The seismic structure (e.g. velocity, velocity gradients, anisotropy) of the shallow upper mantle of oceanic lithosphere constrains the degree of melt extraction at mid-ocean ridges and the shear deformation of the lithosphere. The variation of fine-scale structure with depth is difficult to resolve with teleseismic data but, with some notable exceptions, seismic refraction techniques - which have excellent depth resolution - have not been used to elucidate oceanic upper mantle structure. Here we report further results from the FAIM (Far-offset Active-source Imaging of the Mantle) seismic refraction experiment conducted along an 800-km-long flow-line transect and a 150-km-long ridge-parallel transect in the western north Atlantic. Sixteen short-period, vertical-component ocean-bottom seismometers (OBS) were deployed along the spreading-parallel transect in 3-km-separated pairs spaced 80-120 km apart, and 3 OBS were deployed orthogonal to the primary transect to a maximum distance of 350 km. Shot spacing was 1 km. Coherent P-wave arrivals were observed to 350-km distance, and the amplitude of this phase and its increasing and fast apparent-velocity suggest that energy is propagating to $\sim$24 km depth below the Moho. Two-dimensional travel-time analyses predict velocities of $\sim$8.25-8.55 km/s over the uppermost 24 km of the mantle on the flow-line-parallel transect and velocities of $\sim$8.05-8.25 km/s over the uppermost 10 km of the mantle on the ridge-parallel transect. At face value, these values indicate P-wave anisotropy is at least $\sim$3.0% throughout the upper 10 km of the mantle. However, velocities in only two orthogonal directions cannot constrain the precise direction and magnitude of anisotropy. To improve this estimate we analyzed the travel times of P-waves with good signal to noise from shots at ranges of 75-250 km, with an azimuth range spanning $\sim$100°. When plotted as a function of propagation azimuth, these travel times display a strong variation, with slower travel times arriving near an azimuth of 100-120° relative to the fossil flow-line, i.e. nearly perpendicular to the fossil spreading direction. Assuming that azimuthal anisotropy in the region is constant, we can estimate its magnitude and direction by fitting delay times with a function that is periodic in 2θ. The best-fitting model has a fast propagation direction at $\theta = 10^\circ$, with a peak-to-peak δt variation of 0.3 s, which corresponds to a P-wave anisotropy of 4.0%, approximately 50% smaller than that observed in comparable experiments on lithosphere formed at faster spreading rates in the Pacific ocean. The large positive velocity gradients measured along both transects are not readily explained with existing predictions of upper mantle deformation. Likewise, the observations are unlikely to be due to depth variations in cracking because cracking in the mantle might be expected to have a preferred direction. One possible explanation for the large gradients is the presence of gabbro plutons in peridotite due to melt retention in the shallow mantle.

T51H-07 1205h

Localized Deformation Beginning more than 15 km Beneath the Mid-Atlantic Ridge, 14 to 16 N

PB Kelemen[1] (508 289 2956; peterk@whoi.edu)

E Kikawa (kikawa@jamstec.go.jp)

J Miller (miller@odpemail.tamu.edu)

. ODP Leg 209 Shipboard Scientific Party (peterk@whoi.edu)

[1]WHOI, MS 8, Woods Hole, MA 02543, United States

ODP Leg 209 drilled 19 holes at 8 sites along the Mid-Atlantic Ridge from 14°43 to 15° N. All sites were surveyed by submersible, and chosen to be $<$ 200 m from peridotite or dunite exposed on the seafloor; outcrops of gabbroic rock were also close to some sites. One of our primary goals was to constrain the mechanism of mantle upwelling, corner flow and exhumation of shallow mantle rocks. Drilling at Sites 1268, 1270-72, 1274 and 1275 penetrated 1075 meters, and recovered 354 m of core. At Sites 1268 and 1270-72 we recovered 25% gabbroic rocks and 75% residual mantle peridotite. Core from Site 1274 was mainly residual peridotite, while core from Site 1275 was mainly gabbroic. Most of the residual peridotites have nearly undeformed, protogranular textures. Orthopyroxenes are interstitial to olivine or even poikilitic. Rare, isolated clinopyroxene grains are also interstitial. Skeletal spinel grains have mm-scale extensions in three dimensions, with no discernable shape fabric. These textures are clearly different from porphyroclastic textures typical in ophiolites and fracture zone dredges. As described elsewhere at this meeting, impregnated peridotites contain olivine, 2 pyroxenes, plagioclase and spinel, and equilibrated at 0.54 GPa ($\pm$0.14 GPa, 2σ) and 1220°C ($\pm$16°C, 2σ) [Kinzler & Grove, JGR 92]. Melts entered the thermal boundary layer beneath the Mid-Atlantic Ridge at about 20 km [e.g., Sleep, JGR 75; Reid & Jackson, MGR 82; Grove et al JGR 92; Cannat JGR 96; Michael & Chase CMP 97; Braun et al., EPSL 00], and began to crystallize within impregnated peridotites and as discrete plutons intruding peridotite. Gabbroic rocks and peridotites from most sites underwent large tectonic rotations since aquiring remanent magnetization. At some sites, rotations may have exceeded 60° around near-horizontal axes parallel to the Mid-Atlantic Ridge. Such large rotations are unlikely to have been accomodated along a single fault, and instead blocks were progressively rotated along a series of fault systems. Sites 1270 (25% gabbroic) and 1275 (75% gabbroic) were drilled into large, low angle fault surfaces previously identified as oceanic core complexes. Deformation at Site 1270 is similar to most other Sites, while core from Site 1275 is the most weakly deformed. However, high pressure igneous assemblages indicate that some Site 1275 rocks were exhumed from depths of 20 km or more, as were residual peridotites at the other Sites. At all sites except 1269, 1273 and 1275, we recovered high temperature mylonitic shear zones (mainly with impregnated peridotite mineralogy, but also mylonitic gabbros), and intervals of low temperature fault gouge. Shear zones and faults are not all parallel; numerous, cross-cutting planes of localized deformation formed at $>$ 1000°C to $<$ 100°C, from $>$ 15 km depth to near the seafloor. These accommodated nearly all subsolidus deformation during corner flow and exhumation of residual peridotites (plus high pressure igneous rocks), in keeping with the inference that the thermal boundary layer in this region extends to at least 20 km. Penetrative, viscous deformation of blocks between shear zones and faults was minor. If this is a general process at slow-spreading ridges, then one would predict that shallow mantle anisotropy in the Atlantic would be less pronounced than in the Pacific, consistent with recent seismic data [FAIM Experiment, Gaherty, Collins et al, this session].

