S11B-06 0945h

Early Postseismic Deformation Following the Mw 7.9 Denali Earthquake, 2002, From GPS Measurements.

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The rapid deployment of GPS receivers following the 3 Nov 2002 Mw 7.9 Denali Fault Earthquake occurred in two phases, with immediate campaign style deployment preceding the installation of new permanent stations. The initial deployment included multi-day to multi-week GPS measurements on existing campaign monuments, as well as on newly established monuments close to where the permanent sites were built. At all of the permanent stations, campaign style measurements from these very nearby points (within 10-20 meters) overlap the start of the permanent station data. Using these survey ties, we can connect the position time-series of these campaign data with the time-series of the associated permanent stations. The resulting records are a unique window into the earliest stages of post-seismic response of a large magnitude strike-slip event. Several stations close to the rupture show initial post-seismic velocities in excess of 2 mm/day. The data allow us to test models of afterslip and poroelastic and/or viscoelastic deformation operating on timescales of days to a month or two following the event.

S11C MCC: Level 1 Monday 0830h

Crustal Seismic Anisotropy as a Measure of Tectonic Deformation Posters *(joint with T, V)*

Presiding: **D Okaya,** University of Southern California**; N Christensen,** University of Wisconsin

S11C-0292 0830h POSTER

Field Observations of Crustal Seismic Anisotropy: Implications for Mapping Tectonic Structure in Metamorphic Terranes

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The study of seismic anisotropy within continental tectonic provinces provides earth scientists with a powerful tool for measuring and quantifying deformation within the crust. Preferred mineral alignment observed in metamorphic terranes produced by recrystallization during metamorphism is associated with planar structures such as slaty cleavage, schistosity, and gneissic layering. These structures are often pervasive for tens to hundreds of kilometers and produce significant compressional wave seismic anisotropy as well as shear wave splitting. Observations of crustal anisotropy within (1) slates of the chlorite subzone of the Haast schist terrane of South Island, New Zealand, (2) lower greenschist facies phyllites and metagraywackes of the Valdez Group Chugach terrane in southern Alaska, (3) amphibolite facies mica schists within the Yukon-Tanana terrane in the eastern Alaska range and (4) amphibolite facies quartzofeldspathic gneisses, approaching granulite grade, within the Nanga Parbat-Haramosh massif demonstrate that crustal anisotropy is not limited to rocks of any particular metamorphic grade and thus can be present at all crustal levels. Two refraction lines at approximately right angles shown up to 10% compressional wave anisotropy in relatively low grade metapelites of the Haast schist terrane. Fast velocities parallel the strike of the upturned slaty cleavage. Measured field velocities in the Chugach terrane, obtained from observed first arrival travel times, demonstrate significant compressional wave anisotropy (9%) with fastest directions oriented approximately east-west and parallel to foliations observed in outcrops. Within the Alaskan Yukon-Tanana terrane variations in seismic velocities of the first arrivals correlate with field observations of regional dips of foliated schists. A northward shallowing of foliation dips produces an observed northward increasing seismic velocity. The core of the Nanga-Parbat massif forms a large-scale antiformal structure with an axial orientation of N10 degrees E with near vertical lineations. Observations of local seismicity show shear wave splitting which originates within the high-grade granitic and metasedimentary gneisses of the massif. Laboratory velocity measurements on rocks collected from surface exposures within these four regions are consistent with the magnitudes and directions of the observed anisotropies. We conclude that future field investigations designed specifically to study crustal seismic anisotropy, combined with laboratory measurements, will provide valuable information on the structure, magnitude and extent of crustal tectonic deformation.

S11C-0293 0830h POSTER

Intrinsic Anisotropy of Textured Rocks

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The seismic anisotropy of crustal terrains has been detected in numerous passive and active source seismic experiments and confirmed by the ultrasonic laboratory measurements on textured samples of the metamorphosed rock formations. This observed anisotropy might be produced by variety of causes, including developed texture (lattice preferred orientation (LPO) of constituent minerals), structural layering and aligned fracturing of the formations of interest. In the case of the deformed metamorphic rocks with highly developed texture, LPO is generally accepted to be the main cause of anisotropy and this type of anisotropy is called here intrinsic anisotropy. Forward modelling of the intrinsic anisotropy is based on the theory of elasticity of polycrystalline aggregates and takes into account information about the texture of the rock and elasticity of constituent minerals. Elastic constants of a textured mica aggregate, which is one of the sources of anisotropy in metamorphosed rocks, were calculated on the basis of the widely used Voigt, Reuss and Hill assumptions. Taking into account significant anisotropy of the single mica mineral and the consequent wide separation of the Voigt and Reuss (upper and lower) bounds of some of the elastic constants of the anisotropic aggregate, the Geometric mean method was employed to further refine the elasticity. The Geometric mean method is based on simple and physically meaningful assumption of the invertibility of the elastic constants into the elastic compliances and yields unique set of elastic constants that are independent of the averaging domain and usually lie within the Voigt-Reuss bounds. Limits of the seismic anisotropy of the mica aggregate have been estimated. Intrinsic anisotropy depends primarily on the level of anisotropy of constituent minerals and their alignment (strength of texture). Similar technique could be applied to investigate elasticity of multiphase polycrystalline aggregates as more realistic model for anisotropic metamorphic rocks.

S11C-0294 0830h POSTER

P-wave Velocity Anisotropy and Shear-wave Splitting of Sheared Metasediments from the Flin-Flon Belt, Trans-Hudson Orogen

