velocity pulse, and the other is a circular crack model with a constant rupture velocity [Sato and Hirasawa, 1973], which generates a ramp-like velocity pulse. Source parameters of these two models are estimated by waveform inversion of a first half cycle of the observed velocity pulse using both the grid search and the non-linear least squares method. First we apply the constant rupture velocity model with a constant Q operator to exclude events whose nucleation phases may be generated by the path effect. The accelerating rupture velocity model is applied to the remained 11 events, giving a size of the pre-existing crack and a size of the eventual crack.

From the results we can recognize the following relationships among the size of pre-existing cracks, which is considered to be the size of the nucleation regions, the size of eventual cracks, and the eventual seismic moment; (i) the eventual seismic moment is approximately scaled as the cube of the size of pre-existing cracks, (ii) the eventual seismic moment is scaled as

the cube of the size of eventual cracks, and (iii) the size of eventual cracks is roughly proportional to the size of pre-existing cracks. We, thus, conclude that the size of eventual earthquakes is controlled by the size of the nucleation regions.

S52B-1087 1330h POSTER

Simulation of Tensile Cracks Generation during an Earthquake: Application to the 2000 Tottori (Japan) Earthquake

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Tensile cracks generation during an earthquake can be plausible for shallow faulting because the pressure becomes low and may be easy to break the ground closer to the free-surface. We started with this assumption to simulate the tensile crack generation during a 3D dynamic shear rupture propagation. The shear rupture was simulated on the assumption that shear slip occurs only in a pre-existing fault and it is governed by the simple slip-weakening friction law. For internal tensile cracks, that propagate as a consequence of the dynamic process of shear slip propagation, fracture occurs, following classical Griffith theory, when the critical value for tensile fracture surface energy is reached. First the model was used to simulate the rupture process of a pure strike slip shallow fault. The results show that the tensile cracks generated by shear slipping mainly are propagated from the borders of the pre-existing fault and asperity borders, forming a flower-like structure. We consider it is the mechanism of the flower structure near surface. The free-surface and variation in the hypocenter and asperity locations with depth markedly affect the cracks generated from the border of the fault and free-surface rupture. The flower structures that originate from the top of the fault mainly are affected by fault geometry with respect to the free-surface whereas, those originating from the bottom mainly are affected by rupture directivity about the hypocenter location. The results also show that when the asperity is located at less than a certain depth, the flower-like structure that originates from the top of the fault reaches the free-surface. We applied the model to simulate dynamically the 2000 Tottori (Japan) Earthquake. The seismic profiling from a reflection survey done in the 2000 Tottori (Japan) earthquake area and analyzed by Inoue et al. (2001) suggests existence of fractures developed as a flower structure near the free-surface. During field observations reported by Fusejima et al. (2000) after the 2000 Tottori (Japan) earthquake, several small cracks were found on the free-surface parallel to the trace of the causative fault. Ueta et al., (2002) reported fracture zones in an existing tunnel, 200 m below the surface in the epicentral area. In order to get a better understanding of the surface rupture and possible flower structure caused by this earthquake, we applied the model described before. The simulation results of the dynamic shear rupture process of the 2000 Tottori earthquake shows that the shear rupture process generated tensile cracks reaching the free-surface on only one side of the fault, in a direction parallel to the trace of the main fault and at a 2.0km distance from the fault. The trace of this surface rupture corresponds to some of the several cracks observed on the field by Fusejima et al. (2000). The new cracks grew from the two sides of the fault following different patterns and forming new fractures as a complex flower structure. The new cracks began mainly from the asperity zone and from the top of the fault. Some of the new cracks are also associated with the aftershock distribution, suggesting that some of the cracks originated during the shear rupture could have been zones of potential aftershocks.

S52B-1088 1330h POSTER

Peak Slip Velocities Within Distinctive Small Patches of Inland Earthquakes Specifically Determined From Strong Motion Records in Japan

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To predict strong ground motions for future inland earthquakes with high precision in an intermediate frequency range (0.5 to 2 Hz), which is the controlling frequency range of building damage (Nagato and Kawase, AGU 2001), we need to specify both the sizes of patches (asperities) and the slip velocities within them (Kawase

and Matsushima, AGU 1999). As for the size a scaling relationship with respect to the whole ruptured area or the total seismic moment has been established based on the source inversion studies (e.g., Somerville et al., 1999). On the other hand the peak slip velocities within them in these inversion studies tend to be underestimated primarily because of strong filtering of high frequency component in the inversion. Here we conduct trial-and-error inversions of the peak slip velocities inside small patches for two moderate-size inland earthquakes in Japan, namely, the Kagoshima-ken Hokuseibu earthquake of 1997 and Tottori-ken Seibu earthquake of 1999, using strong motion data of the K-Net and KiK-Net (NIED) without strong filtering up to 3Hz.

As for the Kagoshima-ken Hokuseibu earthquake Mj6.5, we first determine S-wave velocity structures for the target K-Net sites, since amplification effects at these sites in an intermediate frequency range cannot be neglected. An inversion procedure we used here is the so-called GA approach for the site amplification factors obtained by a standard spectral separation method of Andrews (1980). Once we determine S-wave structures for the target sites around the source, we then calculate theoretical seismograms for a simple source with two patches, which was proposed by Miyakoshi et al. (2002). We found the best slip velocity functions of these two patches through a forward modeling procedure. The peak slip velocities determined as such are 533 cm/sec (in the east) and 400 cm/sec (in the west), respectively.

As for the Tottori-ken Seibu earthquake Mj7.3, we have several sites in a near-source region where site conditions are relatively good. Thus we assume the same representative velocity structure for these sites and do a similar forward modeling for the slip velocity functions within patches. Two small patches are extracted based on the source inversion results of Iwata and Sekiguchi (SSJ 2000). Resultant peak slip velocities are 625 cm/sec (in the center) and 367 cm/sec (in a shallow part), respectively.

If we combine these numbers of the peak slip velocities with those obtained for four patches of the Hyogo-ken nanbu earthquake of 1995 Mj7.3 (Kawase and Matsushima, 1999), which are 400, 815, 210, and 330 cm/sec from western (deeper) patches to eastern (shallower) patches, we can say that the range of the peak slip velocity for Japanese inland earthquakes could be 200 to 800 cm/sec within a small patch, with the average of 460 cm/sec and one S.D. of 190 cm/sec. There seems to exist weak dependence on the depths of patches, however, the numbers of data (eight) are still too small to draw a line of regression. We need to have additional results of inverted slip velocity functions in order to predict peak ground velocities with good precision in a near-source region.

S52B-1089 1330h POSTER

Extraction of Continuous Spatio-Temporal Slip Distribution on a Fault Plane from Results of Conventional Kinematic Source Inversion

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Kinematic source inversion techniques such as multi-time window linear inversion have been widely applied to broadband seismic records including teleseismic and strong-ground motion records to estimate spatio-temporal slip distribution on seismic fault planes of middle to large earthquakes. In kinematic source inversion source fault is conventionally divided into many subfaults to express spatial variation, and each subfault is represented by a single or many point sources placed at constant intervals on the planar surface. Such conventional subfault discretization is convenient for the representation of spatial distribution of slip in kinematic source inversion. However, it is not continuous at the subfault boundaries, and in the case of a single point source at a subfault, the inversion results (e.g., moment release time history) include not only a slip time function but also a rupture propagation effect inside each subfault. Therefore such inversion results may not be directly suitable for fine-scale numerical modeling such as the FDM computation to simulate near-fault strong-ground motion or to calculate stress

field on the fault planes for dynamic source analysis. In this study we propose a new technique for extracting a slip time function continuous spatio-temporally from such conventional inversion results.