T52A MCC: Level 1 Friday 1330h

Analysis of Plate Boundary Deformation Using Stress and Strain Rate Data in Tandem III Posters

(joint with G, S)

Presiding: **J Townend,** Victoria University of Wellington**; S Mazzotti,** Geological Survey of Canada**; S Miyazaki,** Stanford University**; K Wang,** Geological Survey of Canada

T52A-0229 1330h POSTER

Strain and stress partitioning of the Pacific/North America interaction along the Queen Charlotte Islands-Alaska Panhandle

Stephane Mazzotti[1] (smazzotti@NRCan.gc.ca)

Roy D Hyndman[1,2] (rhyndman@NRCan.gc.ca)

Amanda Bustin[2] (abustin@UVic.ca)

[1]Pacific Geoscience Centre, Geological Survey of Canada, 9860 W. Saanich Rd, Sidney, BC V8L 4B2, Canada

[2]School of Earth and Ocean Sciences, University of Victoria, PO Box 1700, Victoria, BC V8W 2Y2, Canada

Along the western margin of central British Columbia and southern Alaska, the Queen Charlotte (QC) and Fairweather faults accommodate most of the predominantly transform motion (50 mm/yr) between the Pacific and North American plates. This fault system is 1000 km long and was the locus of M=7-8 earthquakes in the last century. Off the Queen Charlotte Islands, the relative Pacific/North America motion also has a 10-15 mm/yr convergence component. New GPS data acquired over the last 5 years allow us to estimate the distribution of transient and permanent strain along this plate boundary. We show that the Queen Charlotte-Alaska Panhandle margin is affected by both transient and long-term dextral shear strain, respectively in response to the interseismic locking of the QC-Fairweather Fault and a 6-7 mm/yr NNE migration of the continental margin. The impact of postseismic deformation following the 1949 M=8.1 QC earthquake is likely not significant. The stress pattern derived from earthquake focal mechanisms is consistent, to a first order, with the GPS kinematic model. Earthquake mechanisms indicate a partitioning between strike-slip and compression on the oceanic side (QC Fault and Terrace). The continental margin (northern QC Islands and Hecate Strait) is affected by a N to NE maximum compression associated with dextral shear of the crust. Long-term dextral shear and shortening of the continental margin is also supported the tectonic inversion of the Miocene normal faults that form the QC Basin. Several kilometers of shortening and strike-slip deformation have been identified on these structures that affect Upper Miocene and Pliostocene deposits.

T52A-0230 1330h POSTER

Assessing lateral variations of stress and strain build up along the Himalaya from geodetic and seismicity monitoring

Laurent Bollinger[1] (bollinge@gps.caltech.edu)

Jean-Philippe Avouac[1] (avouac@gps.caltech.edu)

Rodolphe Cattin[2]

Madhav Raj Pandey[3]

[1]Caltech, 100-23, Pasadena, CA 91125, United States

[2]Ecole Normale Superieure, 25 rue Lhomond, Paris 75252, France

[3]NSC, DMG, Katmandu 0000, Nepal

The uneven micoseismic activity along the Himalayan arc might be taken suggests significant lateral variations of stress and stress build up. On the other hand, the geodetic data show a rather uniform pattern of interseismic straining, colinear with long term geological deformation and the stress distribution as indicated from focal mechanisms. The uneven distribution of microseismicity is shown to result in fact from the influence of the topography on the stress field. The geodetic data and seismicity distribution are indeed reconciled from a model in which microseismicity is intrepreted as triggered by Coulomb stress increase due to elastic build up in the interseismic period. The model assumes a fully locked fault zone with its downdip extremity following the arcuate shape of the High Himalaya front. The observed influence of the topography requires the deviatoric stresses to be low, less than about 30 MPa, implying an apparent friction of the Main Himalayan thrust Fault of the order of 0.1. Arc normal thrusting along the Himalayan front and E-W extension in Southern Tibet are quantitatively reconciled from the model. So we can exclude that asperities on the himalayan megathrust would result from heterogeneous strain buildup in the interseismic period. Recurring transient slip events, including large earthquakes an aseismic slip event, in particular afterslip, must sum up so that heterogeneities are smoothed out in the long term. The pattern of co-seismic slip during a particular earthquake is thus probably strongly controlled by the heterogeneous stress distribution left by previous transient events.

T52A-0231 1330h POSTER

Collisional Deformation, In Situ Stress, and Topographic Relief in Central Japan

John Townend[1] (64 4 463 5411; john.townend@vuw.ac.nz)

Mark D. Zoback[2] (1 650 725 9295; zoback@pangea.stanford.edu)

[1]Victoria University of Wellington, School of Earth Sciences P.O. Box 600, Wellington 6015, New Zealand

[2]Stanford University, Department of Geophysics, Stanford, CA 94305-2215, United States

By amalgamating travel time and first motion data from three Japanese seismic networks, we have obtained a comprehensive focal mechanism catalog with which to investigate tectonic stress directions throughout most of Japan. The axis of maximum horizontal compressive stress agrees well with the axis of greatest contractional strain rate in central and southwest Japan once the effects of interseismic strain accumulation have been removed from geodetic observations according to an elastic dislocation model of subduction thrust locking. This residual deformation is presumed to be independent of deformation associated with strain accumulation and release in the subduction zone earthquake cycle, and to represent net geologic deformation of the upper plate. Moreover, it is broadly confined to the area of pronounced topography in central Japan, and is consistent in both spatial extent and principal strain rate directions with the deformation expected for horizontal motion of the Amurian plate with respect to northeastern Honshu. We conclude that the state of crustal stress in central Japan and the concentration of neotectonic deformation within the Japanese Alps are controlled by crustal collision and are relatively insensitive to earthquake processes on the main subduction zone thrusts beneath.

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T52A-0232 1330h POSTER

Intraplate Stress Directions and Magnitudes Induced by an Orogenesis: Data From Pyrenean, Alpine and Appalachian Collisions

Rocher Muriel[1] ((33) 01 58 35 76 21; muriel.rocher@irsn.fr)

Baize Stéphane[1] ((33) 01 58 35 93 50; stephane.baize@irsn.fr)

Cushing Marc[1] ((33) 01 58 35 76 65; edward.cushing@irsn.fr)

Lemeille Francis[1] ((33) 01 58 35 88 05; francis.lemeille@irsn.fr)

[1]IRSN, BP 17, Fontenay-aux-Roses 92262, France, Metropolitan

Several studies indicate a nearly exponential decrease of orogenic stresses with the distance to the range. The aims of our study are (1) to determine the variations of the curves of decrease (speed of decrease, mean far field stress value, ...) from an orogenesis to another, and (2) to precise the meso-scale intraplate stress variations. In this study, we focussed on the Palaeozoic Appalachian stresses in the North American Plate, on the Mio-Pliocene Alpine stresses and Eocene-Oligocene Pyrenean stresses in the West European plate. Calcite crystals are primarily deformed by twinning at low temperature and confining pressure. The tectonic analysis of calcite twins allows to reconstruct both the directions and differential values of the stress tensors, from decimetre size samples. We thus used inverse analysis of calcite twin data, with an improved process from the Etchecopar's method, to determine paleostresses, along transects perpendicular to each range. Results from calcite twin inversion were validated with fault slip inverse analysis in sampled sites. The obtained results highlight various phenomena: 1- At a same distance to the collision front, the differential stress values of the three studied orogeneses are roughly the same. 2- When leaving the collision front to the far field, the compressional state of stress (σ3 vertical) is rapidly changing to a strike-slip regime (σ2 vertical), and then to a perpendicular extension (σ1 vertical) at far field. 3- Differential stress values rapidly decrease in the first 100 km from the thrust front then a more slowly decrease in the plate. 4- The trend of Pyrenean compression is nearly the same all over the plate (N-S), as for the Appalachians (WNW-ESE), whereas the intraplate Alpine compression is fan shaped, from E-W in southern France to NW-SE in Belgium-Netherlands. The fan shape can be attributed to the alpine indenter to the Jura Mountains. Induced stress directions are maintained in the plate, indicating that the intraplate crust performs as a rigid homogeneous material. 5- The intraplate differential stress values varies of $\pm$ 20 MPa. The invoked factors are (1) the crustal and lithospheric thickness variations, (2) the stresses at intrados and extrados of folds due to crustal and lithospheric flexuring, and/or (3) the stress relaxation in already fractured areas.

