by asthenospheric flow due to the lack a thick overlying lithosphere. The observed fast polarization directions are used to investigate the following hypotheses regarding mantle flow. First, we tested for a possible lithospheric contribution by comparing the splitting measurements to fossil spreading directions and found that they are a poor fit to the data at stations located >500 km from the ridge axis. Thus, we conclude that the observed anisotropy is dominated by asthenospheric flow. We then considered several models with varying assumptions about the velocity at the base of the asthenosphere: that it is 1) stationary below plates moving in the no-net-rotation (NNR) and hotspot reference frames, 2) driven by plate motion at the Earth's surface, and 3) driven by a combination of plate-motion and mantle density heterogeneity inferred from seismic tomography. We find that the best-fitting flow field is one that includes density heterogeneity associated with large-scale upwelling originating in the lower-mantle beneath southern Africa, and is manifest as a radial pattern of flow at the base of the asthenosphere. The resulting sub-asthenospheric flow field is characterized by velocities of 0-3 cm/yr, and an asthenospheric viscosity of $1\text{-}3{\cdot}10^{19}$ Pa·s is found to be most consistent with the regional anisotropy, geoid height, and dynamic topography.

T51B-06 0925h

Upper Mantle Structure Beneath the East Pacific Rise

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Depth extent and characteristics of low velocity zones under spreading centers have long been debated. Evidence from recent global and regional surface wave studies suggests considerable shear velocity variations at depths possibly as large as 300 km. The upper mantle beneath midocean ridges are also known to exhibit highly anisotropic behaviors, especially in the top 200 km. In this study we combine regional observations with global constraints to investigate shear velocity structure (both isotropic and anisotropic) and mantle discontinuities under the East Pacific Rise (EPR). The data set consists of intermediate-period (15-35 sec) records from ocean-bottom seismometers (OBS) deployed by the TOES (1995) and MELT (1996) experiments, as well as long-period surface (>45 sec) and body waves from on-land, permanent stations worldwide. Our preliminary surface wave (mostly Rayleigh wave) analysis of the OBS recordings shows considerable differences in 1-D isotropic velocities between cross-ridge and along-ridge paths. The presence of a distinct low-velocity zone within the top 100 km is required to fit the observed waveforms. The average velocity for several source-receiver paths in the distance range 8-25 degrees appears to correlate with the path-integrated age of the oceanic lithosphere. A joint inversion for isotropic/anisotropic shear velocity structures reveals a radially anisotropic anomaly (possibly as strong as 2.5%) ~230 km beneath various parts of fast spreading ocean ridges, most notably north EPR. A positive difference between the vertical and horizontal wavespeeds implies near-vertical alignments of olivine fast crystallographic *a* axis at asthenospheric depths. The anomalous nature of the EPR is further evidenced by the presence of a deep (~270 km) reflector in north EPR. This feature could potentially represent a deep Lehmann discontinuity, though the latter is generally associated with major continents. Waveform comparisons between observed S multiples and synthetic calculations suggest either a positive jump that is nearly as strong as the 220-km discontinuity in PREM or, alternatively, a gradient in the V_{SV} wavespeed exists below 200 km. The nature of this anomaly, especially its potential association with anisotropy under ocean ridges, is being investigated.

T51B-07 0940h

A causal relationship between the migration of oceanic spreading centers and the magmatic segmentation of ridges