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Metasediments of the upper greenschist - lower amphibolite facies of metamorphism from two ductile shear zones of Flin-Flon Belt (FFB) of Trans-Hudson Orogen (THO) were used to carried out laboratory measurements of compressional wave (Vp), shear-wave (Vs) velocities and shear-wave splitting. The investigated metasediments vary in composition from felsic to mafic. Test sites with outcrops of sheared metasediments were correlated with a series of inclined seismic reflectors possibly extending from the midcrust and intersecting a well mapped shear zone at the surface. Determination of lithological and physical properties of highly deformed metasediments is essential for proper interpretation of the nature of observed seismic reflectors. To investigate anisotropic properties of the rocks compressional velocity was measured to confining pressures of 300 MPa in three mutually orthogonal directions with respect to the visible textural properties. In addition, on nine selected samples shear-wave velocity was measured at two orthogonal polarizations for each of three propagation directions to determine shear-wave splitting and correlate it with P-wave anisotropy. For most of the hand specimens seismic heterogeneity was investigated by measuring P- and S-wave velocities on several cores cut in the same direction. Elastic velocities were measured on the 147 core samples in total. Observed Vp anisotropy varied from quasi-isotropic to highly anisotropic (Ap=24%). Maximum observed shear wave splitting reaches the value of 0.77 km/sec at confining pressure of 300 MPa. An estimated splitting of the SKS wave propagating through the ten kilometres thick crustal slab of metasediments, characterized by the averaged value of laboratory observed shear-wave splitting, may reach value of 0.2 sec. Pressure invariance of observed P-wave anisotropy and shear-wave splitting indicates that lattice preferred orientation (LPO) of highly anisotropic minerals such as mica and hornblende is mainly responsible for measured seismic anisotropy.

S11C-0295 0830h POSTER

P- and S-Wave Velocities in Crustal Rocks: Evidence from Measurements and Calculations

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Elastic anisotropy is an important property of most rocks constituting the Earth crust, and it has various sources. Most important is lattice (crystallographic) preferred orientation (LPO) due to the anisotropic properties of most rock-forming minerals and the LPO of the polycrystalline aggregates. In addition, oriented microcracks and grain shape preferred orientation (SPO) may also be of importance. Because elastic wave propagation is sensitive to cracks, elastic wave velocities travelling through a rock are higher parallel to the fractures than across them. With increasing pressure microfractures close and their contribution to elastic anisotropy diminishes. The remaining part of velocity anisotropy is nearly pressure-independent and largely caused by the LPO of the constituent minerals, such as mica and hornblende. In order to evaluate the respective contribution of the various parameters, on needs to discriminate between the two effects. This poster reports results obtained from the simultaneous measurement of P- and S-wave velocities in three orthogonal directions (up to 600 MPa and 600°C) on cube-shaped samples of metamorphic crustal rocks (amphibolites, gneisses) and investigates the relationship between crystallographic fabric, oriented cracks, shear wave splitting and shear wave polarisation. The laboratory measurements are complemented by 3D velocity calculations based on the LPOs of the rock-forming minerals (hornblende, mica). The measurements and calculations show that velocity anisotropy, shear wave splitting and shear wave polarisation are interrelated to the structural frame of the rocks (foliation, lineation). This information provides a powerful tool for the understanding and interpretation of seismic data.

S11C-0296 0830h POSTER

3D Strain Geometry and Crystallographic Fabric in Experimental HT Deformation of Solnhofen Limestone

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Under conditions where calcite deforms plastically, high temperature deformation tests on Solnhofen limestone have been run using different strain configurations: axi-symmetric shortening and extension, and direct shear. The aim of the work is to relate strain geometry and the development of crystallographic fabrics in different strain paths. We produced constrictional, flattening, and nearly plane strain deformations. In addition to this, we were also able to obtain strain geometries where the vorticity axis in a non-coaxial deformation was either perpendicular to the extension direction (as in simple and sub-simple shear) or parallel to it. In order to keep constant as many parameters as possible, all experiments used the same starting material and the same experimental conditions of temperature 600 °C, confining pressure 200 MPa and comparable strain rates $10^{-4}s^{-1}$. At these conditions, and taking into account the special features of Solnhofen limestone (i.e. fine grain size and the presence of impurities preventing grain growth), the predominant deformation mechanism was intracrystalline plasticity. We used pole figures of different calcite lattice elements, measured by electron back-scattered diffraction techniques (EBSD), to characterize the asymmetry of the crystallographic patterns and particularly *c*-axis pole figures to identify the presence of different fabric components. Further analysis of inverse pole figures in particular experimental directions allowed us to characterize the extension and compression directions of the strain ellipsoid as they geometrically determine the operation of slip systems. Two main aspects can be highlighted from our experimental results. First, it proved particularly useful to combine inverse pole figures with pole figures to characterize not only the shape of the strain ellipsoid in predominantly plastic deformation but also the sense of shear. Second, there is an extraordinary sensitivity of crystal-plastic deformation of calcite to changes in strain geometry, involving changes in shape of the strain ellipsoid but also variations in non-coaxiality. We would expect the same principle to apply to other mineral phases, as long as crystal plasticity is the predominant deformation mechanism.

S11C-0297 0830h POSTER

Variation Of Seismic Wave Velocity Of Sedimentary Rocks With Pressure Increase

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Variations of compressive wave and shear wave velocities of two sandstones, a mudstone and a tuff taken from Japanese Islands and a basin next to Shikoku Island, Japan were determined with increase of static confining pressure conditions. Additionally, variations of both the velocities and variations of amplitude of compressive wave and shear wave were measured in a complete compression process from the initial point of loading to the point of ultimate fracture under triaxial compression on a specimen of Tako sandstone. The compressive and shear velocities of all the four rocks increased with the static confining pressure increased monotonously. The relations between the velocities and the confining pressure were however non-linear, increasing gradients of the velocities decreased as pressure increased. Increment of compressive velocity with the increase from atmospheric pressure to about 20MPa normalized by the initial velocity corresponding to the same rock varied with the different rocks, and ranged from about 10 percent to 30 percent; whereas the increment of shear wave velocity ranged in about 5-20 percent. In the compressive process under a confining pressure 10MPa, the compressive wave velocity in a direction perpendicular to the major stress direction slightly increased as differential stress increases from the initial point to a stress level equal to about 10 percent of ultimate strength, then decreased several percents from the stress level of about 10 percent to the ultimate strength. However, the shear wave velocity almost did not changed in the confining pressure condition. In contrary, variations of the amplitudes of two waves were distinct than those of the velocities. Ratios of amplitude at arbitrary stress level and the amplitude at initial point of loading corresponding to both kinds of the waves were nearly equal to each other, and the ratios decreased about 40 percent from the initial point to the ultimate strength. These results suggested the variations of amplitude may be more sensitive than those of the velocities with the change of stress state.