T52A-0233 1330h POSTER

Interplay between internal deformation of the Gorda plate and spreading rates along the Gorda Ridge

Jason D Chaytor[1] ((541) 737 9002; jchaytor@coas.oregonstate.edu)

Chris Goldfinger[1] ((541) 737 5214; gold@coas.oregonstate.edu)

Robert P Dziak[2] ((541) 867 0175; dziak@pmel.noaa.gov)

Christopher G Fox[3] ((541) 867 0276; Christopher.G.Fox@noaa.gov)

[1]College of Oceanic & Atmospheric Sciences, Oregon State University, 104 Ocean Admin Building, Corvallis, OR 97331, United States

[2]Cooperative Institute for Marine Resources Studies, Oregon State University/NOAA, Hatfield Marine Science Center, Newport, OR 97365, United States

[3]National Oceanic & Atmospheric Administration, Pacific Marine Environment Laboratory, Hatfield Marine Science Center, Newport, OR 97365, United States

Recent work has shown that small tectonic plates or plate fragments act as non-rigid accommodation zones or buffers between the larger plates, absorbing deformation and allowing larger plates to act in a more rigid fashion. Although complex deformation occurring within these zones requires detailed investigation to understand them, they offer the opportunity to investigate fundamental plate forces, to which larger plates may not respond to as dramatically. Within the Gorda plate, an excellent example of a non-rigidly deforming tectonic buffer plate or diffuse oceanic plate boundary, complex internal deformation allows us to ask whether mid-ocean ridge spreading and subduction processes control internal deformation or does internal deformation provide feedback that influences spreading rates of this and other plate systems. A new structural analysis of the Gorda plate based on full-plate bathymetric coverage, augmented by seismic reflection data and earthquake locations, reveals that this region undergoes complex deformation under the influence of the competing and interacting regional and intraplate tectonic forces. Internal deformation of the Gorda plate is accomplished through reactivation of spreading-ridge fabric faults as strike-slip faults, with an overprint of newly-formed and previously unknown second-generation faults. As the plate approaches the subduction zone, we find renewed extensional deformation. Based on these new constraints, we interpret internal deformation of the Gorda plate as a modified flexural-slip buckle, driven predominantly by the N-S compressive stress field created by the continued convergence of the plate between the non-parallel Mendocino and Blanco Fracture Zones. We further suggest a relationship between ridge spreading rates and internal Gorda deformation, in that severe deformation of the plate may be controlling spreading rates along the length of the nearby Gorda Ridge. In other words, accommodation space opening within the plate as a result of the internal deformation is filled by faster spreading along sections of the ridge, rather than opposite as we expected.

T52A-0234 1330h POSTER

Changes in Continental Area Inferred from Space Geodesy

Brian C Hahn[1] (6316321114; bhahn@mantle.geo.sunysb.edu)

William E Holt[1] (6316328215; wholt@mantle.geo.sunysb.edu)

Paul G Silver[2] (2024788834; silver@dtm.ciw.edu)

Corne Kreemer[3] (+33(1)44322257; kreemer@mailhost.geologie.ens.fr)

[1]SUNY Stony Brook, Department of Geosciences, Stony Brook, NY 11790, United States

[2]Carnegie Institution of Washington, Department of Terrestrial Magnetism, Washington D.C. 20015, United States

[3]Collège de France, Europôle de l'Arbois, Aix en Provence 13545, France

Continental area is reduced during continental collision events and increased during rifting and extension. But what is the net effect: reduction, expansion, or neither? To address this question we calculated the present-day areal rate of change for the continents using a global strain-rate model. A finite-element approach with over 24,000 grid elements is used to define the velocity gradient tensor field within all continental plate boundary zones. Over 3,800 GPS velocity vectors, along with Quaternary fault-slip rates, are used to define the deformation field within the plate boundary zones and to define spherical cap motions. Regions near subduction margins, such as the west coast of South America, are corrected for recoverable elastic strain from large seismic events. We calculate an approximate worldwide rate for continental areal change equal to -0.19 $\pm$ 0.02 km^2/yr. The global RMS plate velocity inferred from space geodesy is in good agreement with RMS plate velocity estimates inferred from a three million year average of sea floor spreading rates (e.g., NUVEL-1A). Even allowing for RMS plate velocities to differ by as much as a factor of 2 or 3 over geologic time, our measurement of a net shortening of continental area has far reaching implications. The -0.19 km^2/yr roughly corresponds to continental areal shrinkage of 10% per 100my, or about a factor of 2.5 in a billion years, and if incompressible, causes them to thicken by the same percentage. A negative global rate is not entirely surprising since most continental rifting events produce relatively short-lived continental extension, after which new oceanic crust is created. Thus, plate tectonics preferentially reduces continental area and increases the thickness of continental crust and lithosphere. Assuming that crustal area and crustal thickness have remained roughly constant over time, and that this shrinkage rate is representative, the the worldwide rate of -0.19 km^{2}yr^{-1} implies that about 10 km^{3}yr^{-1} of crustal volume must be added to the margins of continents, through erosion, to balance this shrinkage. This required erosion rate is similar to the worldwide river sediment load, and thus erosion may provide a means of maintaining this balance. An inevitable consequence of reducing continental area, as a fundamental process of plate tectonics, is that continental sediments that sit on top of oceanic lithosphere (apparent continents) must be continuously reincorporated into the continental volume over geologic time in order to maintain constant continental area. Thus the incorporation or addition of oceanic lithosphere into the continental lithosphere, over geologic time, may have a fundamental impact on the character and evolution of the continents. Such a fundamental process may explain why the seismic structure of most Phanerozoic continental lithosphere is essentially oceanic in character.

T52A-0235 1330h POSTER

Dynamics of the Central Mediterranean Region

Sinan Ozeren[1] (ozerens@itu.edu.tr)

William E Holt[2] (631 632 8215; wholt@mantle.geo.sunysb.edu)

A John Haines[3] (haines@esc.cam.ac.uk)

Lucy M Flesch[4] (flesch@dtm.ciw.edu)

[1]Department of Geology, Istanbul Technical University, Istanbul 80626, Turkey

[2]Department of Geosciences, SUNY Stony Brook, Stony Brook, NY 11794-2100, United States

[3]Bullard Laboratories, Cambridge University, Cambridge CB3 0EZ, United Kingdom

[4]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, United States

The Aegean is one of the fastest deforming regions on the planet. The northward motion of the Arabian plate, the westward drift of Turkey, right-lateral shear in Northern Aegean Sea, and complicated deformation patterns in Greece have long been of geophysical interest. In this work we seek to quantify the relative driving forces for active deformation within the Aegean. Specifically, we seek to quantify the role of body forces associated density variations within the lithosphere as well as the role of plate interaction in driving the active deformation there. Our numerical grid covers the entire Aegean region and the Turkish mainland. We first interpolate GPS data with continuous bi-cubic spline functions to define a kinematic solution. The density of grid areas used in the kinematic and dynamic modeling, together with the GPS data, are sufficient to delineate both rapidly deforming and rigid areas. Moreover, the model strain rate tensor field, defined by the fit to the GPS data, is in good agreement with the styles of active deformation inferred from earthquake moment tensor solutions. Our dynamic solutions involve a direct estimate of vertically averaged deviatoric stresses, using a thin-sheet parameterization. The deviatoric stress solution satisfies a set of balance equations for a non-accelerating continuum, where the governing force comes from the lateral variations in the graviatational potential energy, calculated assuming Airy-type isostatic compensation of topography. A second solution to the linear equations, without the body force term, is sought in a formal inversion to define a complete stress boundary solution. The deviatoric stress field associated with the boundary condition solution is added to the deviatoric stress field associated with the gravitational potential energy distribution to define a total solution. In the formal inversion the directions and relative magnitudes of principal axes of the total deviatoric stresses are constrained to be a best-fit with directions and relative magnitudes of principal strain rates, inferred from the interpolation of GPS observations. We obtained quite small vertically averaged deviatoric stress values for Western Turkey of 50-60 bars, which is roughly half of that calculated for the Western United States. The right lateral shear stresses are diffuse across a wide NE-SW trending band connecting the Marmara Sea region to Corinth Strait, where the GPS data show the largest strain rates (around 4.5 x 10-14s-1 within our grid cells). A remarkable feature is that gravitational potential energy distributions alone are sufficient to nearly completely define the right-lateral shear stress pattern in Marmara region. Elsewhere, gravitational potential energy differences and plate interaction act approximately equally to define the deviatoric stress field that drives deformation in the region. Using the vertically averaged deviatoric stress magnitudes from the dynamic solution, and the rates of strain from the kinematic solution, we solve for the vertically averaged effective viscosity field in the Aegean region. The Black Sea shows up as a region of high effective viscosity. Surprisingly the Anatolian block is defined by low deviatoric stress magnitudes, rather than by abnormally high effective strength.