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The elevation of the world's mid-ocean ridges (MORs) displays pronounced undulations which subdivide the MOR into discrete spreading segments bounded by transform faults and smaller offsets of the axis. These morphological changes have been attributed to spatial variations in the supply of magma from the oceanic mantle but the cause of these variations has not been explained. Shallow and broad ridge segments are believed to reflect enhanced magma supply while deeper, more tectonized segments are believed to be magma-starved. Analysis of morphological changes along the ridge crest in the context of absolute plate motions reveals a simple relationship between the magmatic segmentation of the ridge and ridge migration direction. Currently all spreading centers are migrating relative to the "fixed" hotspot reference frame at a rate and direction determined by the absolute motions of the bounding plates. Along the northern East Pacific Rise (NEPR), where the spreading center migrates to the northwest, depth profiles show that the shallow robust ridge segments are consistently offset in the direction of ridge migration relative to the deeper adjoining segments. This relationship is observed at all transform offsets as well as at smaller discontinuities with offsets typically < 15 km. Analysis of other fast and intermediate spreading portions of the world's MOR reveals changes in topography consistent with the ridge migration direction at the majority of transform faults and second-order discontinuities. We suggest that these variations in ridge morphology may be a consequence of a three-dimensional pattern of melt focussing from a broad zone of mantle upwelling in the presence of a migrating spreading center. In the case of a segmented spreading center, focussing of melts should occur not only from the mantle upwelling zone beneath each ridge segment, but also across ridge axis discontinuities. Indeed, melt may be preferentially entrained across discontinuities where horizontal flow paths are shorter to the adjoining ridge axis leading to extraction of melts at one segment which originated in the upwelling zone of the adjoining segment. Simple kinematic models of mantle upwelling in the presence of a migrating spreading center predict faster mantle upwelling and resultant higher melt production by decompression beneath an advancing plate (Davis and Karsten, 1986; Schouten et al., 1987). A consequence of this asymmetry is that the pattern of mantle upwelling and melt production across discontinuities will depend on ridge geometry with more melt available for lateral entrainment across discontinuities to leading segments than to the trailing segments.

T51C MCC: 3010 Friday 0800h

Brittle Deformation and Faulting of the Earth's Crust: Observations and Models I *(joint with G, S, V)*

Presiding: **G Hayes,** Pennsylvania State University**; C Goldfinger,** Oregon State University

T51C-01 0800h

The Dead Sea Transform Fault: electrical conductivity, other geophysical data, and comparison with the San Andreas Fault

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The more than 1000 km long trans-continental Dead Sea Transform (DST) forms the boundary between the African and Arabian plates in the Middle East. Magnetotelluric (MT) data were recorded at more than 200 sites, focusing on the DST in the Arava valley in Jordan. 2D inversion results of the MT data indicate very clearly that the DST is associated with a strong lateral conductivity contrast. The most prominent feature on the MT image is a conductive half-layer beginning at a depth of approximately 1.5 km, which may be caused by brines in porous sediments. The DST can be identified as a sharp vertical conductivity boundary on the east side of the feature and directly beneath the surface trace. On a coincident high-resolution seismic tomography image of the upper crust, a strong increase of the P wave velocities to values exceeding 5 km/s is observed west of the DST, where the MT model indicates lower conductivities. The seismic velocities are consistent with metamorphic basement rocks; however the observed resistivities (50-250 Ωm) are unusually low for unaltered metamorphic rocks. Fractured metamorphic rocks with interconnected fluid bearing veins could explain both the seismic and MT observations. However, the conductivity model suggests furthermore that the DST acts as an impermeable barrier to cross-fault fluid flow. In stark contrast, a prominent flower structure is observed along the central segment of the SAF and interpreted as evidence of pervasive along-fault fluid flow. Here, the high conductivity is attributed to the circulation of saline fluids within the damage zone of the fault system. The width of the conductive zone (0.5 km) is in the same order of magnitude as the width of a seismic low-velocity zone inferred from fault-zone-guided wave observations, while its depth extent (3 km) coincides with the occurrence of a cluster of small earthquakes. It is possible, that the damage zone of the DST is so narrow that it cannot be resolved even with the dense site spacing of the MT experiment. This observation is supported by preliminary results from geological mapping and a seismic study using fault-guided waves that suggest a very narrow low-velocity waveguide of 3 to 10 m width. The reason for this difference between the DST (very narrow fault zone) and the SAF (wide gouge zone) is not yet clear, but seems to coincide with generally slower slip rates and the relatively low recent seismicity associated with this segment of the DST.