S11C-0298 0830h POSTER

The Orocopia-Pelona Schist Terrane, southern California and southwest Arizona: A Calibrated Target for Crustal Seismic Anisotropy Studies

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The Orocopia-Pelona Schist belt represents an enigmatic element within the Late Cretaceous to early Tertiary tectonic framework of the southern Cordillera. This oceanic supracrustal terrane is widely believed to underlie much of southern California and the southwest corner of Arizona. Alternative interpretations of geologic and geophysical data suggest that the schist may have a considerably more limited subsurface distribution, restricted to the vicinity of the curvilinear belt defined by the pre-San Andreas distribution of outcrops of the Orocopia and Pelona Schists. Regional depth and thickness, breadth, and large-scale internal configuration of the schist differ according to the current evolutionary models: (1) low-angle, eastward subduction, (2) trapping of marine rocks along a transpressional continental margin, or (3) tectonic burial of Great Valley-like forearc strata beneath overriding Mesozoic batholithic arc crust. The three-dimensional distribution of the schist could help to constrain these models, but is poorly known. The Orocopia-Pelona Schist is thus a promising candidate for mapping via crustal seismic anisotropy. The Orocopia-Pelona Schist terrane is exposed in some 15 tectonic windows, stretching from the central Transverse Ranges, California, to the Kofa region, southwest Arizona. Along the eastern two-thirds of its extent, exposures of the schist are tightly aligned along the Chocolate Mountains anticlinorium. The schist terrane comprises predominantly homogeneous quartzofeldspathic metagraywacke, with subordinate to minor interlayered metabasalt, metachert, siliceous marble, and ultramafic rock. The schist exhibits strong foliation and pronounced lineation, with regionally uniform orientation. Metamorphic mineral assemblages indicate tectonic burial to depths approx. 25 - 35 km. We have performed petrophysical laboratory measurements on samples of Orocopia Schist from the Chocolate and Trigo Mountains, determining seismic velocities and densities at pressures up to 10 kb. Owing to the pronounced fabric anisotropy of the schist, compressional and shear wave velocity measurements were made not only parallel to the three principal axes but also in the directions of the three axial-plane diagonals (at 45 degrees). The schist exhibits large-magnitude seismic anisotropy ranging between hexagonal to strongly orthorhombic symmetry. VP ranges between 5.27-6.79 km/s (14-26% anisotropy) at 1 kb and 5.85-7.14 km/s (12-19% anisotropy) at 6 kb (22 km). VS anisotropy is as large as 28% at 1 kb (3.05-4.03 km/s) and 24% at 6 kb (3.29-4.14 km/s). (In contrast, a sample of Jurassic granodiorite, which forms much of the continental crust tectonically overlying the Orocopia Schist, is isotropic with VP = 6.38 km/s and VS = 3.69 km/s, both at 6 kb). We present data for the fabric of the schist, the anisotropic velocity ellipsoid (that is, Christoffel-based quantification of propagation and splitting behavior in non-axial propagation directions), and the regional distribution and internal character of the schist terrane from the perspective of seismic wave propagation. We also discuss types of seismic experiments needed for anisotropic subsurface imaging of the Orocopia-Pelona Schist.

S11C-0299 0830h POSTER

Scales of Deformation and Strain Localization in the Lower Crust, Arunta Block, Australia

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The Arunta block, central Australia, is a well-known exposure of lower crustal material exposed at the earth's surface. These lower crustal granulites preserve deformation fabrics developed at lower crustal conditions (7-9 kb, 700-900°), and are largely unmodified by the younger orogenic events that exhumed it. Our work, to date, concentrates on the mafic granulites of the Mt Hay region. This contribution focuses on two aspects of our geological investigations, resulting from detailed (1:500 and 1:12,000) geological field studies: 1) The scales of observed lithological heterogeneity; and 2) The recognition of strain localization in the lower crust. Lithological heterogeneity occurs over several orders of magnitude from 0.01 to 1000 m at Capricorn ridge. At the 100 m scale, the most relevant scale for seismic work, heterogeneity is defined by major lithological changes: anorthositic granulite, pyroxene granulite, pyroxene-plagioclase granulite, and "transitional" zones. Contacts between layers are abrupt, occurring over less than 1 m across strike. The contact zones are semi planar in map view (20°variation in strike). These lithologic domains extend parallel to strike for several km. Direct observation cannot be made at scales larger than 100 m because of the lack of sufficient outcrop. As a sidenote, no lattice preferred orientation of quartz or feldspar occurs. Demonstrable localization (shear zones) at lower crustal conditions occurs on the 100 m scale on Capricorn Ridge, with respect to the less deformed main section of Mt. Hay. Localization is characterized as cm- to m-scale segregations of different lithologies, and rapid changes in lithologies. In general, strain seems to localize preferentially in the quartzofeldspathic domains in this setting.

S11C-0300 0830h POSTER

Localization and Mechanical Instabilities at Different Crustal Levels

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Structural geologists commonly focus on shear zones (strain localization) as a record of the movement history in rocks. The assumption that shear zones are bounded by rigid walls, similar to upper-crustal faults, is implicit in this approach. However, the walls of the localization zones are not rigid, even in the upper crust. Rather, deformation can be divided into high strain (shear zones or faults) and low strain domains, although the lower strain domains that may record a different style of deformation (e.g., distributed faulting or folding) than the high strain zones. This partitioning occurs on a variety of scales, from the mm- to km-scale. This effect can be quantified and results from lithological heterogeneity, which itself depends on tectonic setting and metamorphic grade (i.e., which minerals are present). As general rules: 1) The high strain domains will preferentially record the noncoaxial component of a general shear; and 2) Less competent material will preferentially segregate into the high strain domains. Mechanical instabilities (i.e., folding, boudinage) are idealized models of rock deformation that address the initiation of heterogeneous strain, and strain localization, in deforming materials. Most mechanical instabilities result when adjacent materials do not deform at the same rate, which results from lithological heterogeneity that characterizes the crust. As most geological materials are lithologically heterogeneous and/or anisotropic at many scales, the onset of deformation inevitably leads to the formation of mechanical instabilities in a deforming zone. Naturally deformed rocks at all lithospheric levels contain evidence that mechanical instabilities were produced during deformation. For interpretation of seismic records, mechanical instabilities are important because: 1) They occur at all scales; 2) They provide a method of interpreting seismic images; 3) They characterize the internal configuration of deformed, lithologically-heterogeneous rocks; and 4) They provide a record of relative material behavior (rheology).

