G21A-08 0945h INVITED

Sub-Daily to Interannual Geocenter Motion - Direct and Inverse GPS Results

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The motion of center-of-mass (CM) of the entire Earth system with respect to the surface of the solid Earth is a consequence of mass redistribution on the surface and in the interior. Understanding of such motion is important for the definition and maintenance of the origin of global geodetic reference frames. Accurate measurements of such motion can also provide us with a window of opportunity to infer a global mode of mass variation with the largest spatial scale. In certain cases, determination of geocenter motion is essential when the goal is to know the complete mass variation spectrum. Driven by surface mass variation, the motion of CM with respect to the center-of-figure (CF) of the solid Earth surface has a one-to-one correspondence with degree 1 surface mass load. However, geodetic tracking networks have only finite number of stations, and can be very sparse in many cases. The motions of CM with respect to various networks therefore will be different from that with respect to CF and different among themselves. The network-based measurements will be further complicated by higher degree surface load induced deformation. These issues will be examined as we report our direct and inverse measurements of sub-daily to interannual geocenter motions through GPS orbit dynamics and relative surface deformation. We will also discuss implications of geocenter motion on the study of surface mass variations using time-variable gravity data.

G21B MCC: Level 1 Tuesday 0830h

Insights Into the Earthquake Cycle I Posters *(joint with OS, S, T)*

Presiding: **S L Hamilton,** University of Durham**; J T Freymueller,** University of Alaska, Fairbanks

G21B-0257 0830h POSTER

Interseismic Displacements: Cycle Invariance, Slip Rate, and Rheology

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Geodetic data are commonly interpreted in terms of strain accumulation on faults. Often such interpretations are guided by simple models of interseismic displacements near an infinite strike slip fault (e.g. Savage and Prescott, 1978). These models assume relatively simple rheologies and that the system is in a cycle invariant state, with periodic ruptures such that the displacements throughout the seismic cycle do not vary from one cycle to the next. The displacements are given by perturbations to an average arctangent displacement profile, parameterized by the slip rate and locking depth of the fault. We explore the relationship between cycle invariance, changes in slip rate, and rheology to inferences of slip rate, locking depth, and rheology in models of infinite faults with given histories and sizes of ruptures. The number of seismic cycles required to attain cycle invariance is a function of the strength of the system (parameterized by the Maxwell relaxation time, τ_M) and the recurrence time of the ruptures (period, T). In systems with $\tau_M \ll T$ the invariant average arctangent curve is established over very few seismic cycles. However, for $\tau_M \approx T$ or $\tau_M > T$, it takes many seismic cycles to establish cycle invariance. A consequence of this is that it is easy to confuse a large postseismic relaxation signal (low τ_M) calculated ignoring all but the latest earthquake with a periodic system and a small post-seismic relaxation signal (high τ_M). During transition to cycle invariance, the average stress level of the system changes by an amount $\Delta\sigma$, determined by τ_M, T, and the stress drop in a rupture (σ_{eq}); $\Delta\sigma$ is independent of the magnitude of the initial background stress. For low τ_M, $\Delta\sigma$ is negligible compared to σ_{eq}, but may be much larger than σ_{eq} for high τ_M. A change in slip rate on a fault, accommodated by a change in recurrence time or σ_{eq}, tends to force the system toward a new average stress. For weak rheologies, changes in slip rate are negligible as the system establishes cycle invariance quickly. However, for stronger rheologies, it takes many seismic cycles to attain cycle invariance, and during the non-invariant transitional time, inferences of slip rate, locking depth, and rheology will be incorrect.