T51C-02 0815h

Turbidite Based Earthquake Record Along the Northern San Andreas Fault

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During June and July, 2002, we collected 60 cores from channel and canyon systems draining the northern California continental margin. The objective of this project is to test the hypothesis that many of the turbidites deposited in these channels result from turbid flows triggered by earthquakes on the northern San Andreas Fault (SAF). Along the northern coast of California between San Francisco and Point Delgada, the San Andreas lies close to the coast or just offshore. No regional stratigraphic datum has yet been found in our cores, however correlation of individual turbidites both along individual channels and across non-connecting channels is robust, providing numerous stratigraphic ties between these systems. We are using Gamma density, high-resolution magnetics, x-ray, and color reflectance data to build a comprehensive regional correlation along the length of the northern San Andreas. That we are able to correlate individual turbidites along channels is not surprising, however correlating turbidites from one channel to another, as much as 300 km away, is surprising. The correlation using patterns in imagery and physical properties suggests that, as we found in Cascadia, many turbid events appear to be recording large earthquakes rather than other possible triggers of these flows. Correlation of events along the margin for large distances suggests an earthquake origin for these turbidites, since other potential triggering mechanisms (except very large storms) operate in only single channels. Such synchronous triggering, only possible with earthquakes, is shown for many events. Channels from separate mineralogic provenances come together at confluences, below which we see either doublets, with no intervening time between them, or bimodal coarse fractions in the turbidites, each peak representing a separate provenance. Perhaps of equal or greater importance, the regional correlation of events implies that the physical property "wiggles" contain information about the earthquakes themselves, since the turbidites located in widely separated and non-communicating channels have, to our knowledge, nothing else in common. Based on initial AMS 14C results, we find that regional correlation is possible for the last 6200 years, and identify 35 events above this datum for the entire region. Of these, 10 events can be correlated along the length of the study region, from the northern limit of the SAF to south of San Francisco. Twelve events correlate along a northern "segment" and nine events correlate along a southern "segment" We find no events that occur clearly in only one channel, and only four events that are found in two and three channels only. These events are in close proximity to the seismically active Mendocino Triple Junction.

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T51C-03 0830h

Implications of the 8/21/2003 Mw 7.2 Fiordland New Zealand Earthquake for the Development of the Alpine Fault Plate Boundary

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The transition from subduction of the Australian plate beneath Fiordland to the transpressional Alpine fault represents an abrupt change in plate interactions. Beneath Fiordland, the Australian plate subducts to depths of at least 200 km, with the slip vectors of earthquakes inferred to represent plate interface events aligned in the direction of relative plate motion between the Australian and Pacific plates. To the north, along the Alpine Fault, the eastern edge of the Australian plate serves to define the position of the plate boundary, with the majority of transpressional deformation accommodated by the Pacific plate. Based on plate reconstructions, the eastern edge of the Australian plate that now defines the Alpine fault boundary was previously adjacent to the lithosphere that is currently subducted to depth beneath Fiordland. How this transition occurs has been a point of some debate. The recent Mw 7.2 earthquake (8/21/2003) provides evidence of the lithospheric deformation that allows this change in plate boundary structure. This event is characterized by two thrust planes: one shallowly dipping to the ESE, the other steeply dipping to the WNW. In contrast to subduction interface events further to the east, both fault planes have slip vectors that are nearly pure dip slip, oriented approximately 60 degrees away from the relative plate motion. Although the shallow eastward dipping plane is consistent with the inferred geometry of the slab, its slip vector is incompatible with other subduction events on the plate interface. If however the steeply dipping plane is selected, its orientation, slip vector, and the location of the earthquake are all consistent with it representing an event that occurs as the Australian plate is torn, forming a new eastern edge to that plate. Several other earthquakes with similar mechanisms have occurred on this southwest extension of the Alpine Fault; all with fault planes consistent with a tearing of the plate. This plate edge will translate northward becoming the west side of the Alpine Fault plate boundary. We have previously argued that a tearing of the slab in this way (essentially collinear with the Alpine Fault) was needed to match the patterns of slab deformation, uplift in Fiordland, and the substantial gravity anomaly in the region. This earthquake provides direct evidence of the tearing process and provides constraints on the location within the transition from subduction to translation that the new plate boundary is generated.