S11C-0301 0830h POSTER

Seismic Anisotropy and Mantle Creep in Young Orogens

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We discuss the origin of anisotropy in the crust and uppermost mantle in terms of processes that are controlled by temperature, rheology, and deformation. We disregard anisotropy within sedimentary basins and instead concentrate on anisotropy owing to the lattice preferred orientation (LPO) of anisotropic minerals. We focus on young mountain belts that have thick crustal roots and high geothermal gradients. We compare the orientation of this Pn anisotropy with the direction of compressive stress, which nearly always shows a mountain-perpendicular component in the upper crust. From the discrepancy of directions between the fast axis of mantle anisotropy and compressive crustal stresses, we therefore postulate the existence of a decoupling layer. This layer is generally found in the middle or lower crust in all areas with high geothermal gradients and especially in young mountain belts. A decoupling layer corresponds to a low-viscosity layer capable of creep owing to tectonic stress. Tectonic escape or "lateral extrusion" was first suggested for southern China by Molnar & Tapponier (1975). It is today considered to be a lithospheric process and not limited to the crust.

S11C-0302 0830h INVITED POSTER

Crustal Seismic Anisotropy: Implications for Understanding Crustal Dynamics

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The Nanga Parbat - Haramosh massif, in the core of the western syntaxis of the Himalaya, represents a unique exposure of mid-lower continental crust from beneath a collisional orogen. The exhumed core of the massif forms a large scale antiformal structure with axial orientation of N10E and associated lineation directed north-south with near-vertical dips. Laboratory measurements of seismic velocity on a suite of quartzofeldspathic gneisses from the massif show a relatively strong degree of anisotropy, up to 12.5% for compressional waves and up to 21% for shear waves. The degree of velocity anisotropy is primarily a function of mica content and rock fabric strength. The strong anisotropy measured in these rocks should be observable in recorded seismic field data and provides a means of mapping rock fabric at depth provided the rock fabric is coherent over appropriate length scales. An IRIS/PASSCAL deployment of 50 short period instruments recorded local and regional earthquakes to characterize seismicity and determine crustal structure beneath the massif as part of a multidisciplinary NSF Continental Dynamics study investigating the active tectonic processes responsible for exhumation and crustal reworking at Nanga Parbat. Microseismicity at Nanga Parbat is distributed along strike beneath the massif but exhibits a sharp drop-off laterally into adjacent terranes and with depth. This data set is ideal for studying crustal seismic anisotropy because the raypaths are restricted to the crust, sharp onsets in P and S allow for clear identification of arrivals, and source-receiver geometries sample a range of azimuths with respect to structure. Preliminary analysis indicates that the majority of local events exhibit some degree of splitting and that splitting patterns, while complicated, are coherent. While splitting delay normally increases with distance traveled through anisotropic material, the range of delay times can be due to heterogeneity in composition, lateral variation in % anisotropy, changes in orientation of the regional foliation within the massif, and velocity (splitting) variance due to non-axial propagation through a wide range of event-station azimuths. Because the composition of the massif is basically homogeneous, the rock fabric is well developed, and the structure well constrained, this data set is ideal for studying and quantifying the affect of non-axial propagation through regional foliation. This type of analysis has important implications for understanding crustal dynamics. Vp, Vs, and Vp/Vs ratios are typically used to infer both lithology and rheology of subsurface materials and to provide constraints for thermo-mechanical models of deformation. Current tomography codes do not generally account for anisotropic effects and may potentially under or over estimate velocity structure in the crust. At Nanga Parbat, a prominent low-velocity zone is mapped beneath the core of the massif. The magnitude and extent of this zone constrains crustal flow paths focusing crustal strain, exhumation, and potential zones of partial melting in the crust. Accurate determination of velocity structure is clearly important to understand crustal structure and modification during orogenesis.

S11C-0303 0830h POSTER

One Plus two Equals Five: How Layering and Nonhexagonal Symmetry Mess With Crustal and Mantle Anisotropy Measurements

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The effects of layered anisotropy on seismic observations are not straightforward. We predict observations for crustal anisotropy using a reflectivity method for layers with general symmetry and orientation. Although *P* delays do accrue arithmetically over the anisotropy along the path, shear wave splitting and *P* polarization combine the encountered anisotropy in a nonlinear fashion. Such results are dependent on the wavelength of the signal relative to the layer thicknesses, and variations can be strong functions of station-event azimuth. If the standard single-layer splitting method is applied in the layered anisotropy case, the measured splitting time may be larger (or much less) than the sum of the splitting times of each layer. The measured fast azimuth may point away from the fast azimuths of the individual layers, rather than lie somewhere in between. While it is usually assumed that the crustal contribution to SKS splitting is negligible, we demonstrate that realistic crustal anisotropy can significantly alter the mantle signal in some cases. A second factor affecting anisotropy measurements is a possible oversimplification by assuming hexagonal symmetry (also called transverse isotropy or TI). Foliated crustal rocks such as gneisses and schists often exhibit orthorhombic symmetry, which leads to a bias in measurements when hexagonal symmetry is assumed. We present predictions for anisotropic observations from numerical modelling using crustal and mantle petrological tensors and demonstrate the effects of layering and symmetry class, and give bounds on the range of expected values based on crustal samples.