T52A-0236 1330h POSTER

GPS measurements of crustal deformation across the northern Apennines, northern Italy

Richard A Bennett[1] (617 495-7453; rbennett@cfa.harvard.edu)

Pedro Elosegui[1] (617 496-7645; pelosegui@cfa.harvard.edu)

James E Normandeau[1] (617 496-7811; jnormand@cfa.harvard.edu)

Enrico Serpelloni[2] (+39 051 415 1433; serpelloni@bo.ingv.it)

[1]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS 42, Cambridge, MA 02138

[2]Instituto Nazionale di Geofisica, Via D. Creti, 12, Bologna 40127, Italy

Continuous GPS stations within and around the northern Apennines, northern Italy, provide sparse but very precise constraints on crustal deformation associated with Africa, Eurasia, and Adriatic plate interactions. We analyzed data acquired by these stations during the time period of 1996 to 2003.5, finding distributed northwest range-parallel crustal shortening, totaling some 2 mm/yr, and northeast directed crustal extension across the Apennines hinterland, totaling 2.5–3.0 mm/yr or more. Extensional strain rates

vary as a function of latitude within the northern Apennines, with higher strain rates across a narrow belt in the central part of the northern Apennines (latitude ~43N) and lower strain rates across a broader zone further north (latitude ~44N). Northeast directed crustal extension is prominent in the geology and seismicity of the Apennines hinterland, and forms an important observational basis for contemporary geodynamical models describing present-day deformation processes in northern Italy. Range-parallel crustal shortening is less well understood, however, because there are very few geological or seismological indicators of northwest directed crustal shortening for the northern Apennines. On the other hand, combined paleomagnetic and tomographic inferences suggest that the northern Apennines is an orocline, achieving its arcuate shape as a result of progressive bending of an originally straight orogen. The rates and patterns of range-parallel deformation may thus provide important new constraints on geodynamical models for this complex region.

T52A-0237 1330h POSTER

Geophysical Models of Lithospheric Thinning Beneath the Alboran Sea Basin

Gregory A Houseman[1] (+44 113 343 5206; greg@earth.leeds.ac.uk)

Trudi Hoogenboom[1] (trudi@earth.leeds.ac.uk)

[1]School of Earth Sciences, University of Leeds, Leeds LS8 2PF, United Kingdom

The Alboran Sea Basin in the western Mediterranean is a unique example of rapid and relatively extreme lithospheric thinning in the centre of a continental collision zone. Crust in the Alboran Sea Basin was thinned rapidly to 15-20 km at about 20 Ma while thrust faulting continued in the neighbouring Rif and Betic Cordillera. The region of lithospheric thinning is localised to less than 200 km in diameter, and major thrust systems lie almost on annular zones about the centre of the region. The probable cause of such localised lithospheric thinning is gravitational instability of a relatively dense and thick lithospheric root formed by continental collision. Previous numerical models of lithospheric instability have generally focussed on development of sheet-like structures in a 2D instability. Such models do not adequately represent the almost circular shape of the Alboran Sea Basin. Here we describe new models of the lithospheric gravitational instability in cylindrical axisymmetry. The axisymmetric model differs from the plane-strain model in that either central downwelling or central upwelling might be triggered and each can grow at the same rate, but the two possible developments have fundamentally different geological consequences. In particular, if the axisymmetric instability develops as a central upwelling, with peripheral downwelling, lithospheric thinning is concentrated in the central region and convergence develops in the crust above the peripheral downwelling. We examine the hypothesis that the Alboran Sea Basin may have developed by such a mechanism, comparing observations of surface topography and gravity anomalies with predictions of an axisymmetric model.

T52A-0238 1330h POSTER

Interplate and Intraplate Decoupling: A 3D View from Surface Geology and Seismicity, Eastern Hellenic Forearc, Greece

Karen L. Kleinspehn[1] (klein004@umn.edu)

R. M. Russo[2] (ray@earth.northwestern.edu)

[1]Dept. of Geology and Geophysics, University of Minnesota, Pillsbury Hall, Minneapolis, MN 55455, United States

[2]Dept. of Geological Sciences, Northwestern University, 1850 Campus Drive, Evanston, IL 60208, United States

Shallow active seismicity and neotectonic structures reveal important changes in the degree of interplate and intraplate coupling along the convergent Hellenic plate boundary from Crete to Rhodes. The onshore/offshore Pliocene-Holocene surface geology of the Hellenic forearc records three different deformation states: 1) A western segment (western Crete) where incipient continent-continent collision produces shortening under strong interplate coupling; 2) a central segment (central-eastern Crete) partly coupled to Africa where oblique convergence is partitioned into sinistral strike slip and orthogonal shortening which is confined to the accretionary wedge; and 3) an eastern trantensional segment (Rhodes), mechanically decoupled from African oblique convergence, instead reflecting slab rollback and Aegea's southward motion relative to Anatolia. Such along-strike heterogeneity of neotectonic structures suggests each segment should also display distinct crustal-scale stress patterns. Abundant earthquake focal mechanisms provide a means to gauge stress regimes. Shallowly plunging P (compression) and T (tension) axes of crustal events differ systematically along the three forearc segments. Above the brittle-ductile transition ($< 13km$), the western segment records N-S P axes and E-W T axes. In the central Crete transition zone, P and T axes vary, whereas sparse P axes in the decoupled eastern forearc (Rhodes) parallel the NNE plate margin. Below the brittle-ductile transition ($13 < h < 40km$), P axes beneath western Crete trend N-S normal to the subduction trace, signifying interplate coupling given their similarity to plate-convergence vectors. T axes trend WNW consistent with margin-parallel extension at depth due to Africa's northward convergence. Stress patterns reverse for the wrench-dominated transition zone: P axes trend WNW-ESE and T axes trend N-S, indicating that northward convergence is less important than slab roll back. In the transtensional forearc east of Crete, P axes vary, but T axes trend normal (WNW) to the plate margin (NNE), consistent with forces due to rollback. Thus, the maximum compressive horizontal stress, delineated by shallowly plunging P axes, varies both laterally and vertically within the Hellenic forearc. The western coupled forearc segment displays similar P-axis trends at all depths 0-40 km where the base of forearc crust directly overlies subducting African lithosphere. Eastward, variable P axes become systematic below the brittle-ductile transition where Aegean upper mantle lies between the eastern Cretan Moho and the top of the African slab, suggesting vertical intraplate decoupling where upper mantle underlies forearc crust.