T51C-04 0845h

Integrating Seismological Studies of Crustal Structure in the Northern California Coast Ranges to Construct a Regional 3D Strain Model

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The Coast Ranges of California has been the target of a number of recent seismological studies aimed at constraining various aspects of crustal architecture. The combination of techniques used provides a suite of complimentary constraints; the active source Mendocino seismic experiment gave 2D velocity data and delineated interfaces from reflectivity, while tomography provided a smoothed 3D velocity picture. Receiver function studies have characterized crustal interfaces and provide information on the nature of the velocity contrasts across these interfaces. This latter information is key in determining the way in which processes driven by the passage of the Mendocino Triple Junction have driven crustal evolution of the Coast Ranges. Combining the results of these various studies, we test models of thickening and subsequent thinning of the crust in response to the Mendocino crustal conveyor. Specifically we use crustal structure models from receiver functions generated at a number of stations in the region, combined with the 3D tomography of the area, to develop a model of crustal architecture over the entire Coast Ranges. Analyzing these results within the framework of the Mendocino crustal conveyor model allows us to move beyond simply describing the structure; rather it allows us to develop a 3D model of present-day crustal strain that provides constraints on mechanical properties of the Coast Ranges crust, where shear zones develop within that crust, and the role they may play in the evolution of the San Andreas Fault system.

T51C-05 0900h

The last stages of subduction in the South-Central Mediterranean reflected in geodetic and seismic strain rates

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Subduction, collision and back-arc spreading zones within the Africa-European plate boundary meet in the south-central Mediterranean. Strain rate maps based on new geodetic data and existing seismic catalogs document several recent tectonic changes in this region. (1) Current Africa-European convergence around Sicily is localized north of the island, along what we interpret to be a back-arc thrust. This thrusting is a response to collision of the subduction zone with the African continental margin 1-3 Ma. Faults in west and central Sicily may be reactivated in occasional earthquakes, but do not accommodate significant compression anymore. (2) Back-arc extension in the Tyrrhenian is currently not observed. Within 1-2 mm/yr the area behaves like a rigid part of Europe. (3) There is no geodetic evidence of ongoing southeast migration of the Calabrian arc. (4) The Aeolian islands and northeastern Sicily exhibit an unusual and previously unrecognized velocity pattern. With velocities of up to two times Africa-European motions, this area is extending, and rotating relative to Africa. We suggest that mantle flow and gravitational collapse associated with an up-dip tearing between the Ionian and Sicilian portions of the slab are responsible for these unusual velocities. The tear could have developed when the trench collided with the Sicilian part of the African margin while roll-back at the Calabrian trench continued (until about 0.5 Ma). The existence of such a tear may also explain the occurrence of extensional earthquakes and high uplift rates in eastern Sicily, the location of Etna, and recent changes in the geochemical signature of Aeolian volcanism.

T51C-06 0915h

First Constraints On the Slip Rate of the Yammouneh Fault (Levant Fault System) Determined by Cosmogenic ^{36}Cl Exposure Dating of Offset Alluvial Fans