S11C-0304 0830h INVITED POSTER

Velocity Ellipsoids for Crustal Seismic Anisotropy: Pumpkins and Melons Have Dimples and Bulges

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Geological causes of crustal anisotropy include regional fractures and cracks, isotropic heterogeneity or layering, and material composition and textural properties. In addition, shear or metamorphic foliations in fault zones or structural terranes serve as proxies for intracrustal deformation in a manner analogous to lattice preferred orientation of olivine produced by mantle shear. The primary factor in the production of crustal seismic anisotropy is the relative angle between a seismic wave and the (dipping) symmetry axes representing the crustal material even as either change along the propagation raypath. As a result, in order to analyze observations of crustal anisotropy we must understand the behavior of compressional and shear wave velocities in all propagation directions parallel to and in-between the principal symmetry axes which represent the crustal materials. In this poster we use Christoffel equations and physical properties obtained from petrophysical lab measurements in order to examine anisotropic velocities and travel-time effects for bulk rocks representative of different crustal levels. Ellipses and ellipsoids are commonly used to represent the P- and S-wave velocity directional behavior for materials described using hexagonal and orthorhombic symmetries, respectively. While olivine and pyroxene-based mantle rocks are characteristically fast symmetry axes (the "melons" of Levin and Park, 1997), crustal rocks are typically slow symmetry axes ("pumpkins") due to the predominance of fractures or textural foliations. Careful application of Christoffel solutions indicate that for most crustal (and mantle) rocks the surfaces of their pumpkins or melons are not exact analytical ellipsoids. Rather, the surfaces in the non-axial directions have second-order deflections (bulges or dimples) which potentially may produce observable azimuthal travel-time or shear splitting effects. In the case when the P-wave surface on average is slow (dimpled), due to SV and SH crossover the travel-time of the first-arrival S will have an irregular 8-theta appearance. When the P-wave surface is on average fast (bulged), SV and SH do not cross over and a normal 2-theta S arrival time should occur. In this latter case, however, the shear wave splitting behavior has a 4-theta regularity which is maximized diagonal to the symmetry axes. The ellipsoidal deflections of dimples and bulges are related to VP as measured in non-axial directions (petrophysical diagonal measurments, for example). The deflections can exist for both crustal and mantle rocks (pumpkins and melons). In our poster we will explain the Christoffel derivation of the dimples and bulges, present examples of petrophysically-based P and S wave ellipsoids and discuss travel-time and shear wave splitting implications for observational data collected within the crust.

S11C-0305 0830h POSTER

A new Measuring Technique of Time Delay of Shear Waves and its Application in Northeastern Japan

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In comparison with the measurement of shear wave polarization, measuring the time delay between fast and slow shear waves is more inaccurate. What causes such a problem is the difficulty of identifying accurately the first motion of slow shear wave. Among the various methods for its measurement, the majority neglect the non-orthogonal relation between P and S wave in anisotropy. On the three-component seismograms by aperture network or local observation, the late arriving waves following P wave has an obvious interference upon fast shear wave, while the first motion in slow shear wave is affected simultaneously by the late arriving waves in P wave and fast shear wave. In anisotropic or heterogeneous medium, polarization relations between P and S waves, between fast and slow shear waves are both non-orthogonal. These lead to the difficulty mentioned above. Based on the result of synthetic simulation in polarization vector of seismic body wave, the paper presents a theoretical method which eliminates the mutual interference from each seismic phase upon the time delay between fast and slow waves in shear wave on three-component seismograms. By applying the method in analyzing the hi-net data in north-eastern Japan, the research shows an evident increase in the results of time delay between fast and slow shear waves. It also improves the method of calculating shear wave windows.

S11C-0306 0830h POSTER

One-way Wave Propagator Applied to Imaging in Heterogeneous Anisotropic Media

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Travel time and amplitude errors produced by isotropic propagators applied to wave propagation problems in anisotropic media can not be neglected. Much effort has been spent on wave propagation problems in anisotropic media based on ray theory. Wave equation based methods have good accuracy and can be employed to propagate wave field in arbitrary complex media. One-way wave equation based methods are very efficient in modeling and imaging for transversely isotropic solids with a vertically symmetric axis (VTI) which is the most common case of anisotropy media. However, one-way wave equation methods usually suffer limitations of small propagation angles and weak perturbations of media parameters. Recently we developed an anisotropic one-way propagator that is efficient and accurate for any large isotropic and anisotropic perturbations. Based on elastic wave equations in anisotropic media we first separated the scalar qP-wave from qSV- and qSH-waves and derived dispersion relation of scalar qP-wave. Applied rational approximation to the dispersion relation we obtained approximate dispersion relation and the one-way dual-domain scalar P-wave propagator for modeling and imaging in heterogeneous VTI media. The propagator includes phase-shift term, phase-screen and large angle correction terms. The phase-shift term is implemented in wave number domain and the other terms are implemented in space domain. Fast Fourier transformation is employed for shuttling wave field between the two domains. The propagator can be used to extrapolate P-wave fields in isotropic or VTI background with strong isotropic or VTI perturbations. The results of impulse response and dispersion relation prove that the propagator has good accuracy, stability and wide-angle capacity even for strong velocity perturbations and anisotropy perturbations up to several times of the background medium. We applied the propagator to wave propagation and imaging in anisotropic models with complex structures. The model shows a number of challenging features to one-way propagators. Imaging results show that the propagator gives very satisfied results. Not only the structure is reconstructed clearly, but also the steep faults are correctly imaged.

S11C-0307 0830h INVITED POSTER

Seismic anisotropy within the Tibetan crust

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Three lines of evidence argue for the existence of strong anisotropy within the Tibetan crust. First, Rayleigh waves demonstrate very strong reverse dispersion between periods of 20 and 35 sec, while Love wave dispersion is normal. This discrepancy is explained by radial anisotropy in the middle to lower crust beneath most of Tibet. Second, we map azimuthal anisotropy using surface-wave tomography. The short period maps (e.g., 20 sec), which are particularly sensitive to the upper to middle crust, display predominantly north-south 2ψ fast axes across Tibet whereas these patterns rotate to being predominantly northwest-southeast at longer periods, which are characteristic of the deep crust and/or uppermost mantle. Third, teleseismic body-wave reverberations display strong signals on the transverse-component on Tibetan stations, consistent with the presence of an anisotropic layer (or layers) in the crust. The interpretation of the crustal anisotropy in terms of the models of finite strain is more uncertain than interpreting mantle anisotropy which is mostly produced by the preferred orientation of olivine. Several physical mechanisms relate crustal anisotropy to finite strain. Preferential orientation of faults may be the dominant mechanism in the Tibetan upper crust, whereas in the middle to lower crust beneath Tibet anisotropy may result from preferred mineralogical orientation. Mica, in particular, may play the most significant role in middle to lower crustal anisotropy, with larger shear moduli parallel to the plane of oriented mica crystals than perpendicular to it. These preliminary results on the vertical distribution of radial and azimuthal anisotropy are consistent with a model in which Tibet extends east-west with vertical flattening. This extension would be accommodated in the upper crust by normal faulting with a preferential north-south orientation, which would explain the azimuthal anisotropy observed with short-period Rayleigh waves. In the middle crust, large-scale extension would produce both crustal thinning and viscous east-west flow that would result in a combination of radial and azimuthal anisotropy in which the latter may be oriented differently from that in the upper crust.