The spatio-temporal distribution of slip velocity is expanded with the linear b-spline basis functions in 2D space and time. Each linear b-spline function is an isosceles triangle defined by three knots, and thus this discretization can give a slip distribution continuous everywhere spatially and temporally. This approach is similar to that employed by Ide and Takeo (1997) for a kinematic source inversion, but slightly different from theirs. In our representation unlike theirs, it is possible to treat even rupture velocity variation of sub-fault level if we have its information. The expansion coefficients are determined by fitting the spatial integration of slip velocity over each subfault in a least squares sense with some constraints to the contribution of the subfault derived from the conventional kinematic source inversion.

We successfully applied our technique to the Northwestern 1997 Kagoshima, Japan, earthquake (Mjma 6.5) to extract a spatio-temporally continuous slip velocity function. In the presentation we will show not only the method but also applied results including this earthquake.

S52B-1090 1330h POSTER

Implications of Earthquake-Induced Transient Creep Rates on Creeping Faults

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The seismic hazard associated with a fault is related to the distribution and amount of slip deficit accumulated during interseismic periods. While during this time period most faults remain essentially locked, some faults (and fault patches) dissipate part of the accumulating strain through creep. This strain dissipation can significantly change the pattern of accumulated slip deficit. Therefore developing tools to map creep patterns on a fault plane is an important component in the assessment of the seismic hazard. Combining observations of surface creep rate and the distribution of micro-seismicity, with modeling results derived from a visco-elastic finite-element model driven by far field plate motions, we have analyzed the links between locked and creeping patches on a fault and the above observables. Our results show that the interaction of the fault with the surrounding lithosphere leads to a smooth transition of the creep rate from locked to fully creeping areas. This leads to significant slip deficit accumulation not only in fully locked zones but also in adjacent low friction areas. When applied to the creeping Hayward fault our modeling indicates that a large locked patch likely lies beneath the Oakland region with creep increasing to both the north and south. This area has undergone seismic slip, with the most recent significant earthquake in 1868 along at least the southern segment of the Hayward fault. Creep (and derived slip deficit) maps constrained by present day observables do not incorporate the effects of post-earthquake transient strain in driving temporally varying fault creep and slip deficit accumulation. It is reasonable to think that a significant seismic event would change the pattern and rates of creep on the fault. Here we test this concept by investigating, via our numerical model, the creep rate evolution of the Hayward fault in response to an earthquake rupturing the locked patch beneath the Oakland region. With this approach we can evaluate the effects of such earthquakes on the patterns of creep and the time periods over which the post-earthquake effects modify the

S52B-1091 1330h POSTER

Implications of Patterns of Micro-Seismicity on Creeping Faults: Evidence From the Hayward Fault

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The Hayward Fault is documented to undergo significant creep, with patches likely accommodating more

than 50% of the long-term fault displacement. In spite of this, the fault also experiences moderate to large earthquakes (most recently M ~6.8 in 1868) and is a primary hazard in the San Francisco Bay region. In comparing the patterns of micro-seismicity observed on the fault (Waldhauser and Elsworth, 2002) with our models of fault zone creep, we can begin to analyze the role that partitioning among aseismic creep, creep accommodated through micro-seismicity, and strain accumulation (slip deficit) plays in the long-term deformation on the fault. To accomplish this we have undertaken an analysis of the spatial distribution of moment accumulation and dissipation on the fault. Using the temporal patterns of earthquake activity and measures of earthquake size distributions such as b-value, in concert with our models of fault creep, we can begin to develop an understanding of the patterns of moment accumulation on the fault in light of the patterns of creep and seismicity. This refined view of moment accumulation during the earthquake cycle becomes an additional parameter in analyses of earthquake potential on the fault.

S52B-1092 1330h POSTER

Waveform Analysis from the 1999 Hector Mine Foreshock Sequence

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By inspecting continuous waveform data from nearby SCSN stations, we find 42 foreshocks in the 20-hour period preceding 1999 Hector Mine earthquake. This is a dramatic increase relative to the number of foreshocks (18) identified in the SCSN catalog and suggests that we may be able to increase our knowledge of earthquake behavior substantially by analyzing continuous data for sequences of particular interest. Most of the foreshocks occur during two time periods: one 20 to 13 hours before the mainshock and the other 8 hours to 19 minutes before the mainshock. We locate the events in the foreshock sequence using a combination of waveform cross-correlation and the double-difference location method. Despite low signal-to-noise ratio data for many of the non-cataloged foreshocks, correlation-based arrival-time measurements are sufficient to locate all but three of the events, with typical location uncertainties of 100m to 1km. We find that most of the foreshocks fall on the same plane as the initial subevent of the mainshock, and that the second cluster of foreshocks is more diffuse than the first, perhaps suggesting an expansion of the foreshock zone as the mainshock approaches. Although the location uncertainties are large, the size of the foreshock zone is comparable to that found previously for California earthquakes of this size by Dodge et al, [1996].

S52B-1093 1330h POSTER

Intersonic rupture propagation in a foam rubber earthquake model

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We analyze a set of 34 foam rubber experiments simulating unilaterally propagating strike-slip earthquakes, and compare recorded waveforms with simulated waveforms from a 3D, spontaneous-rupture numerical model of the experiments. Accelerometers are deployed on the free surface along lines parallel to strike to characterize directivity-enhanced, near-fault ground motion. The foam rubber earthquakes are quite repeatable, with the bulk of the events, denoted Type A events, having acceleration waveforms that are very similar to one another. These events show strong near-fault directivity in the fault-normal component of acceleration. The main features of the principal acceleration pulses, such as their shape, duration, and absolute amplitude, are successfully reproduced, within experimental scatter, by the numerical simulations. Approximately 10 percent of the foam rubber events, however, are remarkably different. These Type B events also have waveforms that are very similar to one another, but entirely different from the Type A waveforms. Compared with the Type A events, the Type

B events exhibit fault-parallel acceleration pulses that are much larger in amplitude and higher in dominant frequency, and the acceleration pulse amplitudes decay more slowly with distance from the fault. Comparison with numerical simulations demonstrates clearly that the Type B events are those that rupture at inter-sonic velocity (velocity between the S and P velocities of the foam rubber). The same numerical model that fits the (sub-shear) Type A events also fits the (inter-sonic) Type B events very well if the shear prestress is increased by a few percent (holding all other model parameters fixed) to induce a transition to inter-sonic rupture in the numerical simulations. The inter-sonic numerical simulations predict a shock wavefront attached to the rupture tip, polarized at an angle of about 45 degrees to the fault plane. The predicted shock is clearly observed in the experimental records when the vector components are rotated into the expected polarization direction. While inter-sonic rupture and shock formation have been previously imaged in impact-loaded fault experiments, the current results may represent the first such observations in shear-loaded, spontaneous-rupture experiments.