T52A-0239 1330h POSTER

Spatio-temporal Evolution of On-going Tokai Slow Thrust Slip Event, Central Japan

Shin'ichi Miyazaki[1,2] (s.miyazaki@stanford.edu)

Paul Segall[2] (segall@stanford.edu)

Teruyuki Kato[1] (teru@eri.u-tokyo.ac.jp)

Jeff McGuire[3] (jmcguire@whoi.edu)

Yuki Hatanaka[4] (hata@gsi.go.jp)

[1]Earthquake Research Institute, University of Tokyo, 1-1 Yayoi-1, Bunkyo-ku, Tokyo 113-0032, Japan

[2]Stanford University, Mitchell Building, Stanford University, Stanford, CA 94305, United States

[3]Woods Hole Oceanographic Institution, Clark South 272A, Woods Hole, MA 02543, United States

[4]Geographical Survey Institute, Kitasato-1, Tsukuba, Ibaraki 305-0081, Japan

We investigate an on-going slow thrust slip event that occurred at a subduction zone along the Nankai Trough off central Japan. The area we investimate, referred as the Tokai seismic gap, is located to the east of the 1944 Tonankai earthquake, which did not slip in the 1944 event. Continuous GPS data from April 1996 to the end of 1999 shows that the stations in this region have secular velocities of $\sim 2cm/yr$ to the northwest relative to the landward plate. The GPS time series show an abrupt increase in rate in late June, 2000. The accelerated rate is currently on-going. We model this non-secular deformation, which we refer to the 2000 Tokai slow slip event, by transient slip at the plate interface and estimate their distribution with Kalman Filter based inversion methods. This event initiated around $(137.3^\circ E, 34.9^\circ N)$ almost at the same time of the onset of volcanic activity on Miyake-jima in late June, 2000. This suggests that the 2000 Tokai slow slip event is triggered by the volcanic activity on Miyake-jima. Then the locus of the slip propagated to $(137.5^\circ E, 34.75^\circ N)$ in second half of 2000, and kept slipping at the maximum rate of $\sim 15cm/yr$ through 2001. The peak slip-rate propagated to around $(137.75^\circ E, 34.9^\circ N)$ in early 2002. The depth of slip zone is $\sim 25km$, which may correspond to the lower edge of the seismogenic zone for the anticipated Tokai earthquake defined from seismicity. The cumulative moment magnitude of the slow slip event to date is $M_W \sim 6.8$. The duration of this event is longer than previously studied slow slip events using GPS data, including the 1996 Bungo slow slip event (about 1 year) and the 1996 and the 2000 Boso slow events (a few weeks).

T52A-0240 1330h POSTER

Interplate Coupling and a Recent Aseismic Slow Slip Event in the Guerrero Seismic gap of the Mexican Subduction Zone, as Deduced From GPS Data Inversion Using ABIC

Shoichi Yoshioka[1] (81-92-642-2646; yoshioka@geo.kyushu-u.ac.jp); Takeshi Mikumo[2] (52-55-5622-4127; mikumo@ollin.igeofcu.unam.mx); Vladimir Kostoglodov[2] (vladi@servidor.unam.mx); Kristine M. Larson[3] (kristine.larson@colorado.edu); Anthony R. Lowry[4] (arlowry@himalaya.colorado.edu); Shri K. Singh[2] (krishna@ollin.igeofcu.unam.mx)

[1]Dept. of Earth and Planetary Sciences, Kyushu Univ., Hakozaki 6-10-1, Higashi ward, Fukuoka 812-8581, Japan

[2]Institudo de Geofisica, UNAM, Ciudad Universitaria, Del. Coyoacan, Mexico City, D.F 04510, Mexico

[3]Dept. of Aerospace Engineering Science, Univ. of Colorado, Campus Box 429, Boulder, CO 80309-0429, United States

[4]Dept. of Physics, Univ. of Colorado, 4222 Monroe Dr #C, Boulder, CO 80303, United States

Displacements associated with a large-scale aseismic slow slip event have been detected at seven continuous GPS stations located in the Guerrero region, southern Mexico for several months during late 2001 to early 2002. We re-analyzed the observed GPS time series data to estimate the displacements and the displacement rates during the interseismic period prior to the slow slip event, by applying an inversion technique using a Bayesian information criterion (ABIC). We then carried out inversion of the re-analyzed data again with ABIC to estimate spatial distributions of the drag rates and the slow slip on a 3-D curved plate interface between the subducting Cocos and the overriding North American plates. The inversion results show that the average direction of the drag rates is N31.3°E$\pm$5.6°, which almost coincides with that of plate convergence in this region. Interplate coupling is found to be very strong down to a depth of about 45 km, indicating a coupling ratio of 0.83 to 0.86 except for a few segments on the model region, and decreases dramatically down below. The drag rates at middle-depth segments increase southeastward, being consistent with the increase in the rate of plate convergence and in the distance to the volcanic front from the Middle America trench. The slow slip detected at the middle-depth and even on the shallowest segment reached about 10 cm in the landward region of the Guerrero seismic gap. We also estimate stress change due to the slow slip event. From these results, we conclude that the slow slip may have invaded a deeper part of the strongly coupled, seismogenic zone at least up to a depth of 24 km. If such slow slip events occurred episodically, it would be possible to delay the time of occurrence of a future large subduction earthquake in the Guerrero gap.

T52A-0241 1330h POSTER

INTERSEISMIC STRAIN ALONG THE SUMATRA SUBDUCTION ZONE: A CASE FOR A LOCKED FAULT PORTION EXTENDING WELL BELOW THE FOREARC MOHO

Martine Simoes[1,2] (simoes@gps.caltech.edu)

Jean-Philippe Avouac[1,2] (avouac@gps.caltech.edu)

Rodolphe Cattin[1] (cattin@geologie.ens.fr)

Pierre Henry[1] (henry@geologie.ens.fr)

Danny Hilman Natawidjaja[2] (danny@gps.caltech.edu)

[1]Laboratoire de Geologie - Ecole Normale Superieure, 24 rue Lhomond, Paris 75005, France

[2]GPS department - California Institute of Technology, 1200 E. California Bvd, Pasadena, CA 91125, United States

A current and most accepted view about the seismogenic zone along subduction zones is that the downdip extent of the locked fault portion would correspond either to the 350°C isotherm if this temperature is reached above the Moho, or to the intersection with the forearc Moho for colder subduction zones [Oleskevich et al., 1999]. This limit would reflect the transition from slip-weakening friction to aseismic stable-sliding, or else ductile flow. In the first case, when the downdip end of the locked zone is temperature-controlled, stable-sliding of quartzo-feldspathic rocks

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would be the controlling factor, while the systematic presence of serpentinite or other hydrated minerals is advocated to explain aseismic interplate slip in the mantle at temperatures much less that the 750°C needed for ductile flow of mantle rocks [Peacock and Hyndman, 1999]. Here, we consider the case of the Sumatra subduction zone where the 53 Myr Indian oceanic crust subducts below an island-arc characterized by a relatively thin crust, with a Moho depth estimated to 23 km. We model interseismic deformation from a creeping dislocation embedded in an elastic half-space, using the back-slip approach. In addition to recently published GPS velocities, we take advantage of recent data on the pattern and rate of interseismic uplift that have been obtained from the study of coral growth [Natawidjaja, 2003; Sieh et al., 1999]. These data are found to put tight constraints on the horizontal position of the downdip limit of the locked fault zone, at 127 +/- 4/2 km from the trench. This position corresponds to a depth between 40 and 58 km and to a temperature of 269°C +/- 155°C, when compared with thermal modeling. So, in this particular setting, the locked fault portion extends well into the mantle. However, temperature is not high enough to advocate stable sliding or ductile flow of unaltered or altered mantle rocks. This case appeals to some reappraisal of the physical control on the depth of the locked fault zone along subduction zones. References. Natawidjaja, D.H., Neotectonics of the Sumatran fault and paleogeodesy of the Sumatran subduction zone., PhD thesis, California Institute of Technology, Pasadena, 2003. Oleskevich, D.A., R.D. Hyndman, and K. Wang, The updip and downdip limit to great subduction earthquakes : thermal and structural models of Cascadia, South Alaska, SW Japan and Chile., Journal of Geophysical Research, 104 (B7), 14965-14991, 1999. Peacock, S.M., and R.D. Hyndman, Hydrous minerals in the mantle wedge and the maximum depth of subduction thrust earthquakes., Geophysical Research Letters, 26 (16), 2517-2520, 1999. Sieh, K., S.N. Ward, D. Natawidjaja, and B.W. Suwargadi, Crustal deformation at the Sumatra subduction zone revealed by coral data., Geophysical Research Letters, 26 (20), 3141-3144, 1999.