G21B-0258 0830h POSTER

Stress-Driven Earthquake Cycle Model of the Active Taiwan Collision Zone

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We have developed a 2-D earthquake cycle model for compressional deformation in Taiwan in which active faults slip in response to the stresses in the lithosphere. The earth is modeled as an elastic lithosphere overlying a Maxwell viscoelastic asthenosphere. Slip on major earthquake-producing faults is modeled with sudden periodic slip at a specified recurrence interval. Coseismic rupture is modeled as a full stress-drop. Creeping faults slide at zero resistive shear stress throughout the earthquake cycle. The purpose of our modeling is to infer the geometry of active faults and partitioning of slip-rates among the faults. We seek a model that is consistent with surface deformation measured by GPS, deformation patterns at depth inferred from earthquake focal mechanisms, and longer-term geologic data such as paleoseismology and subsurface structure revealed by reflection seismology. Our study focuses on central Taiwan where an extensive GPS network has recorded preseismic, coseismic, and postseismic deformation associated with the Mw = 7.6, 1999 Chi-Chi earthquake. Active deformation in central Taiwan is concentrated mainly in two regions: the Longitudinal Valley of eastern Taiwan, which is thought to be the suture zone between the Philippine Sea Plate and the Eurasian continental margin, and the western fold and thrust belt. Interseismic deformation recorded with GPS for seven years leading up to the Chi-Chi earthquake displays high shortening rates of about 35 mm/yr across the Longitudinal Valley and subsidence of up to 15 mm/yr. About 25 mm/yr of shortening is occurring across the western fold and thrust belt. We model this deformation with slip on an eastward dipping Longitudinal Valley Fault and slip on a ramp-decollement geometry under the western fold and thrust belt. We find that the data is best explained with a decollement that dips about 10° under the western foothills and then dives down at a steeper angle of approximately 40° under the Central Ranges. In our model the decollement creeps continuously throughout the earthquake cycle and the frontal ramp breaks periodically in large earthquakes and is locked interseismically. The Longitudinal Valley fault creeps between 0 and 11 km depth and between 20 and 30 km. The fault is locked interseismically between 11 and 20 km. The long-term slip rate on the Longitudinal Valley fault is nearly twice the long-term slip rate on the frontal ramp under the western foothills. This viscoelastic cycle model explains the horizontal and vertical interseismic GPS data and deformation patterns at depth inferred from focal mechanisms of earthquakes occurring just before and just after the Chi-Chi earthquake. The long-term uplift rates are also consistent with the general patterns inferred from dated uplifted terraces. We also compare the fault geometry obtained form the stress-driven cycle model with inversions of GPS data for fault geometry using standard kinematic dislocation models in which the slip is prescribed as a displacement discontinuity rather than solved for as in the stress-driven cycle model. A bootstrap analysis is performed using the kinematic model to identify a range of solutions that fit the data satisfactorily. We show that many of the fault geometry models, which fit the data using the kinematic model, do not fit the data with the stress-driven model. This indicates that we can better constrain the range of possible models by enforcing stress boundary conditions on the faults.

G21B-0259 0830h POSTER

Seven big strike-slip earthquakes

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We examine seven large ($M_w > 7$) strike-slip earthquakes that occurred since the beginning of ERS 1 and 2 missions. We invert GPS observations and InSAR interferograms and azimuth offsets for coseismic slip distributions. We explore two refinements to the traditional least-squares inversion technique with roughness constraints. First, we diverge from the usual definition of “roughness” as the average roughness over the entire fault plane, and allow “variable smoothing” constraints. Variable smoothing allows our inversion to select models that are more complex in regions that are well-resolved by the data, while still damping regions that are poorly resolved. Second, we choose our smoothing parameters using the $_jR_i$ criterion. The $_jR_i$ criterion draws on the theory behind cross-validation and the bootstrap method. We examine the theoretical basis behind such methods and use an analytical approximation technique for linear problems. We provide maps of model variance and spatial averaging scale over the fault plane, to explicitly show which features in our slip models are robust. We examine the 1992 Landers (CA), 1995 Sakhalin (Russia), 1995 Kobe (Japan), 1997 Ardekul (Iran), 1997 Manyi (Tibet), 1999 Hector Mine (CA), and 2001 Kunlun (Tibet) earthquakes. We compare features of the slip distributions such as the depth distribution of slip, the inferred magnitude and the degree of heterogeneity of slip over the fault plane, as resolved by the available InSAR and GPS data. We end with a brief description of the data coverage required for future earthquakes of similar size if we want to infer some of the above quantities to within a given confidence interval. We describe both the number of InSAR scenes and the distribution of GPS points that would be required, based on theoretical treatments of the fault plane/data point geometry using the $_jR_i$ method.

G21B-0260 0830h POSTER

3-D Viscoelastic FEM Modeling of Postseismic Deformation Caused by the 1964 Alaska Earthquake, Southern Alaska

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To complement previous modeling efforts to understand the postseismic deformation following the 1964 Alaska earthquake, we are implementing a three-dimensional viscoelastic model using the Finite Element Method. Rapid postseismic uplift, as much as 125 cm, occurred on the central part of the Kenai Peninsula over the 35 years following the earthquake. Recent precise GPS observations show heterogeneous plate coupling, and a vigorous ongoing postseismic response to the 1964 earthquake. Past models of the postseismic deformation have focused on afterslip models because earlier viscoelastic-only models did a poor job at predicting the cumulative uplift observations, but this might be due to unrealistic assumptions for the model geometry. We are working toward a realistic 3D viscoelastic model that, in concert with afterslip models, can be used to understand how much each component contributes to the total postseismic deformation. Our model suggests that viscoelastic relaxation contributes to the total 30 years postseismic uplift moderately in the Kodiak region (40 %), slightly in the western Kenai Peninsula (<20 %) and not significantly in the northern Kenai Peninsula (<10 %). Most of the observed total uplift in Kenai Peninsula must be explained by afterslip. The depth of afterslip (30-70 km) is deeper than that of coseismic rupture (10-25 km). Some recently observed trenchward horizontal deformation far inland from the trench is explained by the viscoelastic response of the 1964 earthquake. But transient slip is required to explain the large trenchward motion in the northern and western Kenai Peninsula.