S52B-1094 1330h POSTER

Clustering Characteristics of Seismicity at Two Different Tectonic Regimes.

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Much debate has been sparked by the claim that earthquakes follow a Self Organized Criticality (SOC) process. Some studies have focused on the overall characteristics of seismicity as it pertains to typical SOC systems (Bak, et al., 2002) while others have indicated that the overall characteristics are due mainly to aftershock activity which dominate earthquake catalogs (Knopoff, 2000). We have studied the clustering characteristics of seismicity at two distinct tectonic environments in order to test whether cluster seismicity depart from the aftershock or mainshock activity characteristics. For this purpose we analyzed the seismicity of Southern California (SC) with particular emphasis in the vicinity of the 1992 Landers, Big Bear and Joshua Tree mainshocks and that of the subduction regime of Mexico (MX), near the states of Guerrero and Oaxaca. In the California case we used data spanning from 1983 to 1997 and for the Mexico seismicity case we analyzed the interval from 1988 to 2001. The minimum magnitude for SC data was 1.6 while that of MX data was 3.5. We employed Reasenbergs algorithm to separate clusters and examine their temporal and frequency-magnitude occurrence. Our preliminary findings indicate that in both cases earthquake clusters tend to occur in a regular pattern which may be dependent on regime. For the SC case clusters appear to take place at regular intervals of approximately 1 to 1.5 years while the MX data show shorter intervals than 1 year. While there is still a possibility that earthquakes are a result of a Self-Organized Critical state in the crust, our results would also indicate that clusters occur after a limiting stress is reached.

S52B-1095 1330h POSTER

Shear-wave splitting study on seismic data associated with the 1999 Chi-Chi earthquake

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Shear-wave splitting is analyzed from data collected before, during and after the 1999 Chi-Chi earthquake with an automated procedure. The purpose is to investigate possible evolution of stress-induced crustal anisotropy in relation to great earthquakes. The extensive data set collected by the Taiwan Central Weather Bureau Seismic Network (CWBSN) is used in this study. An objective automated method is required to analyze such large data set uniformly. The cross-correlation (CC) method [e.g., Fukao, 1984] determines simultaneously the polarization direction (PD) of the fast shear wave (FSW) and the time delay (DT) of the slow shear wave (SSW) by comparing the cross correlation coefficients of the two horizontal seismograms with various projections. The aspect ratio (AR) method proposed by Shih et al. [1989] calculates PD from the waveforms before the arrival of the SSW, and then the DT is determined by comparing the FSW to the SSW. The reliability of both methods is tested with

synthetic data formed by mixing noise (taken from real data) with seismograms (generated from observed shear waves). We then operate on the synthetic data with assumed DT and PD properties and attempt to recover those using the CC and AR methods. Results show that both methods can recover well the PD and DT with noise to signal ratio (NSR) up to 25 percent. The CC method has problems when one of the horizontal seismograms is much weaker than the other, while the AR method is more sensitive to NSR than the CC method. The AR method is more suitable than the CC method when the two split shear waves have strongly dissimilar waveforms. In general, the AR method is used if the AR value is larger than a certain value (e.g. 15). Otherwise, the CC method seems to give better results. We also employ visual inspection methods to examine the results of the automated measurements. Preliminary results of shear-wave splitting analysis on 1998 and 1999 strong-motion data show that the above hybrid method can measure shear-wave splitting reliably. The distribution of obtained PD is in good agreement with the direction of maximum compressional tectonic stress. The analysis so far has not revealed clear temporal variations of SWS that might be related to large tectonic earthquakes.

S52B-1096 1330h POSTER

Variations in b- and p-Value Seismicity Parameters and Their Relation to Physical Processes for Earthquakes in Japan

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This work systematically reviews some results obtained already for the variations of the seismicity parameters b and p in different seismogenic and tectonic regions in Japan. We bring as well new evidence that the time and space changes in seismicity parameters are correlating well with the crustal structure and/or some parameters of the earthquake process. The use of highly accurate sets of data, including relocated earthquake catalogues, gives reliability to our findings. There are three main case studies on which we focus our attention, but we refer as well to other world-wide results.

The first case is the seismic activity (Kyoto Univ. catalogue) between 1976 and 1998, in a broad area surrounding the epicentre of the 1995 Kobe earthquake ($M_W = 6.9$) as well as in the source area. Our result shows that various precursors, such as quiescence followed by increased seismic activity, b -value and fractal dimension changes, appear 2-3 years before the major event. These changes are correlating well with other geophysical precursors, such as crustal deformations and electromagnetic anomalies. Most of the anomalies are not confined to the source area, but occur in a larger region corresponding probably to the preparation zone of the future event.

The second case is the aftershock sequence (JMA catalogue) following the 2000 Western Tottori earthquake ($M_W = 6.6$). We analysed the spatial change in b -value and the decay rate of aftershock activity as expressed by p -value in the Omori law. We found that both b - and p -value are larger in an area that corresponds roughly with the highest slip during the mainshock. Our results show that both the stress after the mainshock and the history of previous ruptures may have "shaped" the pattern of the seismicity parameters. However, taking into account the regional crustal structure in relation with the thickness of the seismogenic layer, we conclude that the heterogeneity in the crust may be responsible as well for the b - and p -value spatial distribution. Further study and new data may clarify the role of each factor.

Finally, we shifted our attention to a volcanic region. We analysed the spatio-temporal distribution of b -values for the 1998-1999 Hida Mountain (central Honshu) earthquake swarms. We found a b -value that varies from 0.8 to 1.7 when depth is increasing from 4 to 6 km. The high b -value is located in a crustal region that is characterised, according to other geophysical studies, by low-velocity and low-density. The results suggest that the b -value can be a useful tool for mapping such "anomalous" areas, possibly associated with magma movements. Our study confirms other similar investigations in volcanic regions.

URL: <http://www.rcep.dpri.kyoto-u.ac.jp/~benescu/>

S52B-1097 1330h POSTER

Spatio-Temporal Distribution of Repeating Earthquakes in the Kanto District, Japan

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'Repeating earthquakes' with very similar waveforms must be occurred closely with the same focal mechanisms. In the northeastern Japan subduction zone, Igarashi et al. [2002] suggested they are caused by repeating slips of small asperities surrounded by stable sliding areas on the plate boundary, and their slip rates are consistent with that estimated GPS data. In this study, I investigated the spatio-temporal distribution of repeating earthquakes by analyzing the similarity among the waveforms of the events occurred in and around the Kanto District, Japan. The method used in the waveform similarity analysis is as follows: (1) Search earthquake pairs whose horizontal intervals are less than 30 km. (2) Calculate cross-correlation coefficients of band-pass filtered seismograms between the paired events. I set the length of the time window from P-wave onset to the time over three seconds after S-wave arrival. (3) Treat the paired earthquakes as repeating earthquakes if the coefficients calculated for plural stations are greater than 0.95 (in 1-4 Hz band). (4) Applying these procedures to all the pairs, classify the events into several groups. I analyzed waveform data recorded by the seismic network of the Earthquake Research Institute, the University of Tokyo for about 20 years from April 1982. From this analysis, I found many repeating earthquakes in the subducted Pacific plate boundary of the Kanto district. In particular, many groups that continued for a long period were located in the deepest part in the occurrence region of the low-angle thrust fault type earthquakes at depths about 50 to 80 km. On the other hand, they were not found in the intermediate earthquakes within the subducted Pacific plate with a few exceptions. I also found several repeating earthquakes in shallow part in the land area. They exist within the seismic activity with volcanic activity or fault rupture, although the most of these groups show a short period, burst-type activity even if swarm activity have continued for a long period in the region. Moreover, I found repeating earthquakes occurred around the subducted Philippine Sea plate. They continued for a short period with a few exceptions at depths about 50 km. Several groups at depths from 20 to 40 km are correspond to the edge of source regions of large interplate earthquakes and the regions of slow events in this subduction zone. These results suggest that they also show the local slip condition in the subducted plate and fault plane in land area.