T52A-0242 1330h POSTER

Present-day Deformation Across the Southwest Japan Arc: Oblique Subduction of the Philippine Sea Plate and Lateral Slip of the Nankai Forearc

Takao Tabei[1] (81-88-844-8288; tabei@cc.kochi-u.ac.jp)

Manabu Hashimoto[2] (hasimoto@rcep.dpri.kyoto-u.ac.jp)

Shin'ichi Miyazaki[3] (miyagsi@pangea.stanford.edu)

Yusaku Ohta[4] (oota@eps.nagoya-u.ac.jp)

[1]Department of Natural Environmental Science, Kochi University, Kochi 780-8520, Japan

[2]Disaster Prevention Research Institute, Kyoto University, Uji 611-0011, Japan

[3]Department of Geophysics, Stanford University, Stanford, CA 94305-2215, United States

[4]Graduate School of Environmental Studies, Nagoya University, Nagoya 464-8602, Japan

Interseismic deformation of the forearc at an oblique subduction zone may be a mixture of short-term crustal shortening in the direction of plate convergence and long-term/permanent arc-parallel block movement. We estimate long-term/permanent crustal deformation in the Nankai forearc, southwest Japan that would remain after one earthquake deformation cycle at the subduction zone. A short-term deformation caused by oblique subduction of the Philippine Sea plate is modeled based on coseismic fault slips associated with the latest subduction earthquakes at the Nankai Trough, and subtracted from the interseismic crustal velocity field observed by GPS. The long-term/permanent deformation left in the data shows arc-parallel movement of the forearc at a rate of 5-10mm/yr, with its rear side bounded by the Median Tectonic Line (MTL), the arc-parallel strike-slip fault system that separates the forearc from the rest of the overriding plate. We interpret that the forearc movement is driven by the oblique plate convergence and accommodated by steady aseismic slip on the deep portion of fault plane of the MTL. The rate of the forearc movement estimated is consistent with the geological slip rate of the MTL in the late Quaternary, and also with that expected from a slight deflection of slip vector of the latest subduction earthquake from current plate convergence vector.

T52A-0243 1330h POSTER

In-slab Stresses and Damaging In-slab Earthquakes in Southwest Japan

Ikuko Wada[1] (ikukow@uvic.ca)

Kelin Wang[1,2] (kwang@nrcan.gc.ca)

Yuzo Ishikawa[3] (catfish@wa2.so-net.ne.jp)

[1]School of Earth and Ocean Sciences, University of Victoria, PO Box 3055 STN CSC, Victoria, BC V8W 3P6, Canada

[2]Pacific Geoscience Centre, Geological Survey of Canada, PO Box 6000, Sidney, BC V8L 4B2, Canada

[3]Meteorological Research Institute, Japan Meteorological Agency, 1-1 Nagamine, Tsukuba, Ibaraki 305-0052, Japan

The Philippine Sea (PHS) plate subducts obliquely beneath Southwest Japan at a concave seaward plate boundary. The stress regimes of both the overriding and downgoing plates provide critical information on the geodynamics of this plate boundary. We infer the state of stress in the PHS slab at the Nankai and Kyushu subduction zones from earthquake distribution and from newly determined focal mechanisms of in-slab earthquakes that occurred during 1997-2002. The majority of the fault plane solutions used in this study were obtained by the Japan Meteorological Agency. Because of significant network improvements since 1997, these new solutions have a better accuracy than those reported previously. At Nankai, the slab has undergone severe deformation, which we attribute to the buoyancy and mechanical incompetence of the young PHS plate and to the immaturity of the subduction zone. Despite the complex slab geometry at Nankai, a simple stress pattern characterized by a general E-W tension and a parallelism of the tension axes with the local strike of the slab surface is observed. The parallelism indicates that the slab is a stress guide. At Kyushu, the older and colder part of the slab experiences down-dip tension due to a greater slab pull. We propose that the margin-parallel component of mantle resistance to the obliquely subducting young slab at Nankai provides an easterly stretch, acting against the westerly slab-pull of the older part of the slab at northern Kyushu. The interaction between the slab in this stress regime and the overriding plate probably contributes to the roughly margin-parallel E-W compression in the overriding plate. Large in-slab earthquakes occur in a high-seismicity band (the Geiyo-western Kyushu (GWK) seismicity band), the northern part of which approximately separates the Nankai region from the Kyushu region. In this band, the slab experiences the maximum E-W stretching and a sharp bending and is thus in a stress environment favoring large in-slab earthquakes. The temperature and pressure conditions at Nankai allow dehydration reactions in both the slab crust and slab mantle. Facilitated by dehydration embrittlement and driven by tectonic stresses, the M 6.7 damaging Geiyo earthquake of 2001 occurred at the northern end of the GWK seismicity band, rupturing both the crust and mantle of the slab. Using a simple elasto-plastic model of bending stress, we demonstrate that rupture of both crust and mantle of the slab can occur under such conditions.

T52A-0244 1330h POSTER

Coseismic Fault Model of the M6.2 Northern Miyagi Earthquake, Northern Japan, Estimated from Multiple Geodetic Data

Takuya Nishimura[1] (81-29-864-1111; t_nisimura@gsi.go.jp); Tetsuro Imakiire[1] (imq@gsi.go.jp); Hiroshi Yarai[1] (yarai@gsi.go.jp); Taku Ozawa[2] (taku@gsi.go.jp); Makoto Murakami[1]; Masaru Kaidzu[1] (kaizu@gsi.go.jp)

[1]Geographical Survey Institute, Kitasao-1, Tsukuba 305-0811, Japan

[2]Japan Society for the Promotion of Science/ Geographical Survey Institute, Kitasato-1, Tsukuba 308-0811, Japan

A shallow M6.2 earthquake occurred in Miyagi prefecture, northern Japan on July 26, 2003. The focal mechanism roughly shows that the earthquake released strain accumulation in the northeastern Japan arc under the stress regime of east-west compression due to the interplate locking on the subducting plate boundary between the Pacific and the North American plates. The coseismic displacement was observed not only by the GEONET (continuous GPS) but also by campaign GPS, leveling, and InSAR. We have a plenty of the deformation data by multiple geodetic measurements, which is unusually abundant as the M6-class earthquakes. It is noted that the leveling route in the epicentral area was surveyed on the day just before the earthquake by chance, and that it was resurveyed just after the earthquake. Though correlation of SAR images by RADARSAT is poor except urban area, SAR interferograms provide high resolution of surface displacements which reach 24 cm. We construct coseismic rectangular fault model by inversion of all available geodetic data. The number of observation points used in the inversion are 20, 17, 49 and thousands for continuous GPS, campaign GPS, leveling, and InSAR, respectively. We found that two thrust-type faults whose strike differs by 60° are necessary to reproduce the observed deformation. Because rake angle of two faults is different by only 15° , azimuth of slip vectors is significantly different between two faults. It suggests heterogeneity of stress field in the hypocentral region, which cannot be explained by the interplate coupling on the subducting plate boundary. Two faults having different orientation may be supported by apparent disagreement of focal mechanisms estimated from initial phase of P wave and CMT waveform inversion. Seismic moment for both faults is 1.8×10^{18} Nm (M_w 6.1), assuming rigidity of 30 GPa.