G21B-0261 0830h POSTER

Spatio-temporal distribution of interplate coupling in southwest Japan deduced from inversion analysis

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We obtain the spatio-temporal distribution of the slip on the subduction interface of the Nankai trough over an entire earthquake cycle, using geodetic data (including leveling, triangulation and trilateration, sea level, and GPS surveys) observed during the last 100 years in southwest Japan. We develop a new inversion method that can treat the long-term crustal deformations, the coseismic earthquake displacements and the stress relaxation of the viscoelastic asthenosphere. From this analysis, we obtain a model that shows post-seismic afterslip on the deeper part of the plate interface following the 1946 Nankaido earthquake. The significant afterslip is found beneath central Shikoku and totals about 0.8m. The slip deficit rate during the interseismic period is 5∼6 cm/year in the N50°W∼N60°W direction, which is consistent with the relative plate motion between the Philippine Sea and the Amurian plates. A strongly coupled region is found in the shallower portion (<30 km), and the slip deficit rate has a maximum at a depth of about 20 km. The interplate coupling is very weak on the plate interface deeper than 30 km. The amount of slip deficit reaches about 3.3m off Shikoku and about 2m off the Kii peninsula 50 years after the 1946 earthquake. This suggests that fault healing and full interplate coupling has occurred by this time along the Nankai trough.

G21B-0262 0830h POSTER

Diatom-based elevation transfer function along the Pacific coast of eastern Hokkadio, northern Japan - an aid in paleo-seismic study along the coasts near Kurile subduction zone

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This paper provides a training data set for diatom-based elevation transfer functions, which are applicable to paleoseismic studies at southwestern Kurile subduction zones, northern Japan. Contemporary diatom samples were collected from four transects at Akkeshi and Onnetoh salt marshes along the Pacific coast of eastern Hokkaido. The relationships between diatom species and environmental variables were elucidated by canonical correspondence analysis (CCA) and partial CCAs. Partial CCAs associated with Monte Carlo permutation tests show that elevation accounts for a significant portion of the total variance in the diatom data. Therefore, statistically significant transfer functions quantifying the relationship between contemporary diatom assemblages and elevation can be developed. Diatom-based transfer functions (DBTFs) were developed using weighted averaging and partial least squares (WA-PLS) and applied to fossil diatom assemblages from Onnetoh estuary. The reconstructed curve of elevations contains at least three obvious emergence and DBTFs evaluated the magnitude of the three emergences as approximately 80 cm. The results are consistent with paleoecological data produced by previous studies. If these cycles represent subsidence during an interseismic period and uplift associated with interplate earthquake along the Kurile subduction zones, DBTFs at salt marshes of eastern Hokkaido can contribute to reconstruction of the recurrence intervals and the magnitudes of earthquakes.

G21B-0263 0830h POSTER

Evidence of Possible Precursor Events for Mega-thrust Earthquakes on the West Coast of North America

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Megathrust earthquakes in western North America may be preceded by precursors several years ahead of the main event. For example on March 27, 1964, a 9.2 magnitude (on the Richter scale) earthquake occurred on the coast of Alaska. Changes in foraminifera and diatom biotas provided evidence of a precursor to this earthquake, thereby detailing a previously unknown sequence of events. We describe further evidence from marshes in Turnagain Arm, Alaska, USA and farther south in Netart's Bay, Oregon, USA; this is the first time that two widely spaced locations have been examined for precursors. The Alaska earthquake offers the possibility to compare a modern sequence (1964) of events with the geologic record. The Netart's Bay marsh has experienced no modern earthquake that could be used for comparison, but the nature of mega-thrust earthquakes implies that the modern and ancient events should be physically similar. The new cores examined from Turnagain Arm include both the 1964 earthquake and an event identified and dated at 1800yBP. The foraminifera and thecamoebian biota change from a forest sequence to a mildly brackish sequence just before the 1964 event; this zone was dated as being 15 years or less in length using Pb210 and Cs dating techniques. The event at 1800yBP was also associated with a similar transition indicating a small subsidence just before the major subsidence event. In Netart's Bay a new core was taken from a previously cored site because the chronology had already been determined by carbon-14 dating and also because at least four events were known to have occurred over the last 3000 years. The new core had four visual lithological transitions of which three were from marsh peat to mineralic deposits (possibly deposited by tsunamis) and back to a marsh deposit. Foraminifera indicated that these units represented high marsh transition to lower marsh, the earthquake event, and then rebounding back into marsh deposits. Sand deposits with either no or few foraminifera marked the tsunami/earthquake intervals. These transitions in two widely separated geographical areas indicate that similar mechanisms operate for large megathrust earthquakes from Alaska to Northern California in the Cascadia Subduction Zone thus implying that precursor events also occur and be detected by foraminiferal zonations all along this area as well. In a recent newspaper article scientists from the west coast suggested that "slow" or "silent" earthquakes they had measured with tiltmeters might be indicators of megathrust earthquakes. The transitions we document may be the prehistoric representations of these "silent" quakes. Foraminiferal evidence may help provide more accurate positioning of seismometers along the west coast of North America and therefore lead to more precise and timely earthquake predictions.