S52B-1098 1330h POSTER

Numerical simulation of the seismic nucleation phase with circular crack model including a preslip crack

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We explain slow initial phase and weak abrupt accelerations of seismograms seen after the first P arrival of small earthquakes by numerical simulation with circular crack model including a preslip crack. But violating seismograms cannot be explained by the preslip model. Recent observations revealed that seismograms after the first P arrivals have slow initial phase that cannot be explained with convolution of path effect and source seismograms expected from the self-similar model. Violating seismograms and weak abrupt accelerations at rupture initiation are also observed. A source model for the beginning of earthquakes based on the Griffith's fracture criterion can explain slow initial phase, but it cannot explain violating seismograms and abrupt accelerations. Ellsworth and Beroza (1995) suggest that a cascade model or a preslip model can explain violating seismograms. Beroza and Ellsworth (1996) also suggest that the cascade model or the preslip model can explain abrupt accelerations. We tried to examine whether the preslip model can explain violating seismograms, abrupt accelerations, and slow initial phase. We gave relative shift of the face both on the expanding crack and on the pre-existing crack subject to the same law described by Eshelby (1957).

We obtained moment rate function that has lack corresponding to the preslip crack, but the lack of moment release proportional to the size of preslip crack is small. However, the model can explain slow initial phase by arranging the preslip crack around center of the expanding crack. Weak abrupt accelerations are also reconstructed by the preslip model after slow initial phase although accelerations changes not enough abrupt to be expected. On the other hand, violating seismograms cannot be generated with the model that have one preslip crack, and will be able to generated with combination of more than one preslip crack. However, preslip cracks will have to be arranged on an arc of which center locates the center of the expanding crack. We think that it is not realistic assumption, and the cascade model is preferred to the preslip model to explain violating seismograms.

S52B-1099 1330h POSTER

Joint Interpretation of Elastic and Electric Anisotropy During Stronger Earthquakes

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Through discriminating polarization of fast and slow shear waves and time delay between their arrivals, characteristics of anisotropy in the media can be investigated. However, since shear wave splitting is an integral effect along ray path, it is difficult to decide the location where anisotropy exists. Electric anisotropic layers with low accuracy can be distinguished through MT inversion. It is expected that when elastic and electric analysis both indicates strong anisotropy, a combined explanation of the two methods could provide clearer image of media conditions such as direction of fluid-filled crack alignment, stress status, conductivity, location of abnormal layers and so on. The Extension Dilatancy Anisotropy Model (EDA) of upper crust is the foundation of joint inversion and interpretation of elastic and electric anisotropy. Based on elastic and electric theories and numerical simulation of elastic wave fields and MT in stratified inhomogeneous anisotropic media, the characteristics of elastic and electric anisotropy in crust can be studied. Computational methods for joint interpretation of elastic and electric anisotropy have been developed, and means to pick up anisotropic properties, porosity and aspect ratio by using synthetic seismograms has been obtained.

For the Yongdeng M5.8 earthquake occurred on July 22, 1995 in China, we got following main results: 1. Fast shear wave polarization changes gradually from northeast to northwest before the earthquake, then back to northeast after it, which is coincident with the major principal compression stress in the field. 2. Time delay between fast and slow shear waves accelerates and reaches the maximum when the main quake occurs. 3. The direction of the electrical principal axis also changes before the main shock, exhibiting identical features at different frequencies. 4. The direction of the electric principal axis, which is originally perpendicular to the earthquake fault, changes from N17E to N15W, corresponding to the elastic P-axis at N15W in the field, and returns to northeast after the main shock. 5. Variation of apparent resistivity of the electric principal axis is prominent in periods of 160s-226s, but resistivity variation of the other axis is minimal. 6. Porosity and crack aspect ratio fluctuate before 1994, but increase sharply from 1994 to several days before the main shock, and reaches the maximum before the main shock. They recover to normal after the earthquake.

Similar results are found for the Tianzu-Gulang M5.4 earthquake occurred on June 1, 1996 in China. The results demonstrate that the variation of polarization direction of shear wave splitting generally agrees with the variation of electric principal axis direction. They both are coincident with the major principal compression stress in horizontal direction. Joint elastic and electric analysis based on EDA brings us useful insights into anisotropy in the crust.

S52B-1100 1330h POSTER

Dynamic vs Static Stress Triggering Models of Aftershocks

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In order to make a meaningful comparison of two models, it is important to distinguish them in a statistical sense. This means that the errors and uncertainties in the models must be less than the differences between them. In the case of static and dynamic stress transfer models, this standard is surprisingly difficult to achieve. Peak dynamic stresses are very similar to static stresses, especially close to a mainshock source. The reflectivity models which have been most commonly used to evaluate dynamic stresses were originally designed for the analysis of waveform data in the far field, and cannot reproduce the static stress field close to the mainshock with much fidelity or efficiency. A new dynamic point source model has been developed in order to overcome these limitations. It is also approximate, but its approximations are more accurate in the near field, and it is vastly more efficient. Dynamic stress transfer models evaluated with this new algorithm are directly comparable to static stress transfer models, and permit a full-scale comparison of the two classes of triggering models. I have carried out

such a comparison in the case of the aftershocks of the 1999 Hector Mine earthquake, and found that the dynamic stress model is actually more successful than the static model for aftershocks more than 65km from the mainshock. The static stress model is more consistent with the location of near field Hector Mine aftershocks than the dynamic model. If dynamic triggering of the near-source aftershocks is assumed, the best-fitting background stress state is inconsistent with independent observations, but this stress state does make the peak dynamic failure stresses resemble the static failure stresses more closely. Additional cases should be studied to clarify whether this pattern holds generally, or applies only in this particular case.

S52B-1101 1330h POSTER

Seismic Structures of Baikol Prognostic Ground as a Result of Analysis of Electromagnetic Monitoring Data

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The Baikol Prognostic Ground is located on the south-eastern Baikol coast in the region of Selenga Delta. The high seismic activity of the Ground is associated with development of modern neotectonic structures and it results in numerous earthquakes. Regular surveys of an electromagnetic field (active electromagnetic monitoring) were originated in 1984 at several points of the Ground. The power plant is used as a field source. Currently with the monitoring, electrical prospecting field tests are carried out by different methods aimed at investigation of a geological structure. Processing results of over-year electromagnetic monitoring data show that it is impossible to optimize the survey network without complete data on the Ground structure as well as to justify the effect of geodynamic processes on these data. The sensitivity diagram of the equipment for monitoring by the method of vertical electrical soundings (VES) has been constructed. It was observed that the wholly certain geological structure are in the directions of maximum sensibility of the equipment. In particular, the Proval Bay, which is a zone of seismotectonic subsidence after catastrophic earthquake, is among such structures. Using computer techniques for interpretation of electromagnetic data allows visual representation of the detailed geolectrical structure of the upper part of earths crust of as the Ground itself, so its main structural elements. The geolectrical model of the Proval Bay segment is verified that this tectonic block is confined by faults. Fractured zones exhibit the areas with decreased rock resistivity. Numerous earthquakes are confined just to these fractured zones. The earthquakes are responsible for significant anomalies in time series of electromagnetic monitoring. Further analysis has shown that a high sensibility of VES monitoring series to seismic events is due to the presence of a thick conducting sedimentary cover in the region, the fluid regime seems to change significantly in the cover during the period preceding the seismic event.