T52A-0245 1330h POSTER

A Physical Model for the Motion of the Sierra Nevada-Great Valley Block

Pippa L Whitehouse[1] (pippaw@earth.ox.ac.uk)

Philip C England[1] (Philip.England@earth.ox.ac.uk)

Greg A Houseman[2]

[1]Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, United Kingdom

[2]School of Earth Sciences, The University of Leeds, Leeds LS2 9JT, United Kingdom

We investigate the motion of the Sierra Nevada–Great Valley block, treating it as a rigid inclusion within a viscous lithosphere, whose motion is governed by external in-plane forces applied to the boundary of the North American plate. This aseismic block of continental lithosphere lies within the wide zone of deformation arising from motion along the Pacific–North America plate boundary adjacent to California. Geodetic studies have shown that the motion of the block can be approximated by rigid body motion, and low surface heat flow measurements strengthen the argument that this may be treated as a region of higher viscosity than the surrounding continental lithosphere. We use a numerical method, employing the thin viscous sheet approach, to solve for the motion of a rigid block of a given aspect ratio lying within a non–newtonian fluid undergoing simple shear. We also use a force balance approach to place theoretical bounds upon the motion of such a block in a viscous fluid. We obtain similar results from the two methods for a range of physical parameters. We wish to constrain the value of the stress–strain exponent, n, in the constitutive equation which governs the flow of the lithosphere, as represented by a non–linear viscous fluid. We compare GPS estimates for the velocity of the Sierra Nevada–Great Valley block, relative to a North-America-fixed reference frame, to our estimates for the velocity of a rigid block, with the same aspect ratio as the Sierra Nevada–Great Valley block, embedded within viscous fluids of varying power–law rheologies. The best fit to observed velocities, for both numerical and theoretical approaches, is obtained when n=3. This result is corroborated by the close agreement between GPS velocity profiles, taken across the Great Valley and perpendicular to the strike of plate boundary motion, and profiles from our numerical method when n=3.

T52A-0246 1330h POSTER

Constraints on the mechanics of the Southern San Andreas fault system from GPS velocity and stress

Thorsten W Becker[1] ((858)534-4643; tbecker@igpp.ucsd.edu)

Jeanne L Hardebeck[2] (jhardebeck@usgs.gov)

Greg Anderson[3] (ganderso@gps.caltech.edu)

[1]IGPP, Scripps Institution of Oceanography, University of California San Diego, IGPP-0225, 9500 Gilman Drive, La Jolla, CA 92093, United States

[2]United States Geological Survey, 345 Middlefield Road, MS 977, Menlo Park, CA 94025, United States

[3]United States Geological Survey, 525 South Wilson Avenue, Pasadena, CA 91106, United States

We use Global Positioning System (GPS) derived velocities and stress-orientations to study the distribution of long-term slip on the system of faults comprising the southern California plate boundary region. Of particular interest is how slip is partitioned over multiple earthquake cycles between the San Andreas Fault (SAF), the San Jacinto Fault (SJF) and the Eastern California Shear Zone. Some prior paleoseismologic and geodetic work places the majority of slip on the SAF. Other studies, however, find that the SJF accommodates about half of the slip in the south, implying half as much slip on the San Bernardino segment of the SAF. Two new data sets are used to further constrain the mechanics of the SAF. The first is the Southern California Earthquake Center's geodetic velocity field version 3 (Shen et al., 2003), which includes much improved coverage over prior models. The second is a regional map of stress field orientations at seismogenic depths, as determined from an inversion of earthquake

focal mechanisms. While GPS data has been used in similar studies, this is the first application of stress field observations to this problem. We construct a simplified version of the southern California fault system, and model the surface velocities using a block model with elastic strain accumulation, following Meade et al. (2002). Additionally, we model the stress orientations at seismogenic depths, assuming that the stress field results from the loading of active faults. An inversion for fault slip rates is performed to simultaneously fit the GPS and stress observations. The model fit to the data is good in general, indicating that a simple mechanical model can capture both observed interseismic strain and stress accumulation. We evaluate the sensitivity of the slip rate solutions to the different datasets and identify "anomalous" fault segments with stresses that deviate from our simple loading model.

T52A-0247 1330h POSTER

Reinterpreting Stress Orientations Near the San Andreas Fault

Jeanne L Hardebeck[1] (jhardebeck@usgs.gov)

Andrew J Michael[1] (michael@usgs.gov)

[1]USGS, 345 Middlefield Rd MS 977, Menlo Park, CA 94025, United States

The strength of the San Andreas Fault (SAF) and the orientation of stress in its vicinity are controversial. Two end-member models have been proposed: the strong fault model (SAF strength equivalent to laboratory samples) and the relatively weak fault model (SAF an order of magnitude weaker than the surrounding crust). These two models predict maximum compressive stress axes at low angle (∼30°) or at high angle (∼80°) to the fault strike, respectively. Several recent studies have attempted to test these models by inverting the focal mechanisms of small earthquakes for stress orientation near the SAF, but are inconsistent as to which model is supported. Particularly at odds are two studies in southern California (Hardebeck and Hauksson, 1999, 2000; and Townend and Zoback, 2001) that use identical focal mechanism data but reach opposite conclusions. We investigate whether the disagreement between studies comes from discrepancies in the observed stress orientations, which would indicate flawed methodology, or from differences in interpretation. Townend and Zoback proposed that the stress orientations reported in their study are different from those of Hardebeck and Hauksson due to the use of different schemes for spatially binning the seismicity for inversion. We test this idea by comparing the results of the two studies over the entire region, and find that the stress orientations are actually very similar, usually to within the uncertainty of the inversion results. The largest differences occur in regions with few earthquakes, as the two techniques mainly differ in how stress orientations are assigned to the areas between earthquake clusters. The inconsistency between the studies therefore lies in the interpretation. The stress orientations reported by both studies are often at intermediate angles (∼40-60°) to the SAF, not consistent with either the high angle or the low angle model, which understandably has confused the interpretation of these results. We perform two additional stress inversions on a high-quality focal mechanism data set for southern California, obtained using a new focal mechanism technique (Hardebeck and Shearer, 2002.) In one inversion, we stack stress orientation vs. distance profiles across all segments of the SAF, to cancel out signals not related to the SAF. In the other, we bin the seismicity using cluster analysis. In both experiments, we again obtain intermediate angles near the SAF. Similar intermediate angles have also been observed in central and northern California (Provost and Houston, 2001, 2003). Neither the strong fault nor the relatively weak fault model satisfactorily describes the SAF. Alternative models are needed which can explain the intermediate stress angles along much of the fault. One such model is a slightly weak SAF, with a coefficient of friction approximately half that of strong faults, or containing pore fluids at elevated but sub-lithostatic pressure. Alternatively, observed stress rotations caused by earthquakes suggest low deviatoric stress magnitude at depth, and variable stress orientation through the seismic cycle due to tectonic loading and seismic release. In this low-stress model, all active faults must be weak, and the observed stress orientations along the SAF reflect its loading state and earthquake history, not its strength.