G21B-0264 0830h POSTER

Repeating Slow Slip Events Which Correlate Deep Low-Frequency Tremor Activity in Southwest Japan

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Non-volcanic deep low-frequency tremors are observed along the Nankai trough subduction zone, Southwest Japan (Obara, 2002). This observation provides us a new point of view in seismotectonics at subduction zones. Recently, Obara and Hirose (2003) found the following characteristics in the tremor activity. First, the tremor is not distributed homogeneously in the narrow belt-like zone along the strike of the subducting Philippine Sea Plate but some clusters exist in the zone. Second, the major activity of most clusters repeats periodically. Here we report the observed crustal tilt changes which correlate the tremor activity. These crustal deformations can be explained by repeating slow slip events at the bottom end of the transition zone on the plate interface. The tremor activity is observed by high-sensitivity seismograph network, NIED Hi-net. Every Hi-net observatory is equipped with a high-sensitivity accelerometer, whose long period horizontal component can be analyzed as ground tilt. One of the most active clusters is located on the western Shikoku area, where the major tremor activity repeats with about a half-year interval. For two years from the beginning of 2001, the major tremor emerged four times, i.e., January and August 2001, and February and August 2002. During these active periods, we found slow tilt changes which last 2-3 days around the source area of the activity. The tilt change is about 0.1 μrad in maximum. The spatial pattern of the tilt changes suggests that a slow slip event, which accompanies the tremor activity, occurs near the plate boundary at depth. We estimate the fault parameters for each period, which can explain the observed tilt changes. The estimated slow slip fault is located around the tremor cluster. The moment magnitudes of the events are estimated to be 5.9. Expected surface displacement from this fault model is 1-2 mm in maximum, which is in accordance with the fact that little change is observed by GSI's nationwide GPS network. We conclude that the tremor activities and the slow slip events occur simultaneously and quasi-periodically at the deeper part of the subduction zone, as seen at Cascadia subduction zone (Rogers and Dragert, 2003).

G21B-0265 0830h POSTER

Reexamination of interplate coupling model in the Tokai region,based on the GPS data

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The slow slip event is detected by continuous GPS measurements in the Tokai region, central Japan, where is the subduction zone of the Philippine Sea Plate (PHS), in 2001(Ozawa et al., 2002). Also a high-dense seismological network makes clear the plate boundary structure in this region with more detail. From such background, we reexamined about the interplate-coupling model based on the GPS measurements in the period of 1997 to 2000. Generally, as the PHS is subducting northwestward in the Suruga-Nankai Trough, southern central Japan, horizontal displacements with 1-2cm/year are detected by the national wide GPS network (GPS Earth Observation Network, GEONET) in the Tokai region (Sagiya et al., 2000). Vertical ground deformation observed by precise leveling, tide measurements and GPS measurements shows clearly a tilt toward trough. As a typical example, vertical movement shows a subsidence of 4-8mm/yr at Cape Omaezaki and an uplift of 3-4mm/yr at Nagoya in western Tokai region. Great thrust earthquakes of magnitude 8 have occurred repeatedly in the period of 100-150 years. Interplate coupling in the Tokai region are discussed from the seismic data by Matsumura [1997], and from the GPS data by Sagiya[1999]. Aoki et al (2003) also estimate the interplate coupling using the vertical deformation detected by GPS measurements, but they discuses the coupling only along the one direction toward northwest. However these back-slip distribution are disaccord each models. We applied the inversion method of Yabuki and Matsu'ura(1992) and estimated distribution of back-slip on the plate boundary. The back-slip model is a way of interpreting interseismic deformation in terms of virtual fault slip on the plate boundary [Savege, 1983]. Geometry of the plate boundary is determined from hypocenter data by Japan Meteorological Agency (JMA). For the inversion analysis, we extracted 70 GPS stations of GEONET in the Tokai region in the period from April 1997 to May 2000,and we process the GPS data at each site using PPP method of GIPSY/OASIS II. Back-slip distributes within 20-25mm/year at the 15-20km depth of the plate boundary, which show the agreement with the convergent rate of PHS plate along the Suruga trough (Miyazaki and Heki, 2001). Maximum back-slip rate is detected in the area between Atsumi Peninsula and Hamana Lake, which is the eastern adjacent area of the 1944 Tonakai earthquake fault (Yamanaka et al., 2003). A back-slip rate is smaller along the Suruga trough than that along the Nankai trough. A subsidence observed at Omaezaki is calculated with more detailed from the back-slip model. However, an uplift detected around western Tokai region is not synthesized completely from our back-slip model. It suggests Niigata-Kobe Tectonic Zone is related to the uplift.