S52B-1102 1330h POSTER

Asperity Depicted by an S-wave Splitting Observation

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Tadokoro et al. [1999] proposed that fault-parallel fractures generated by a mainshock faulting can be detected by means of S-wave splitting observations, i.e., the direction of faster S-wave polarization on an earthquake fault-zone (several hundred meters in width) is roughly parallel to the fault strike. In this study, we performed S-wave splitting observations just above the inferred fault-zone of the Western Tottori, Japan, earthquake (M_w 6.6) which occurred on October 6, 2000, in order to depict fracture distribution inside of the fault-zone.

We carried out temporal seismic observations for the following three periods: October 9-15, 2000, April 21-24, 2001, and April 20-June 3. The directions of faster S-wave polarization shows a bimodal distribution with averages of $\sim N150^\circ E$ and $\sim N110^\circ E$. The former direction is parallel to the aftershock alignment, suggesting fault-parallel shear fractures generated by the

mainshock faulting; the latter is parallel to the orientation of maximum horizontal compressional stress in the study area, suggesting cracks of tectonic stress origin. Considering the ray paths of the earthquakes showing the fault-parallel polarization, the region of fault-parallel fractures is located beneath the epicenter of the mainshock, possibly at 3-8 km in depth. The degree of anisotropy in the region is 1-2 %. The region of fault-parallel fractures corresponds to a part of the asperity of the fault-zone. This correspondence suggests that the rupture of asperity during the mainshock generated the fault-parallel fractures in the fault zone, which is interpreted by introducing the shear fracture energy. The shear fracture energy to create a unit area of fault by shear fracture is proportional to the square of stress drop [e.g., Aki, 1980]. The shear fracture energy is spent for creating a new rupture surface. Therefore shear-fractures are mainly generated at asperity regions, and anisotropy caused by shear fractures should be obvious at the asperity regions. The S-wave splitting is effective to depict asperity regions.

S52B-1103 1330h POSTER

A Study of Recurrence Models of Earthquakes in Taiwan

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Taiwan has one of the most complete instrumental catalogs of earthquakes. Combination of listings in the Seismological Bulletins of the Central Weather Bureau and the Catalogs of earthquakes in Taiwan by the Institute of Earth Sciences, Academia Sinica provides a complete catalog of earthquakes with magnitude greater than 5.0 since 1900 and with magnitudes greater than 3.0 since 1973. We have made a study of recurrence models of earthquakes in Taiwan using this combined catalog. We compared several models often mentioned in the literatures. The results show that the Weibull and Gamma models consistently fit the data better than the others for all magnitudes. Both the moments and maximum likelihood methods are used for the fitting. It is found that the former tend to give better fittings. Potential applications of these recurrence models for estimation of seismic hazards and for forecast of earthquakes in Taiwan will also be discussed.

S52B-1104 1330h POSTER

THE PHYSICAL FOUNDATION OF SEISMIC CYCLES OF LARGE ROMANIAN EARTHQUAKES, AND ON THE NEXT LARGE EARTHQUAKE IN VRANCEA

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The large intermediate-depth Romanian earthquakes (EQs) all occur in the Vrancea intraplate zone, in the seismically active subducted slab, at depths about 60-200 km. No large shallow (interface and in slab) EQs, $M \geq 6.5 - 6.7$, occurred there.

Purcaru (1974, 1979) first gave the empirical laws of Vrancea seismic cycles of occurrence time and magnitude: the law of quasicycles and supercycles, for large (L) and most largest (M-L) events ($M \geq 7.3$), respectively. These were found using their long history, 1100-1973, and the estimated magnitude. The quantitative model with these cycles has three time-bands (the periods of L and M-L earthquake occurrence)/century.

This long-term prediction model is essentially deterministic, predicting uniquely the earthquake; since it is not completely deterministic, the forecasting is interval valued.

It has predicted the future large earthquake in 1980 (Purcaru, 1974) in the 3rd time-band (1970-1990), which occurred in 1977 ($M7.1$, $Mw7.5$). However since the laws are phenomenologic, we give their physical foundation based on the scales of the rupture zone (RZ) and rupture process. First results show that: (1) the 1940 event ($h = 120 - 130$ km, $M7.4$, $Mw7.5 - 7.7$) ruptured the lower part of the slab entirely along strike, and down dip, and similarly in 1977 but the upper part, (2) the RZ of 1977 and 1990 events overlap and the first asperity of 1977 event was rebroken in 1990. Thus the size of the events strongly depends on RZ size, asperity size/strength or failure stress level (FSL), but not on the depth, and (3) when the FSL of larger zones is higher, most largest events (eg. 1802, 1940) occur. This would explain the supercycles (duration of about 300 yr). The 1940 event occurred in the 2nd band 2030-2040, and (4) the smaller RZ or asperities rupturing separately generate L events (eg. 1986, 1990) with quasicycles of about 100 yr. The model predicts the next

large earthquake in the first time-band 2000-2010, centered in 2005. We conclude that it is the stability of a specific law that allows making a prediction.

S52B-1105 1330h POSTER

Earthquake swarms consisting of multiple aftershock sequences

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Swarm activity significantly differs in its temporal clustering and energy release from seismicity patterns typically observed at tectonic plate boundaries. In contrast to aftershocks triggered by a mainshock, a dominant earthquake does not characterize swarm activity, even though the earthquakes are highly clustered in space and time. Furthermore, the b -value of the frequency-magnitude distribution is typically higher for swarm earthquakes. We focus on earthquake swarms, which occurred in Vogtland/NW-Bohemia, where swarm activity is episodically generated. Our detailed analysis reveals a complicated fine structure of the earthquake swarms. Fluids which are commonly assumed to play the major role in generating swarm activity seem to be responsible for the initiation of the swarms. However, the main activity occurs in form of multiple mainshock-aftershock sequences overlapping in time. The whole sequence is characterized by a fractal clustering in time, being revealed by the power law distribution of interevent-times. These and further results show the relevance of stress triggering within the swarm evolution. Thus the triggering mechanism is mainly the same as that for typical aftershock sequences, but the loading process seems to be different. Besides a weak tectonic stress loading, a pore pressure increase related to the fluid intrusion seems to drive locally the crust in the swarm region into an unstable stress state. Once critically loaded, stress triggering becomes important resulting in local aftershock sequences. This point of view is supported by model simulations.