S11C-0308 0830h POSTER

Receiver functions in central Tibet, implications for crustal structure and anisotropy

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The dense INDEPTH III seismic array, which extended from the Lhasa terrane across the Banggong-Nujjang suture (BNS) into the Qiangtang terrane in central Tibet, yielded a large, high quality teleseismic data set. Results from stacking and migration of receiver functions with various frequencies reveal that (1) the crustal thickness ranges between 65-70 km. (2) A small ($\sim$ 5 km) Moho offset is observed when using a constant crustal Vp/Vs ratio of 1.73 for the entire profile. On the other hand, using a higher Vp/Vs ratio of 1.80 for the Qiangtang terrane, as suggested from the timing of multiples, produces a nearly flat Moho. (3) For higher frequencies, the amplitudes of the P to S conversions at the Moho (PmS) diminish along a $\sim$ 100 km wide zone across the BNS, which implies a gradational velocity contrast. (4) A shallow ($\sim$ 10 km) low-velocity zone (LVZ) appears $\sim$ 40 km south of BNS and is coincident with high conductivity observed from magnetotelluric studies. (5) In the mid-crust a strong continuous LVZ is present at $\sim$ 30 km depth in the southern section and becomes shallower ($\sim$ 15 km) and more pronounced to the north. The northward increasing trend of the Vp/Vs ratio, the low Q values, and the large depth change of the mid-crustal layer observed from wide-angle seismic data are spatially consistent with this LVZ. (6) In general, the lower crust has more intra-crustal arrivals with large amplitudes under the Qiangtang terrane than in the Lhasa terrane. (7) The presence of dipping layers and/or seismic anisotropy is evident in the crust near the BNS based on azimuthally varying amplitudes and large tangential energy. The sharp onset of strong SKS splitting suggests crustal anisotropy with fast polarization directions varying from E-W to NE-SW. These splitting observations align well with the direction of shear in the present-day crustal strain field in Tibet. In order to constrain the origin and geometry of crustal anisotropy, observed variations in receiver functions with backazimuth will be modeled for hexagonal anisotropy parameters by using a global minimization technique. This approach will provide additional information on crustal fabrics, and in conjunction with geologic data, will enable us to distinguish crustal flow from fossilized fabrics of older tectonic events.

S11C-0309 0830h POSTER

Shear-Wave Splitting Observed In The Taiwan Area: An Effect Of Actively Convergent Process

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Seismic anisotropy is found to be a ubiquitous property that is due to lithospheric deformation from past and present orogenic activity. Some analyses of shear wave splitting derived an accordance between crustal and mantle deformation, which suggested that the mantle plays a major, while may not be dominant, role in orogenies (e.g. Silver, 1996; Savage, 1999, etc). In the case of the Taiwan orogen, nevertheless, the observed splitting parameters tend to be regrouped with varied-scale tectonic frameworks. The previous study from regional and teleseismic shear-wave splitting revealed that the orientation of the upper mantle anisotropy affected by the collisional tectonics and generally submitted to the direction parallel to the strike of the Taiwan mountain belt (Rau, et al., 2000). On the contrary, the splitting parameters evaluated from crustal earthquakes show local-structure dependent for the Taiwan area. In this study, the fast polarization directions and delay times are analyzed from the local earthquakes recorded by both short-period and accelerometric stations at Taiwan. Some larger earthquakes are examined by aspect-ratio method to justify its polarization direction of the leading S wave. The resultant shear-wave splitting parameters from the southwestern Taiwan display about 0.2 second of delay times. The earthquakes located at the northern subduction zone of Taiwan are used to study seismic anisotropy characteristics with varied path propagation. Ultimately, we tend to interpret the seismic anisotropy in the Taiwan area as accommodation of lithospheric deformation provoked by the active convergence of the neighboring plates. Refs: Rau et al., 2000, EPSL, 177, pp177-192. Savage, 1999, Reviews of Geophysics, 37, pp. 65-106. Sliver, 1996, Annu. Rev. Earth Plant. Sci., 24, pp. 385-432.

S11C-0310 0830h POSTER

Significant Seismic Anisotropy in the Shallow Unconsolidated Layer beneath the Southwestern Taiwan

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Taiwan is located on the convergent boundary zones between the Eurasian and the Philippine sea plates. Due to the collision between Taiwan and Luzon arc, the central Taiwan is undergoing remarkable crustal deformation and consequently results in disastrous earthquakes like the 1999 Chi-Chi, Taiwan Earthquake (Mw 7.6). In this study, we have analyzed the seismic shear wave splitting at a borehole station in the Southwestern Taiwan, where is overlain a thick and soft sedimentary layer, to study the subsurface structural deformation. The fast direction and delay time were estimated by applying the waveform cross-correlation technique. Both the direct and free surface reflected S waves show significant splittings. We found their mean polarization of the leading S waves is in ESE-WNW direction, which is compatible with the surface velocity field derived from geodetic GPS measurements. The delay time obtained from the reflected S wave is around 0.08 s at a two-way travel time of 1.01 s, which demonstrates that the anisotropic degree is as large as 8% or 23% in s/km for the top 173 m unconsolidated layer. This value (8%) is similar to that derived from the direct S wave. In addition, it doesn't change much before and after the 1999 Chi-Chi, Taiwan Earthquake. This observation suggests that the tectonic force induced, prevailing crack-like structures might also exist in the very shallow unconsolidated and water-saturated layer and seems to be less sensitive to the stress redistribution after a nearby large earthquake. However, the anisotropy caused by the alignment of mineral grains cannot be completely excluded.