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G21B-0266 0830h POSTER

Vertical Ground Deformation Detected by the Leveling and the Tidal Observation in Tokai Region, Central Japan in 1980 - 2002

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Great earthquakes more than M8 have occurred along the Suruga-Nankai subduction zone of the Philippine Sea Plate (PHS), southeast Japan, every 100 to 150 years. The last events are 1944 M7.9 Tonankai and 1946 M8.0 Nankai earthquakes. Interseismic subsidence is detected along the subduction zone from the precise leveling and tide gauge. Discussion of the occurrence of great earthquake in near feature brought the expanding the measurements and observation of earthquake and ground deformation in Tokai region. Whereas nation-wide dense GPS network (GEONET) makes clear of the ground deformation of contraction in west-northwestward contraction and east-southeastward tilting in Tokai region, no northwestward horizontal displacements are observed since 2001 in the western Tokai

region. Slow slip event (SSE) toward trough is discussed (Ozawa et al., 2002). Precise leveling and line length measurements also suggest the episodic changes with time interval of 4-5 years in the late 20 years (Kimata and Yamauchi, 1999; Kimata et al., 2001). Moreover pre-seismic ground tilt is suggested in the same area of the 2001 Tokai SSE from the leveling of the day in 1944 Tonankai Earthquake. Meanwhile pre-seismic slip is estimated in the SSE area from the numerical experiment of rock crusher (Kato, 2003). We discuss the episodic change of the ground deformation and the recurrence of the SSE in Tokai region with more detail from the vertical ground deformation detected by precise leveling and tide gauge in the period from 1980 to 2002. Geographical Survey Institute of Japan (GSI) has repeated the precise leveling in Tokai region every year since 1980. Tide gauge measurements have also been continued at more than 10 sites in Tokai region by GSI, Japan Meteorological Agency (JMA) and Aichi prefecture (AP). Time series of vertical movements at the benchmarks are analyzed by spline function and Annual relative sea levels at tide stations are corrected (Savage and Thatcher, 1992). The 2001 Tokai SSE is characterized by the uplift of 3-4cm around Hamana Lake, central Tokai region, which is detected by GPS measurements, precise leveling, and tide gauge measurement (Ozawa et al., 2002; Oota et al., 2003). The same uplift is detected by precise leveling and tide gauge in late 1988, Episodic changes of tilt movements also detected by bore hall tilt meter north Hamana Lake site in 2001 and 1988 (Yamamoto et al., 2003). It is sure that Tokai SSE should be occurred in the central Tokai in 1988. We have one conclusion that SSE has repeated in Tokai region at least in last 20 years.

G21B-0267 0830h POSTER

Imaging depth variations of interplate coupling

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Recent geodetic measurements have revealed that brittle-plastic transition zones (BPTZs) are loci of slow slip episodes. Furthermore, recent seismic observations detected non-volcanic harmonic tremors at the BPTZ. It is important to estimate the depth range of BPTZs and how interplate coupling changes within the BPTZ, not only for understanding the interseismic stress accumulation process in subduction zones but also exploring the causes of slow slip and harmonic tremors. Here we imaged depth variations of interplate coupling in the Nankai trough, southwest Japan, by inverting Global Positioning System (GPS) velocities to gain more insight into the rheology of the BPTZ in subduction zones. Interplate coupling was estimated for three profiles: the source region of the 1946 Nankaido earthquake, that of the 1944 Tonankai earthquake, and the Tokai seismic gap. The results show a gradual decrease of interplate coupling between about 20-25 and 35-45 km depth with a plateau region between 25-35 km for all three profiles. Because there are GPS sites near the trench, the Tokai profile was capable of resolving interplate coupling at shallower depths than the other two profiles. The result from the Tokai profile shows that interplate coupling decreases from full to zero above 6 km depth. The updip limit of the seismogenic zone for the Tokai profile is significantly shallower than expected for the Nankaido profile, consistent with seamount subduction under the accretionary prism.

G21B-0268 0830h POSTER

Spatio-Temporal Variations of Post-Seismic Deformation after the June 2000 Earthquake Sequence in SW Iceland

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We observe post-seismic deformation over at least two spatio-temporal scales after two Mw6.5 earthquakes that occurred in the South Iceland seismic zone (SISZ) in June 2000. At the first scale, we see a rapidly decaying deformation transient lasting no more than 2 months within 5 km of the two main shock ruptures. This local, month-scale transient is captured by several radar interferograms (InSAR) and is also observed at a few campaign GPS sites located near main shock faults. The second scale takes place over a characteristic time of the order of a year and is only detected by GPS measurements. Combining GPS observations from campaigns and continuous stations operated by the IMO (two of which were installed after June 2000), we observe significant changes of the velocity field out to a distance of about 20 km surrounding the main shock faults. This perturbation of the velocity field is most profound during 2000-2001, but decreases significantly during 2001-2002. Two different mechanisms are needed to explain the observed post-seismic deformation. The month-scale deformation pattern has been explained by poro-elastic rebound due to pore-fluid flow in response to the main shock induced pore-pressure changes [Jonsson et al., Nature, 2003]. In contrast, the year-scale deformation seems to be caused by visco-elastic relaxation of the lower crust and upper mantle in response to the coseismic stress changes. To simulate the year-scale deformation, we use a spherically stratified earth model with relaxing layers represented by visco-elastic lower crust and upper mantle, underlying an elastic upper crust. Preliminary modeling results suggest that the viscosity of the lower crust and upper mantle must be of the order $\sim 10^{18}$ Pa s to fit the observations. This value is near the lower bounds of previous estimates of sub- and lower-crustal viscosities, from post-glacial rebound and post-rifting relaxation in Iceland.