S52B-1106 1330h POSTER

Earthquake-induced static stress of the 1985 Nahanni earthquakes, Northwest Territories, Canada

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The 1985 Nahanni earthquakes [05/10/1985 ($M_w=6.6$), 23/12/1985 ($M_w=6.8$)] were the largest observed events not only in the Nahanni region but in the NE Cordillera and so appear to represent bursts of crustal seismicity exceptional for the past 100 years. The short duration (about two months) between the two mainshocks and their shallow depth (about 5 km) makes them interesting. I address stress changes and correlate static stress buildup caused by these unexpected events and examine their relationship to present-day seismicity. The changes in the static stresses caused by these events are determined using the Coulomb failure criterion based on dislocation theory assuming uniform slip in elastic half-space. The models of fault specific (with no regional stress) and optimal orientation (with regional stress) are used in the calculation. However, changes in static stresses based on these dislocation models are found to be insignificant. The suggested rupture model of Choy and Boatwright (1988) for the Nahanni earthquakes involves complex ruptures with two sub-events (0 +3.6 sec) and three sub-events (0 +0.8 +3.5 sec) for the first and second mainshocks, respectively. So, static stress changes for each subevent are determined and then combined. The combination for the October event appears to have caused the December event. Regional static stress maps as modified by stress changes caused by the December event, are correlated with subsequent larger events to understand if and how they may be triggered. Static stress changes caused by the sub-events of 1985 events are concluded to be a hazard indicator useful for separating zones of stress encouraged and stress shadow. Furthermore, the shadow zone is found to be about double the area of the stress enhancement zone. The static-stress changes of October 5, 1985 indicates that December fault rupture (as defined by its aftershocks) corresponded to the area of stress enhancement defined by October event. Thus, the December event is suggested to be triggered by October event. A large subsequent event occurred in 1988 ($M6.2$). Its aftershocks are primarily to the south, in a region where increased stress was caused by the 1985 events. The 1988 earthquake is deeper (15 km) than the previous 1985 quakes (5 km) and so activated

a deeper part of the crust. The seismicity pattern from 1961-2002 corresponds well with the pattern of earthquake-induced static stress changes caused by 1985 events. The self-similarity between the stress and seismicity indicates that stress-change maps are useful for identifying future mainshock locations for other active faults around the world.

URL: <http://www.angelfire.com/al/geophysics>

S52B-1107 1330h POSTER

New insights on long distance fault interaction

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While fault interaction at local or regional scale is supported by wide phenomenological evidence and is considered an important feature in seismic hazard assessment, the possibility of interaction between seismogenic structures at longer distances is still a matter of debate.

We present the results of our investigation about the plausibility of remote fault triggering on global scale as a result of postseismic stress transfer by large subduction earthquakes.

The cumulative postseismic stress field generated by eight of the largest events occurred in the Pacific area acted to promote the rupture of about 54% of all the $M \geq 5$ events recorded in the last century in the circum-pacific ring. By means of a set of new statistical simulations with respect to those presented in the past we tried to assess the significance of this slight excess of promoted ruptures, and found there is a high probability of observing it by chance.

We then analyzed the correlation between the spatial distribution of seismic moment release and the fraction of promoted ruptures, and we found that as we apply more realistic geometrical constraints to the spatial distribution of "source" events, we obtain a fraction more close to the observed value. This suggests a physical connection between the geometrical configuration of a plate margin and its seismic activity with the geometrical configurations and seismic activities of all the other plate margins.

S52B-1108 1330h POSTER

Stress Change Prior to the Major Events in the 1989 Earthquake Swarm off the Eastern Izu Peninsula, Japan

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Stress state is one of the most important parameters for describing the physical processes of earthquakes. In particular, learning its temporal variation in seismic source regions of the Earth's crust just prior to seismic events is essential for understanding the earthquake development process. Laboratory experiments with granite samples confirm that instability (dynamic rupture) occurs after peak stress, both in triaxial fracture and in frictional sliding.

We calculate a stress parameter, the energy index (EI), of earthquakes that occurred in the 1989 swarms off the eastern Izu Peninsula in Japan. This parameter has been monitored in deep South African gold mines for predicting major events. EI is an estimate of E/M_0 normalized to remove dependence on M_0 caused by both real source effect, and also site and frequency bandwidth effect. We find significant decrease in EI prior to the largest events ($M = 5.2$ and 5.5).

We propose a mechanism of precursory change in EI for the major earthquakes in the 1989 earthquake swarm off the eastern Izu Peninsula as follows:

1) On July 4, 1989, strain accumulation accelerated in the eastern portion of the source region of the major earthquakes ($M = 5.2$ and 5.5), due to magma intrusion, and local yielding started in the region with the lowest yielding strength followed by yielding in the stronger region. The EI and stress drop of earthquakes that occurred in this stage increased.

2) Further strain accumulation due to magma intrusion caused the whole source region of the $M = 5.5$ earthquake to yield on July 6, and stress quasi-statically decreased because of anelastic deformation. Earthquakes occurring at this stage (the earthquake development stage) had smaller stress drops than those in the previous stage, so that EI decreased.

3) After occurrence of the $M = 5.2$ earthquake on early July 7, the $M = 5.5$ earthquake took place in the vicinity of the strong asperity on July 9, and the accumulated stress around the $M = 5.5$ source region was released. After the $M = 5.5$ earthquake, the EI remained at a constant level.

S52B-1109 1330h POSTER

Spatio-temporal Distribution of Interplate Quasi-static Slip in the Northeastern Japan Subduction Zone, Estimated From Repeating Earthquake Analyses

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We estimated spatio-temporal distribution of interplate quasi-static slip in the northeastern Japan subduction zone using small repeating earthquake data. In order to detect repeating earthquakes, we used waveform similarity analysis according to Igarashi et al. (2002) who first revealed small repeating earthquakes are occurring in the northeastern Japan subduction zone. We identified event pairs whose band-pass (1-4Hz) filtered seismograms showed cross-correlation coefficients >0.95 at two or more stations as repeating earthquakes. Time window lengths for seismograms were set to be 40s in order to analyze both P and S waves. We used waveform data recorded by the microearthquake observation network of Tohoku University for the period from July 1987 to July 2001.

As a result we found more than 2700 repeating earthquakes with magnitude 2.5 or larger. These repeating earthquakes have almost identical waveforms and thought to be caused by repeating slips of small asperities surrounded by stable sliding areas on the plate boundary. Then, the history of the quasi-static slip can be estimated from the sequences of the repeating earthquakes (Nadeau and McEvilly, 1999). In order to estimate the slip of each repeating event, we used the relationship between the seismic moment and slip proposed by Nadeau and Johnson (1998). We averaged the cumulative slips of repeating earthquakes spatially and obtained smooth and reliable spatio-temporal distribution of quasi-static slips.

The main results are as follows. (1) There are almost static slips for all analyzed periods near the western limit of low angle thrust fault type event distribution. (2) Most of interplate earthquakes with magnitude six or larger are followed by afterslips. (3) In the last 17 years, there are four large quasi-static slip events, 1987 off Fukushima prefecture, 1989 off Sanriku, 1992 off Sanriku and 1994 off Sanriku related to the occurrences of large earthquakes or swarm activities. (4) The afterslip of the 1994 Far-off-Sanriku earthquake distributes not only on the land side of source region but also trench side of the region.