S11C-0311 0830h POSTER

Near-Surface Anisotropy of Crustal Velocity and Attenuation

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Seismograms from local aftershock events of the 1999 Chi-Chi earthquake recorded at a 200 m deep downhole station CHY of the Taiwan Central Weather Bureau Seismic Network (CWBSN) have clearly direct up-going shear waves ($S^{/}$) and their surface-reflected down-going phases ($S^{\backslash}$). The horizontal waveforms are projected into the fast and slow polarization directions, which are determined from direct up-going phases using the aspect ratio method of shear-wave splitting. Measurements of the time difference between the $S^{/}$ and $S^{\backslash}$ phases of the fast and slow components give approximately a value of 8% velocity anisotropy in the top 200 m of the crust. Both the $S^{/}$ and $S^{\backslash}$ phases are windowed with a cosine taper and their amplitude spectrums are calculated. The amplitude spectral density ratios between the $S^{/}$ and $S^{\backslash}$ phases are approximately linear in the range 3 - 15 Hz. We then estimate Q_{β} from the slope of the amplitude spectral density ratios (in dB/Hz) in this range. The results show clear evidence of attenuation anisotropy in the near-surface structure. The estimated values from stacked amplitude spectral ratios of about 180 high-quality records are $Q_{\beta f} = 60$ for the fast components and $Q_{\beta s} = 45$ for slow components. The observed attenuation anisotropy may be a manifestation, similarly to velocity anisotropy, of aligned microcracks and macro-fracture related to the in-situ stress. Strong attenuation anisotropy (25% in this study) will significantly affect the properties of shear-wave seismograms and therefore should be taken into account in studies employing shear-wave amplitude data.

S11C-0312 0830h POSTER

Nation-wide Upper Crustal Anisotropy Distribution Beneath the Japan Island -Shear-wave Splitting Analysis of Hi-net Data-

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There have been several regional shear-wave splitting studies of crustal anisotropy in Japan (e.g. Kaneshima, 1990). Recently, a high-sensitivity short-period seismic network, called Hi-net, has been installed, which realizes the high-density station spacing of 20 km over the Japan Islands. Then, we have executed shear-wave splitting analyses using seismic waveforms observed at such Hi-net stations to reveal the upper crustal anisotropy structure beneath the Japan Islands with higher spatial resolutions than those in previous regional studies.
We used two horizontal components of seismograms recorded for earthquakes with depths of 0-15 km. Since Hi-net stations have been installed in the ground, there is little influence of free surface. At first, seismograms were low-pass filtered at 10 Hz to remove the high frequency noises, and to distinguish each shear wave easier. Then, the leading shear wave polarization direction (LSPD) and the travel time differences (DT) between leading and slower split shear waves have been obtained from the horizontal components of the splitting shear waves by the cross correlation method (Shih and Meyer, 1990). The horizontal component seismograms are rotated clockwise from north to east with an incremental step of 5 degrees. For each step the cross correlation coefficient (coff) between two rotated waveforms is computed for a lag time from +0.4 to -0.4 s with increments of 0.01 s. We adopt the values of LSPD and DT, respectively, for the rotated waveforms giving the maximum coff.
Finally, we have obtained about 5000 LSPD and DT observed at about 300 stations during a period from 2000 to 2003. We found that the polarized directions of the faster shear waves at most of stations are generally constant, and independent of arrival directions and incident angles less than the critical angle. The polarized directions agree with the axes of the maximum horizontal compression obtained from fault mechanism analyses. These results suggest that the crack induced anisotropy is present in the upper crust beneath Japan. A larger number of measured LSPD and DT and used stations than those in previous studies would improve our understanding of the upper crustal anisotropy and provide a possibility of shear-splitting tomography.

S11C-0313 0830h POSTER

Temporal variation in the shear wave anisotropy detected with ACROSS

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Temporal variation in the shear wave anisotropy was detected in a monitoring experiment using an accurately controlled routinely operated signal system (ACROSS). We made an experiment lasting for 15 month, from January 2000 to April 2001 at a site near the Nojima fault, which ruptured during the 1995 Kobe earthquake (Mw7.2) {Yamaoka et al. 2001; Ikuta et al. 2002}. Two vibration sources that generate 2 x 10^5 N with centrifugal force are firmly fixed on the ground. The emitted elastic waves are received with seismometers deployed in the bottom of 800m- and 1700m-deep boreholes near the ACROSS sources. We extracted small temporal changes in the travel-time for P- and S-wave calculating cross-spectral density among the records at each calendar time. During the experiment, sudden delays of S waves travel-time were observed at the time when the 2000 Western-Tottori earthquake (Mw6.6) and the 2001 Geiyo earthquake (Mw6.4) occurred. Their epicenters were 165 km and 215 km away from the site, respectively. The travel-times for the S waves showed the abrupt delay and gradual subsequent recovery between the surface and the bottom of 800m-deep borehole associating with each earthquake, though P waves scarcely changed. The delay in travel-time suggests increase of cracks in the media. Additionally the small changes in the travel time for P wave suggest that most of the cracks were saturated with water. The delay of S was about 0.4% and 0.1% for the Western-Tottori earthquake and the Geiyo earthquake, respectively. Both the delays were polarized in the direction perpendicular to the Nojima fault. This polarization indicates preferred orientation of the cracks, density of which temporally increased, in the direction parallel to the Nojima fault. We checked if the static anisotropy exists by examining the splitting of S wave using ACROSS. The S wave was revealed to be splitting into two orthogonal directions, the leading one was parallel to the fault and the lagging one was perpendicular to it. This suggests that cracks which orientate to the fault strike had been dominant. One explanation is that increasing pore pressure caused by earthquake shaking expanded the dominant cracks, which orientated to parallel to the fault. [References]; Ikuta et al,GRL,29,No.13,5,2002; Yamaoka et al,IslandArc,10,336-347,2001