G21B-0269 0830h POSTER

Influence of rheology and tectonic loading on postseismic creep

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Postseismic creep, as observed by GPS, indicates probably transient deformation of the lower crust or upper mantle triggered by earthquake-induced stress perturbations. In these regions, deformation can be localized on a frictional surface or on a ductile shear zone. These two hypotheses imply specific rheologies and therefore time dependence of postseismic creep. Hence, postseismic creep may constitute a probe into the rheology of aseismic regions of the lithosphere. I derive an analytical general relaxation law for a power law rheology which can be used to model postseismic creep in the absence of reloading of the proposed shear zone. The stress exponent, n, is diagnostic of the deformation mechanism. The rheology appropriate for frictional sliding produces a relaxation law similar to the power law case in the limit 1/n=0. GPS data following several earthquakes are adequately modeled using the generalized relaxation law. However, for at least three examples (1997 Kronotsky, 1999 Izmit, and 2001 Peru earthquakes), the inferred stress exponent is negative. Rather than the shear zone rheology, these negative exponents indicate that reloading of the shear zone by tectonic forces is important. Numerical simulations of postseismic deformation with non-negligible reloading produces curves that are well fit by the generalized relaxation laws with negative stress exponent, although the actual stress exponent of the rheology is positive. Although this prevents rheology from being well constrained by the studied GPS records, it is clear that reloading is important in the postseismic time interval. In other words, the stress perturbation induced by earthquake is not much larger than the ambient stress field.

G21B-0270 0830h POSTER

Mechanics of Postseismic Deformation Following the 2002 , Mw=7.9, Denali Fault Earthquake

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The occurrence of the Mw 7.9 November 3, 2002 Denali earthquake has created the opportunity to collect the surface deformation measurements needed to make significant improvements in our knowledge of the dominant deformation mechanisms in the Earth's lithosphere and the rheological parameters of the fault zone and surrounding crust and upper mantle. With the technical support of UNAVCO, we installed 16 continuous GPS sites at a wide range of distances from the rupture, including some at > 150 km, in order to distinguish relaxation processes in the deep fault zone, the lower crust and upper mantle. Campaign measurements of about 50 sites are scheduled at least twice a year for the next 3 years. Horizontal postseismic displacement rates at continuous sites up to 200 km from the rupture reached 1-2 mm/day in the first month after the event. They gradually decayed to 0.2 mm/day 8 months after the event at the sites closest to the rupture. Displacement rates measured 8 months after the event at sites that had been operating before the earthquake were still 10 times larger than the pre-earthquake secular rates. We will present models of the early transient deformation that investigate candidate deformation mechanisms such as velocity-strengthening afterslip, poroelastic rebound, and linear versus power-law viscous flow in the lower crust and upper mantle. Preliminary inversions for the time-dependent distribution of possible afterslip on and below the rupture suggest that the source of postseismic deformation reaches deep in the lower crust and/or upper mantle. The spatial and temporal evolution of the transient deformation should provide information about which mechanism dominates the early relaxation process and constrain the range of plausible rheological parameters.

G21B-0271 0830h POSTER

Post-Seismic Deformation from Geodetic Observations Following the 1999 M7.1 Hector Mine Earthquake

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The 16 October 1999 Mw7.1 Hector Mine earthquake ruptured only 20 km to the east of the 1992 Mw7.3 Landers earthquake in a region of the Mojave desert that experiences large earthquakes approximately every 10,000 years. While it is well-known that major earthquakes cause aseismic deformation transients, the mechanisms behind this deformation are the subject of some debate. For this reason there has been a concentrated effort to collect both survey-mode and continuous GPS measurements of the postseismic deformation following the Hector Mine rupture. The currently available geodetic data measures ground deformation with unprecedented spatial and temporal resolution, however it is important to remove seasonal signals from the continuous GPS time series. The quality of the time series at each of these sites varies significantly, but by carefully analyzing the spatial and temporal distribution of the vertical deformation, we can potentially resolve the rheology of the lower crust, and whether strain is accommodated by localized deformation, or a more distributed viscous flow (Pollitz et al., 2001). A GIPSY-OASIS point-positioning approach with ambiguity resolution is used followed by a principal component analysis to remove the time-correlated noise in the time series. The final time series are compared to currently available models to determine the likely processes at work. Stations within the observed network display both horizontal and vertical postseismic signals which decay rapidly in the first few months following the earthquake.

G21B-0272 0830h POSTER

Observations of Surface Deformation Following the 1992 M7.3 Landers Earthquake, Southern California: Robust Test of the Post-Seismic Relaxation Models.