S52B-1110 1330h POSTER

Relationship Between Rupture Process and Heterogeneous Structure on the Mainshock Fault of the 2000 Western Tottori Earthquake

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For the 2000 Western Tottori Earthquake (6 October 2000, $M_j = 7.3$), a detailed rupture process of the mainshock was obtained using strong motion waveforms and crustal movement data from GPS stations near the source area (Sekiguchi and Iwata, 2001). Detailed 3-D rupture models of P and S velocities in the vicinity of the mainshock fault were also obtained from a tomographic inversion of travel time data from a dense aftershock observation (Joint Group for Dense Aftershock Observation of the 2000 Tottori-ken Seibu Earthquake, 2001). In the source area of this earthquake, swarm-like seismic activity had occurred since 1989, which included six moderate events with $M_j = 5.1-5.4$ (Shibu-

tani et al., 2002). The purpose of this paper is to clarify relationship between the heterogeneous structure on the fault plane, the occurrence of the preceding swarm-like activity and the rupture process of the mainshock.

Relocation of the hypocenters using P and S times from both permanent and temporary stations revealed that the preceding seismic activity in 1989, 1990 and 1997 occurred in the area adjacent each other on the same plane as the mainshock fault. The b-value of the preceding swarms was 0.51-0.67, which is significantly smaller than $b = 1.24$ for aftershocks in the same area. The rupture of the mainshock in 2000 started in the area of the preceding activity.

From the results of the tomographic inversion the depth distribution of P velocity along the mainshock fault showed that 3-4 high velocity anomalies (several %) are located near the lower edge of the aftershock area. The area of the preceding swarms with relatively low b-values corresponds to one of the high velocity anomalies. This suggests that the area had higher strength than the surrounding areas and was under high stressed condition.

The mainshock rupture initiated in the area, propagated with small slip for ~ 3 s, then developed to main rupture with large slip (2-4 m) outside to the south-east. The area of the main rupture is enclosed by another high velocity anomaly to the southeast. This suggests that the main rupture was guided by the high velocity anomalies.

S52B-1111 1330h POSTER

Regional tectonic stress and the interaction between Landers and Hector Mine fault systems

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The mechanical coupling between fault systems is investigated by a model based on a 3D finite element approach. The deformation pattern caused by the earthquakes is controlled by the initial condition of remote stress loading pre-existing faults with prescribed geometry and frictional law. To test the potential of this approach we investigate the Landers-Hector Mine fault systems. The good agreement between computed coseismic displacement and geodetic measurements for both earthquakes validates the method adopted here. The modeled slip distribution along the fault planes reproduces quite well that resulting from seismological and geodetic data inversions. The coseismic displacement and the induced stress transfer are mainly affected by the orientation of the initial stress field with respect to the non-planar fault geometry. The mechanical coupling between these two large earthquakes is directly investigated by comparing two models with different initial stress condition. In the first model the Hector Mine event occurs in a uniform initial stress field, not perturbed by the 1992 Landers earthquake. In the second model the Hector Mine fault is loaded by the initial stress field modulated by the stress changes due to the previous Landers earthquake. Our results show that the Landers earthquake reduces the slip during the subsequent Hector Mine event. In our 3D modeling we also consider the 3D rheological heterogeneities of the elastic and viscoelastic properties of the lithosphere. We investigate the role of postseismic relaxation in modifying the stress field during the 7 years following Landers.

S52B-1112 1330h POSTER

Structural Constraints on the Spatial Distribution of Aftershocks

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Real-time, forward modelling of spatial distributions of potentially damaging aftershocks by calculating stress perturbations due to large earthquakes may produce socially useful, time-dependent hazard estimates in the foreseeable future. Such calculations, however, rely on the resolution of a stress perturbation tensor onto planes whose geometry is unknown and decisions as to the orientations of these planes have a first order effect on the geometry of the resulting hazard distributions. Commonly, these decisions are based on the assumption that structures optimally oriented for failure in the regional stress field exist everywhere and stress maps are produced by resolving onto these orientations. Here we investigate this proposition using a 3D calculation for the optimally oriented planes for a number of California earthquakes. In areas dominated by strike slip events, we find that maps based

solely on 2-D optimally oriented planes best describe the aftershock activity whereas in thrust, or mixed-mode regions, the 3-D calculation is more consistent with the data. We develop a graphical technique to compare the mapped regional structure in each area with both the aftershocks and with the pre-mainshock events and, in all cases, find that both the preshocks and the aftershocks occur on faults consistent with the mapped structural trend. This result implies that the best way forward is to use any available information about mapped structure and preshocks to constrain the orientations of faults capable of producing aftershocks in any particular area. Maps of the likely spatial aftershock distribution can then be produced by resolving stress perturbations onto planes within that limited range of orientations.

S52C MCC: 134 Friday 1330h

Seismic Discontinuities, Phase Transitions, and Mantle Dynamics II
(joint with T, V, DI, MR)

Presiding: Y Shen, University of Rhode Island; Y Gu, Harvard University; Y Fei, Carnegie Institution of Washington

S52C-01 1330h

A systematic search for seismic discontinuities in the upper and lower mantle

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We perform a systematic search for reflectors in the upper and lower mantle using a global data set of SS-precursors. A bootstrap resampling algorithm is employed to determine robust reflectors (within the 95% confidence level). The results demonstrate that reflectors can be found from a range of depths and our observations can be used as a probe for local mantle composition and temperature.

A stack for the entire data set clearly shows the transition zone discontinuities at 410, 520 and 660 km depth. Stacks for particular tectonic regions, for example North America or Indonesia, show additional reflectors in both upper and lower mantle at depths of 220 km and 1000-1200 km. To address the question of regional existence and lateral variations of upper mantle discontinuities, we systematically searched spherical caps with 10° radius for robust reflectors and compared with synthetic seismograms. The locations of the discontinuities are also compared with shear wave velocities from tomographic models.

Leaving the transition zone discontinuities aside, the largest number of robust reflections comes from a depth of 220 km, suggesting that the Lehmann discontinuity is a major reflector in the upper mantle. This discontinuity is observed below both continental and oceanic areas, though the largest amplitudes appear beneath the continents. There is also evidence for weak discontinuities at approximately 260 and 310 km depth, for example in the region of the South Pacific Superwell which could be related to processes in the upwelling plume.

There are also suggestions of lower mantle reflectors with a weak peak for 800 km depth; deeper in the lower mantle there are reflections from a continuous range of depths. Clear reflections from 1000-1200 km depth are found below North America and in the Indonesian subduction zone area, where other studies have found similar reflections. The locations correlate with fast features in tomographic models.

As we find discontinuities from a range of depths in different types of tectonic regions, we do not expect that only one mechanism is responsible for all reflections. We will discuss different possible explanations for the seismic discontinuities in terms of phase transitions, compositional and/or rheological changes.

S52C-02 1345h

Elasticity Measurements of Phase Transition in Pyroxenes and the Upper Mantle Reflectors

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The upper mantle reflectors, Lehmann and X-discontinuities, have been observed locally and interpreted as a result of compositional gradients, anisotropy, phase changes, volatiles and temperature, which all play significant roles in determining the seismic reflectivity structure. The phase transition in Ca-poor pyroxene (enstatite) from orthorhombic to high pressure monoclinic has been proposed to be responsible for the Lehmann or X-discontinuities if the regional petrological environment is a Ca-poor pyroxene-rich mineral assemblage.