S11C-0314 0830h POSTER

Anisotropic Layering in the Proterozoic Crust of the Arabian-Nubian Shield

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The Arabian-Nubian shield (ANS) assembled in the late Proterozoic at the climax of the Pan-African orogeny, primarily from "juvenile" crustal terranes that have been identified as oceanic plateaus or island arcs. Geochemical data suggests that the crust of the shield and the underlying mantle lithosphere have not separated since that time. The shield remained tectonically stable and intact until the Oligocene opening of the Red Sea separated its Nubian and Arabian portions. We contrast two seismic stations on opposite sides of this nascent ocean basin, Ar-Rayn in Saudi Arabia (RAYN) and Kottamiya in Egypt (KEG), with a receiver function (RF) technique that incorporates both regional and teleseismic earthquake data. A broad range of source distances provides opportunity for migration of converted phases, making their interpretation more robust. High frequencies in the P coda allow us to construct RF gathers with useful energy up to 2.5–3 Hz. Crustal thickness is very similar at both sites. Anisotropic layering is found beneath the crust-mantle transition. In their early, "crustal" parts, the RFs display numerous features with characteristic attributes of anisotropic layering, i.e., strong transversely-polarized pulses in broad backazimuth sectors. These pulses change polarity with backazimuth. Because the temporal moveout that would be expected from inclined interfaces is not evident, we conclude that anisotropy is the cause. At KEG the first 4 s of the transverse RF contain multiple phases with clear polarity reversals. The pulse shapes depend on the RF passband, suggesting their origin in fine-scale lamination of the crust. RAYN shows evidence for localized anisotropic layering at the Moho and in the middle crust. Interpretation of the middle crust is challenging, because some pulses exhibit polarity reversals with back azimuth in both radial and transverse receiver functions. RAYN lies more than 700 km from the zone affected by the continental breakup, and thus lithospheric structure here likely reflects Proterozoic tectonics of shield assembly, or earlier processes that shaped the individual terranes that comprise the ANS. KEG lies within the zone affected by the rifting in the Gulf of Suez, and thus may bear marks of both Proterozoic and relatively recent (Miocene) activity.

S11C-0315 0830h POSTER

Lithopsheric anisotropy in the Archean Slave craton, Canada

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Shear wave anisotropy and discontinuity studies of teleseismic earthquakes recorded at single seismic stations help to define vertical mantle stratigraphic columns. Beneath the Archean outcrops of the central Slave craton seismic discontinuities at 38, 115, 140, and 190 km appear to bound two distinct anisotropic layers. The discontinuity at 38 km is the Moho; discontinuities at 110-120 and 140-150 km depths observed at multiple nearby stations indicate that a layer of low velocity or distinct anisotropy exists between these depths. The coherent pulses at about 13 seconds on the radial component indicates a strong decrease in velocity at 110 km depth north and west of the Ekati diamond mine, but not to the south. The response on the transverse component indicates a rotation of anisotropic fabric at 117 km depth, a reversal at 140 km, and another rotation at 190 km. A flip in polarity at a back azimuth of about 280° occurs in the 117 km discontinuity and apparently marks an axis of symmetry of anisotropy, here probably the dip direction of steep layering or planar fabric. SKS anisotropy studies at this station indicate that the upper of two anisotopic layers has a fast-axis direction of 010°. Geochemical studies of xenolith samples from nearby kimberlites suggest that the boundaries at 115 and 140 bound a layer of ultra-depleted harzburgite, almost pure olivine, that formed as oceanic crust.

S11C-0316 0830h POSTER

Imaging the Cheyenne suture beneath the Laramie Array in southeast Wyoming

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The objective of the PASSCAL Laramie Array deployment was to resolve the crust and sub-crustal lithosphere velocity and discontinuity structure beneath the Cheyenne belt, which demarcates the suture between the Archean Wyoming province and the Proterozoic Colorado province. From Sept. 2000 to June 2001, thirty-one broadband sites at a 2 km station spacing were deployed along a N20 W transect in the Laramie Basin. Receiver function (RF) transect from the PASSCAL CD-ROM experiment 100 km to the west of the Laramie Array shows substantial dipping crust and sub-crustal velocity discontinuities across the Cheyenne belt. Assuming these structures are related to the 1.78-1.75 Ga Cheyenne suturing event, significant seismic anisotropy within the suture zone is expected to produce systematic variations in the receiver functions. Joint radial and tangential receiver functions analysis is being used to constrain the difficult trade-off between interfaces dip and anisotropic velocity heterogeneity. Our preliminary results show a clear image of the Moho that appears not to require velocity anisotropy and a north dipping mid-crustal interface beneath the entire array. This north-dipping interface is opposite to the generally accepted south-directed polarity of the Cheyenne belt. A strong correlation exists between this mid-crustal interface and large lateral variations in the upper crustal P-wave velocities derived from the teleseismic travel-time inversion. Further analysis to constrain potential crustal velocity anisotropy will be presented.

S11C-0317 0830h POSTER

Crustal Seismic Velocity Anisotropy Beneath the Ruby Mountains Metamorphic Core Complex from 3-Component Wide-Angle Seismic Data

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Metamorphic core complexes, such as the Ruby Mountains-East Humboldt Range core complex in NE Nevada, expose rocks deformed at deep upper to middle crustal levels during extreme crustal extension. The northern Ruby Mountains expose ductilely deformed mid-Tertiary metamorphic rocks that have been tectonically exhumed from depths of 13-14 km. However, the southern Ruby Mountains expose unmetamorphosed shallow-level sedimentary rocks. Analysis of Moho reflections from seismic data along the eastern flank of the Ruby Mountains shows that crustal thickness varies between 30.5 and 33.5 km, with no apparent correlation between amounts of extension, exhumation, or local topographic relief, implying that large-scale flow of ductile crustal rocks may have been important in the development of crustal structure beneath the Ruby Mountains. Ductile flow in rocks can impart significant seismic velocity anisotropy due to alignment of minerals. However, the calculated velocity anisotropies for all crustal levels beneath the Ruby Mountains are significantly lower than are determined from laboratory measurements on representative metamorphic rocks from the area. Analyses of shear-wave-splitting results from 3-component normal-incidence to wide-angle reflection/refraction data from the Ruby Mountains indicate that upper crustal metamorphic rocks, including areas containing mylonitic fabrics, are characterized by velocity anisotropies of 0.6-2.5%. Orientations of fast shear waves near the surface and in the upper crust are approximately parallel to the regional maximum horizontal stress in the Nevada part of the Basin and Range Province, suggesting that the bulk anisotropy in the upper crust may be controlled by stress-induced fractures. From middle and lower crustal levels beneath the Ruby Mountains, shear-wave splitting was not identified in the 3-component seismic data. Lack of evidence in the data for shear-wave splitting in the lower crust suggests that velocity anisotropy is less than 3% in an area that has experienced intense extensional deformation and probable crustal flow.