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The co- and post-seismic deformation due to the 1992 M_w7.3 Landers earthquake is investigated using the entire catalog of the ERS Synthetic Apetrure Radar (SAR) data, and GPS measurements made between 1992 and 1999. The co-seismic stress perturbations due to the Landers earthquake are computed using a slip model derived from inversions of the SAR data from the ascending and descending orbits. These

stress perturbations are then used to predict the visco-elastic and poro-elastic response of the Earth's crust within a few hundred kilometers from the earthquake rupture. Calculations are performed for both the homogeneous and layered half-space models. The predicted surface deformation is compared to the Interferometric SAR and GPS data. The stacked InSAR data spanning the time period between 1992 and 1999 reveal a transient post-seismic deformation with a characteristic decay time of several years. The observed deformation pattern cannot be readily explained by any single mechanism. In particular, the data exhibit high strains across the Landers rupture, inconsistent with visco-elasic models of relaxation in the lower crust or upper mantle. The poro-elastic model quite well predicts the InSAR signal, assuming that the pore fluid flow extends to the middle crust (down to about 15 km), but it underpredicts the far-field GPS data. We demonstrate that a combination of poro-elastic relaxation above the brittle-ductile transition, and afterslip on the Landers rupture is required to satisfactory explain both the InSAR and GPS data.

URL: http://igpp.ucsd.edu/∼fialko/res_land.html

G21B-0273 0830h POSTER

Measuring inter-seismic deformation by INSAR in Eastern Turkey

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We seek to measure interseismic deformation across the fault systems intersecting at the Karlova Triple Junction using radar interferometry at C-band (5 cm) wavelengths. We have obtained ERS interferograms with enough correlated pixels to interpret for pairs spanning up to 3 years, provided that the images are both acquired in the summer months (June-September) and the altitude of ambiguity is very favorable (over 500 m in absolute value). This result extends the work of Wright et al. [GRL, 2001]. We have developed an approach that analyzes changes in range in profiles perpendicular to the strike of the fault. After unwrapping, these profiles show gradients which combine the inter-seismic deformation signal with the unmodeled orbital effects. Previous studies have neglected the orbital errors. To separate the former from the latter, we apply an approach called temporal adjustment that estimates both interseismic deformation parameters and orbital corrections. We compare the INSAR results to available GPS estimates.

G21B-0274 0830h POSTER

Connecting Aseismic Slip and Microseismicity on the Central San Andreas Fault

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High precision micro-earthquake relocations have revealed seismicity structures that may be an indicator of the fault's slip characteristics. Characteristically repeating micro-earthquakes and aligned streaks of micro-seismicity suggest that these structures are associated with areas of active aseismic fault slip. A general inverse correspondence between zones of abundant micro-seismicity and the coseismic slip area of large earthquakes also implies a relationship between creep and micro-earthquakes. We test this relationship using geodetic measurements of near-fault deformation. Modeling of such measurements allow for determination of locked and creeping sections of the fault. We focus on the central San Andreas fault near San Juan Bautista; a segment which experiences both aseismic and seismic fault slip and where there is a long history of geodetic measurements. Aseismic slip on the central San Andreas is time dependent and has varied in response to regional earthquakes and in the form of slow earthquakes. Dislocations in an elastic half space are used to evaluate a range of scenario fault slip models whose geometry is guided by the locations of micro-seismic streaks. The inversions for distributed sub-surface slip are constrained by range-change data from InSAR and GPS site velocities. The InSAR data (ERS1&2 track 299 frame 2861) spans from 1996-2000 and were processed using ROI_Pac with the SNAPHU unwrapper and combined in a patchwork stack to reduce atmospheric errors. Campaign and continuous GPS data were processed using GAMIT/GLOBK and form part of the regional BĀVŪ dataset. To minimize the effect on our analysis of transient slip induced by the 1989 Loma Prieta earthquake, we limit our dataset to GPS observations from 1994 to 2003. Preliminary results confirm that the presence of seismicity streaks and characteristically repeating micro-earthquakes are indicative of aseismic slip. However, the absence of such seismicity patterns does not necessarily rule out active fault creep.

G21B-0275 0830h POSTER

High Resolution Continuous Tilt and Strain Measurement on Trizonia Island, Corinth Rift, Greece. Evidence for a Slow Transient Associated With a Seismic Swarm