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The most active seismogenic structure along the eastern shore of the Mediterranean is the left-lateral strike-slip Levant fault, plate boundary between Arabia and Africa. To this day there is consensus neither on its present slip rate and segmentation, nor on the exact size and frequence of the earthquakes it generates. Between latitudes 33^{o} N and 35^{o} N in Lebanon, the Levant fault's trace veers eastwards by 24^{o}, forming a 160km-long restraining bend, responsible for the uplift of Mount Lebanon (3083m). Most of the resulting transpressive deformation is partitioned between two main structures: the offshore Tripoli-Beirut thrust and the Yammouneh strike-slip fault, whose degree of seismogenic activity has been questioned (various estimations of its modern slip rate range from 0 to 8mm/yr). Using aerial photographs, satellite images, topographic maps and field observations, we mapped and measured left-laterally offset alluvial fans and gullies along the Yammouneh fault. The measured offsets range from less than 10m to about 3km. To constrain the slip rate of the Yammouneh fault, limestone cobbles were sampled on three alluvial fans, each offset by 40–50m. The concentrations of ^{36}Cl and stable Chlorine in the 48 samples were measured by accelerator mass spectrometry at the LLNL-CAMS. The first results suggest an average slip rate of 5–10mm/yr along the Yammouneh fault in the last 8,000 years.

T51C-07 0930h

Determination of Stress From Fault-slip Data: New Models, Algorithms and Accuracy Evaluation

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Stress tensors are regularly determined from fault-slip and/or earthquake focal mechanism data in structural geology and seismotectonics. The inverse problem is nonlinear, unless empirical rules of rupture and friction are employed. All the methods used to date to determine the stress tensor to this nonlinear inverse problem are of local nature, and thus cannot guarantee that the global optimal stress tensor has been obtained. We apply a hybrid global optimization method developed by Xu (J comput appl Math, 147, 301-314, 2002; J comput appl Math, 155, 423-446, 2003; J comput appl Math, 156, 201-219, 2003) to find the global optimal stress tensor. Although the inverse problem is nonlinear, the effect of nonlinearity on the biases of stress tensors has not been investigated. We will examine the biases of inverted stress tensors and their effect on the principal orientations of stress and the shape parameter of the stress ellipsoid. The biases of stress parameters have been shown to be comparable with the estimated stress parameters numerically. We compare the accuracy of the four stress parameters, with and without taking the errors in fault planes into account. If the errors in fault planes are not taken into account, the stress parameters are too optimistically estimated by a factor of $4 \sim 9$ in the example. We will also mathematically reformulate the assumption that the directions of maximum shear stress represent those of slips on fault planes as two functionally independent but equivalent constraints of equality. The new formulation is computationally more effective and provides a correct method for calculating the accuracy of stress parameters.

T51D MCC: Level 1 Friday 0830h

Brittle Deformation and Faulting of the Earth's Crust: Observations and Models II Posters *(joint with G, S, V)*

Presiding: **B Meade,** Massachusetts Institute of Technology

T51D-0186 0830h POSTER

Late Quaternary displacement rate on the Alpine Fault and the timing of glacial advances in southwest New Zealand

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Glacial features in eight river valleys crossing the southern end of the onshore Alpine Fault in South Island, New Zealand, are offset dextrally 435, 1240, or 1850 m and have only small vertical offsets. This is consistent with radiocarbon, surface exposure and speleothem evidence for extensive glaciation followed by retreat at c. 18, 58, and 79 ka. Glacial advances at c. 79 and 60 ka were higher and more extensive than 20 ka advances. Consideration of the three offset-age ranks yields an Alpine Fault slip rate with 95% confidence limit (1.96 sigma) of 22.9 $\pm$ 3.3 mm/yr. Consideration of eight sites offset by about 435 m indicates the rank 1 offset has a 95% confidence limit of 51 m, yielding a displacement rate and 95% confidence limit of 24.2 $\pm$ 3.3 mm/yr for features of this age. Comparison with geologically determined uncertainties from each site shows that geological estimates of uncertainty in age and offset approximately correspond to confidence limits in the range 90-99%. 36.2 $\pm$ 3 mm/yr of total plate motion in southern South Island (NUVEL-1A) is being partitioned into 22.9 $\pm$ 3.3 mm/yr of Alpine Fault dextral strike-slip, 12 $\pm$ 5 mm/yr of heave on oblique dextral-reverse faults up to 80 km southeast of the Alpine Fault, and 5 $\pm$ 3 mm/yr of heave on reverse faults at peripheries of the plate boundary.