High-P clinoenstatite is unquenchable. Because of this, the elasticity of high-P clinoenstatite has to be studied in its stability field. A rapid development of the ultrasonic technique in the large volume apparatus in conjunction with in-situ X-radiation techniques has made possible to the elasticity measurement at mantle conditions. Using these techniques, the key parameters determining the elasticity of mantle materials, travel times (P and S waves), length of the specimen, pressure and temperature, can be collected simultaneously at mantle conditions.

The starting polycrystalline orthoenstatite specimens used in this study were synthesized using the multi anvil pressure at High Pressure Laboratory at University Stony Brook. The high pressure ultrasonic experiments were performed using the 1000 ton press at beamline 13ID, GSECARS, Argonne National Laboratory, Advanced Photon Source. During the acoustic experiments, the orthoenstatite specimens were transformed into high-clinoenstatite in-situ at peak P-T conditions (11.15 GPa, 900 degree C) for two hours. P and S wave velocities were measured across the orthoenstatite phase and the stability field of high-pressure clinoenstatite. Our results have shown clear P and S wave velocity jumps across the phase transformation from orthoenstatite to high-pressure clinoenstatite. As indicated from our measurements, the magnitude of S wave velocity jump at this transition is almost twice that of P wave. In this meeting, we will present the elasticity measurements of the pyroxenes and discuss the relationship of the phase transition in pyroxenes and the upper mantle discontinuities.

S52C-03 1400h

Seismological Evidence for the Presence of Water Near the 410 km Discontinuity

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Water can remain in the subducting plate down to the transition zone as shown by high-pressure experiments. It is, however, unknown whether and how much water indeed is transported to 400 km and below. Also, the effect of water on the behaviour of the 410 km discontinuity is not yet completely understood.

Here we show new seismological evidence for water being present at depths near 400 km. We have searched for P-to-S converted waves in over 500 seismograms recorded at 17 temporary broadband stations from the MIDSEA project and 6 permanent broadband stations in the Mediterranean region. Events are mainly located between 60° and 95° epicentral distance due to the geographical location of the Mediterranean region with respect to seismogenic zones.

We have found that P-to-S conversions from the 410 km discontinuity are not as clear as and spatially more variable than those from the 660 km discontinuity. For several stations we observe an unambiguous frequency dependence of the P-to-S conversion at the 410 km discontinuity. This finding indicates that the phase transition is not sharp and occurs over depth intervals of up to 30 km. We interpret this thickened transition of olivine to wadsleyite as being due to 500 to 700 ppm water, present in olivine, at depths near 400 km.

The presence of H₂O as a free fluid could significantly decrease the velocities in the upper mantle, especially the S-velocities. We suggest that most of the water present around 400 km depth could be incorporated in the minerals themselves and is not present as a free fluid since no sudden drop nor significant lower S-velocities are observed beneath the studied stations.

S52C-04 1415h INVITED

Phase Transition Complexity and Multiple Seismic Reflectors in Subduction Zones

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Patterns of seismic wavespeeds within subduction zones are significantly affected by the laterally varying phase relations associated with slab thermal structures, especially in the upper mantle where equilibrium phase changes contribute fine structure to the overall fast anomalies expected from thermal effects alone. Such lateral variations in the properties of associated seismic reflectors contribute to non-uniformity in the visibility of and detectable topography on seismic "discontinuities" in the transition zone.

The 410-km seismic discontinuity is usually attributed largely to the $\alpha \rightarrow \beta$ phase transition in (Mg, Fe)₂SiO₄ olivine, more accurately written as the $\alpha \rightarrow \alpha + \beta \rightarrow \beta$ reaction series. The apparent sharpness of and apparent topography on the associated seismic wavespeed feature have been subjects of debate, especially in regions near subduction zones.

I argue that some of the apparent discrepancies arise from the common oversimplification of representing the relevant phase relations in the vicinity of subducting slabs simply as an $\alpha \rightarrow \beta$ transition. The low temperatures of subduction zones cause the equilibrium olivine phase relations within slabs to shift from the $\alpha \rightarrow \alpha + \beta \rightarrow \beta$ reaction series to the more complex $\alpha \rightarrow \alpha + \gamma \rightarrow \alpha + \beta \rightarrow \beta$ reaction series. Even lower temperatures in slab interiors cause the entire $\alpha \rightarrow \alpha + \beta \rightarrow \beta \rightarrow \beta + \gamma \rightarrow \gamma$ reaction series to give way to an $\alpha \rightarrow \alpha + \gamma \rightarrow \beta + \gamma \rightarrow \gamma$ reaction series.

The more complex reaction series within cold subduction zones yields bifurcations in seismic wavespeed contrasts. The $\alpha \rightarrow \alpha + \gamma$ onset of the reaction series is strongly uplifted to shallower depths, but this transition is relatively broad. The $\alpha + \gamma \rightarrow \alpha + \beta$ and colder $\alpha + \gamma \rightarrow \beta + \gamma$ reactions, on the other hand, are univariant and therefore very sharp, but these transitions are not as strongly uplifted. The resulting seismic wavespeed signature to be expected above 410 km in a subduction zone consists of a strongly uplifted diffuse contrast overlying a weakly uplifted sharp contrast. Indeed, the univariant portions of the olivine reaction series in a slab may potentially give rise to the brightest seismic reflectors in the upper mantle.

S52C-05 1430h

South African Archaean Cratonic Keels Extend to the Upper Mantle Transition Zone

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Teleseismic body waves recorded by temporary broadband seismic networks are used to image the mantle seismic discontinuity structure beneath southern Africa. Stacking of over 3000 radial receiver functions reveals P-to-S conversions from seismic discontinuities near 410- and 660-km depth, which mark the upper mantle transition zone. Relative traveltimes delays across the seismic networks are used as a first approximation to correct for velocity heterogeneity beneath the stations. Variations in the transition zone thickness coincide with distinct geologic provinces. The transition zone beneath the Archaean Zimbabwe and Kaapvaal cratons is thicker than in the iasp91 model and the global average by up to 20 km. Thinner-than-normal transition zones are found beneath the Cape Fold and Namaqua-Natal belts, and a normal transition zone exists beneath the Bushveld province. The thickening of the transition zone beneath the Archaean cratons results primarily from shoaling of the 410-km discontinuity.

Observations of converted phases with a dominant wavelength of 30 km indicate that the olivine-to-wadsleyite phase transformation associated with the 410-km discontinuity occurs over a depth interval less than 15 km, half the wavelength of the converted phase. Water, which reduces the pressure of, but substantially broadens the olivine-wadsleyite transformation, is therefore unlikely the primary cause of the shallower-than-normal 410-km discontinuity beneath the cratons. The depth to the discontinuity varies in magnitude much greater than the induced effect of moderate compositional variations. For a Clapeyron slope of 2.9 MPa/K for the 410-km discontinuity, the decrease in the depth to the discontinuity beneath the cratons is equivalent to a temperature reduction of 230 K. The findings implicate that the deeply rooted Archaean cratonic keels or associated cold downwelling extend greater than 400 km depth, and are therefore likely to play an important role in mantle flow and plate tectonics.