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The Trizonia Island is located near the northern coast of the Gulf of Corinth, 5 to 10 km above the principal active normal faults, dipping north. The rate of deformation is 1.5 x10-6/yr, according to GPS measurements. Within the CORSEIS project (European Community), strain and tilt continuous measurements began in October 2002 on this island, in order to detect transient strain related to the opening and to the seismicity of the rift. In particular, they aim at detecting possible aseismic deformations related to the frequent seismic swarms of the zone, in a radius of 20 km. Hydrostatic tiltmeters, two NS and two EW, 15 m long, one filled with mercury, the other with water, were built at IPGP and were installed in parallel, 3 m under ground. Their resolution is presently 10-9 rad at short period, with continuous recording at 30 s sampling rate. The Sacks-Evertson dilatometer is installed 1 km away at 150 meters depth, and has a resolution of 10-10, with a continuous record at 5 Hz, and 50 Hz in trigger mode. The 3rd of december 2003, the strainmeter recorded a strong signal, with 10-8 amplitude, lasting one hour.It reaches a peak at about 23:04:30 UT, and then decreases and vanishes back in the tidal signal. At the maximum of the strain anomaly, the record shows the high frequency strain waves of a local earthquake located 14 km west to the site (23:04:39.5 UT,38 deg 20.42N 21 deg 53.79E),at 8 km in depth. It has reported magnitudes 3.7, and is the largest event of a swarm, which lasted about 2 weeks. The precise time coincidence of both events lead us to propose physical correlation between them, in which case the M=3.7 event seems to be triggered by the slow transient which has an equivalent moment magnitude of a 4.5 silent earthquake.

G21B-0276 0830h POSTER

Geodetic and Hydrological Aspects of the Merano Earthquake of July 17, 2001

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Even a relatively small earthquake can become a study case if the seismological data are augmented with non conventional information, such as geodetic and hydrological data. This could be the case of the M=4.8 earthquake of 17 July 2001 with epicentre near Merano, in Northern Italy, where a two year long time series of the permanent GPS station MERA, a few km from the epicentre, and water table data from four wells within 8 km of the estimated epicenter are available. A step-like signal in the time series of the geodetic coordinates of MERA is found to be simultaneous with the epoch of the earthquake. If such jump is interpreted as a co-seismic displacement, the fault plane solution of this strike slip earthquake is constrained in a manner which is consistent with the general tectonic setting of the area. Geodetic and seismological data are used to constrain the depth of the hypocenter. We show that the fault dislocation data and the geodetic displacement of the GPS station clearly support the hypothesis of a shallow earthquake (< 5 km depth), in contrast with other, purely seimological indications of a deeper (12-15 km) hypocenter. We speculate that a visco-elastic relaxation model can explain the postseismic non linearities in the GPS time series, if the upper crust is mechanically decoupled from the lower crust by a ductile channel. However the relaxation times are long compared to the time series and the fit of the model to the data does not constrain the model parameters reliably. Water level data from four wells in the epicentral area show small, random changes which become coincident at the epoch of the earthquake. Assuming that the wells can be treated as hydraulic heads, we numerically compute the strain field generated on the surface of an elastic half space subject to a localized stress drop on the fault. Using the published fault plane solution as a model of the excitation source we show that the form of the changes of the water level are consistent with the one we predict numerically. Because all the wells show a rise in the water level, they must be in a compressional sector and this helps in narrowing the number of candidate epicenters. We conclude that the addition of geodetic and hydrologic data to the seismological data enables, in this study case, both the hypocenter and the fault plane solution to be constrained more uniquely than with seismological data alone.

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G21C MCC: Level 1 Tuesday 0830h

Postglacial Rebound and Sea Level Posters *(joint with OS, C)*

Presiding: **E Schrama,** Delft Institute for Eartjh-Oriented Space Research, Delft University of Technology**; J A Henton,** Natural Resources Canada

G21C-0277 0830h POSTER

An inter-comparison of ocean tide loading estimates for Antarctica from models and GPS

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We present ocean tide loading (OTL) estimates for Antarctica based on several numerical tide models and direct estimates from GPS observations. Accurate estimates of the ocean tides in the Antarctic region are difficult to obtain from numerical ocean tide models due to the lack of bathymetric information and direct tidal observations in the sub ice shelf regions in particular. Consequently, independent measurements, such as from GPS, with an extensive spatial distribution are extremely important to ensure geodetic and altimetric (e.g, IceSat) measurements are not biased by mismodelled OTL. We show that there are large variations in diurnal and semi-diurnal OTL estimates from nine numerical tide models in the regions of the very large Ross and Filchner-Ronne ice shelves. The standard deviations of the M_2, S_2, O_1, K_1 model estimates in these regions have a maximum of approximately 10, 5, 5 and 5 mm respectively for the real components and approximately 10, 5, 3 and 3 mm respectively for the imaginary components. These represent variations of up to 50% of the modelled load. Recent numerical tide models are in better agreement, although substantial variation still exists. In the non ice shelf regions the models are typically in agreement at the 1-2 mm level. We report on the impact of this mismodelling on ice sheet thinning rate estimates from GLAS measurements with the degraded IceSat orbit. In order to provide an external validation of the model estimates we estimated the eight major diurnal and semi-diurnal harmonic loading terms directly in our GPS analysis of data from ∼ 20 sites distributed mainly around the perimeter of the continent. By combining estimates from up to several thousand days at each site constituent amplitudes were determined with uncertainties generally less than 1 mm. Phase uncertainties are dependent on the constituent amplitude but are generally 5-20°. We compare these