T52A-0248 1330h POSTER

Absolute Strength of the San Andreas Fault Inferred From 3D Loading Simulation and Seismological Data Analysis

Toshiko Terakawa[1] (81-3-5841-8331; terakawa@solid.eps.s.u-tokyo.ac.jp)

Mitsuhiro Matsu'ura (81-3-5841-4318; matsuura@eps.s.u-tokyo.ac.jp)

[1]Department of Earth and Planetary Science, University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

Heat flow observations and inferred tectonic stress orientations along the San Andreas fault system in California have raised a controversy about its absolute strength. In the last decade many mechanical models of the San Andreas fault have been proposed to explain the orientations of the axis of maximum horizontal compression. In this study we numerically computed the absolute stress fields around the San Andreas fault on the basis of the elastic dislocation theory and examined the relation between the pattern of the stress field and the absolute fault strength. We also investigated spatial changes in seismic activity and orientation of the axis of maximum horizontal compression around the fault to estimate the absolute fault strength. The strike of the San Andreas fault system is nearly parallel to the direction of relative plate motion (N40W) except for the big bend segment in Southern California. In Northern and Central California the San Andreas fault is simply modeled by an infinitely-long, pure strike-slip interface that divides the elastic surface layer overlying a viscoelastic substratum in two plates. In tectonic loading simulation we specify an absolute fault strength distribution on a model segment of the plate interface. The driving force of this system is steady slip at 40 mm/yr on the remaining parts of the plate interface. Through this simulation we can realize a steady stress field around the fault, caused by the steady slip with a frictional resistance at the plate interface. The background absolute stress fields in Northern and Central California are obtained by adding the litho-static pressure to these steady stress fields. From comparison of the computed absolute stress fields and spatial seismicity changes, we can estimate relative strength of these segments (e.g., the northern locked segment is about three times as strong as the central creeping segment), but not absolute strength. At the big bend segment in Southern California, on the other hand, the fault strike is oblique by 20 degrees to the direction of relative plate motion. In this case we model the fault system by an oblique transcurrent fault segment that connects the northern and southern semi-infinitely long, pure strike-slip plate interfaces. The driving force of this system is steady slip at 40 mm/yr on the northern and southern semi-infinite plate interfaces. At the oblique transcurrent segment the relative plate motion has a convergent component, which cannot be released by fault slip motion. Therefore, in tectonic loading simulation, the stress field caused by the convergent component increases linearly with time. In reality, the background absolute stress around the big bend segment is maintained at a constant level, since the tectonic stress caused by plate convergence is accommodated by inelastic crustal deformation and/or thrust faulting in the surrounding area. On the basis of such an idea, we computed the absolute stress field around the big bend segment, and compared the results with observations to determine the absolute strength of the San Andreas fault in Southern California.

T52A-0249 1330h POSTER

Detailed Stress Analysis of the Tjörnes Fracture Zone in Northern Iceland, Using Microearthquakes.

Björn Lund[1] (bjorn.lund@geo.uu.se)

Ragnar Slunga[1] (slunga@geofys.uu.se)

Reynir Bödvarsson[1] (reynir.bodvarsson@geo.uu.se)

[1]Dep. of Eart Sciences, Uppsala University, Villavägen 16, Uppsala 752 36, Sweden

The Tjörnes fracture zone in northern Iceland is an oblique, right-lateral transform zone connecting the offshore Kolbeinsey Ridge to the west with the Icelandic Northern Rift zone to the west. Seismicity is mostly confined to two major zones, the Grimsey lineament to the north and the Husavik-Flatey fault to the south. The Husavik-Flatey fault is an old, well established strike-slip fault whereas the Grimsey lineament is considered to be the early stages of the formation of a new major fault. This study presents a detailed mapping of the state of stress in the Tjörnes fracture zone using inversion of large numbers of microearthquake focal mechanisms. We show significant variations in the direction of the stress field along strike of the Husavik-Flatey fault and also in the Grimsey lineament. These variations are interpreted in terms of plate boundary deformation. We apply two different methods of stress inversion, one of which is sensitive to the strength of the fault system, and present an analysis of the results in terms of relative fault strength.

T52A-0250 1330h POSTER

New Insights on Stress Rotations From a Forward Regional Model of the San Andreas Fault System Near its Big Bend in Southern California

Delphine D Fitzenz[1] (+1(650) 329 5533; fitzenz@usgs.gov)

Stephen A Miller[2] (+41 1 633 2621; miller@erdw.ethz.ch)

[1]USGS, MS 977 345 Middlefield Rd, Menlo Park, CA 94025, United States

[2]Geophysics Institute ETHZ, ETH Hoenggerberg, Zurich 8093, Switzerland

Understanding the stress field surrounding and driving active fault systems is an important component of mechanistic seismic hazard assessment. We develop and present results from a time-forward 3-dimensional model of the San Andreas Fault system near the Big Bend in Southern California. We assess the model boundary conditions by comparing model and observed tectonic regimes, and explore the forward model of earthquake generation along these fault segments to target measurable properties. We investigate how slip along the faults perturbs stress orientations, and how stress orientations may allow inferences on the stress state. We use a quasi-static fault model [Fitzenz and Miller, 2001], where GPS-constrained tectonic loading drives faults modelled as viscoelastic bodies embedded in an elastic half-space [Fitzenz and Miller, 2003] mostly sealed from the surrounding rocks and subjected to ductile compaction and shear creep. We show that a transpressive tectonic regime develops southwest of the model Big Bend as a result of the loading boundary conditions and migrates toward the Bend due to slip along the model fault. Stress transfer from fault slip is shown to transiently induce significant perturbations in the local stress tensors (where the slip profile is very heterogeneous). These result in off-fault tectonic regimes and optimal orientations for faulting that differ from those generally prevailing in the area around the faults. These transient perturbations in the local stress field then disappear when subsequent model earthquakes smoothen the slip profile. Maps of maximum shear stress show artificial stress concentrations near the bend, and emphasize that future models should include a more continuous representation of the model faults. When no material weakness is considered, results show that hydrostatically pressured intact rock is very difficult to break from the loading boundary conditions.

T52B MCC: Level 1 Friday 1330h

At the Seismogenic Front: Dynamic Processes at Convergent Margins IV Posters *(joint with G, S)*

Presiding: **K Gamage,** University of Florida**; C Rowe,** University of California, Santa Cruz

T52B-0251 1330h POSTER

Receiver Function Study of the Hellenic Subduction Zone

X Li[1]; R Kind[1] (kind@gfz-potsdam.de); G Bock[1]; A Vafidis[3]; H-P Harjes[2]; W Hanka[1]; K Wylegalla[1]; M van der Meijde[4]; X Yuan[1]; F Sodoudi[1]

[1]GFZ Potsdam, Telegrafenbeg, 14473 Potsdam, Germany

[2]Universität Bochum, Institut für Geophysik, 44780 Bochum, Germany

[3]Technical University of Chania, Department of Mineral Resources, Chania 123, Greece

[4]Institut für Geophysik, Höngerberg, 8096 Zuerich, Switzerland

We use data of recently installed broadband seismographs on the islands of Crete, Gavdos, Santorini, Naxos and Samos to constract receiver function images of the crust and upper mantle from the south of Crete into the Aegean Sea. The subducting African plate is clearly imaged at 44km below Gavdos, about 70km below Crete and nearly 100km beneath Santorini. The Moho depth is determined from direct conversions and crustal multiples. It is 31-34km deep below southern and eastern Crete, and 32-39 below western and northern Crete. The Moho signal in western and northern Crete is reversed, possibly indicating velocity reduction instead of increase at the Moho. This phenomenon could be caused by hydration and serpentinization of the mantle peridotite in the forearc. The crustal thickness at Gavdos, south of Crete in the Libyan Sea is only 26km. The Moho in the central and northern Aegean, at Naxos and Samos is at 25 and 28km depth, respectively. S receiver functions are at present analysed to produce an image of the upper mantle unspoiled by crustal multiples.