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Annual Global Positioning System (GPS) campaign surveys since 1995 in the area of the 1964 Great Alaska earthquake (Mw 9.2) show evidence for a large aseismic slip event beginning in late 1997 or early 1998 and apparently ending in 2001. Prior to 1998, velocities of sites in Anchorage and the area to the north were oriented toward the NNW, consistent with strain associated with a locked subduction interface to the south. Between fall 1997 and summer 1998, velocities of GPS sites in an area at least 150 km by 100 km in size changed by as much as 25 mm/year. North of Anchorage, the change in site velocities was large enough that sites changed direction, from NNW-directed motion to SSE-directed motion. One permanent site in the area, installed in late 1998, shows a clear time-dependent signal, moving rapidly to the south shortly after installation and then slowing down over the next two years. A preliminary evaluation of data from summer 2001 suggests that the anomalous southward motion has ended or nearly so. These observations are consistent with the sudden activation (taking less than several months) of some process that causes southward motion of the sites, and a slow decay of that process over a span of 3-4 years.

We can explain this change in velocities by a model of increased creep on a large section of the plate interface downwind of the 1964 rupture zone. In this model, slip on the interface increased from roughly the rate of plate motion to roughly double that, decaying back to roughly the rate of plate motion after 3+ years. This event is different from the recent creep event observed in Cascadia, as it extends well downwind of the seismicogenic zone and appears to have affected a very large area simultaneously rather than propagating along strike. The westward extent of the zone of anomalous creep is uncertain due to a lack of data prior to 1997, but this zone is inferred to be at least 100 km by 100 km, lying at a depth of 35 km or more. The change in velocities was accompanied by a significant change in the rate of microseismicity in two volumes within the subducting Pacific plate, which lie on the edges of the inferred creeping zone. We infer that these changes, in one case a reduction in the rate of seismicity and the other an increase, had the same root cause as the creep event.

G22D-12 1635h INVITED

Episodic Silent Slip: A New Aspect of Cascadia Megathrust Behaviour

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The gradual densification of continuous GPS sites in southwestern British Columbia and northwestern Washington over the past 4 years, accompanied by improvements in GPS data analyses for regional networks, have led to the discovery of aseismic slip occurring on the deeper portions of the Cascadia subduction interface. The most convincing evidence comes from a transient crustal deformation signal observed in the late summer of 1999 (Dragert et al., Science, Vol. 292). This signal, observed at 7 contiguous sites spread over an area of about 300 by 100 km along the northern Cascadia margin, consisted of systematic changes in site positions ranging from 2 to 4 mm over a period of 5 to 15 days in a direction opposite to the longer term secular deformation motion caused by the locked state of the Cascadia subduction fault. A second similar but more spatially limited slip event has been found to have occurred in December 2000, and it is strongly suspected that the hereto unexplained transient motion observed in October 1994 at the Victoria GPS site (ALBH) was also caused by aseismic slip. The total surface displacements observed for these transients can be modelled by silent slip of up to 2 cm occurring on the subduction interface below the seismicogenic zone, bounded roughly by the 30 and 40 km depth contours of the subducting slab. The down-dip boundary of the aseismic rupture is relatively sharp, possibly controlled by the depth of contact with the moho of the overlying crustal margin. The up-dip boundary requires a more gradual transition from full rupture to zero displacement, suggesting that it is thermally controlled. The absence of seismic triggers and anomalous seismicity and the apparent modulation of secular deformation velocities suggest that this deep-slip behaviour is episodic and likely triggered by rheological instabilities. Episodic slip behaviour implies time-variant coupling across the deeper subduction interface which not only generates non-linear transient motions but may also play a key role in the stress loading of the seismicogenic zone, perhaps generating a trigger mechanism for a great subduction earthquake.

G31A MC: Hall D Wednesday 0830h

Explaining Geodetic Observations of Nonlinearly Time-Varying Surface Deformation II (*joint with NG, H, S, T, V*)

Presiding: G W Bawden, U.S.

Geological Survey; **E Harding Hearn,** Massachusetts Institute of Technology

G31A-0120 0830h POSTER

Anatomy of apparent seasonal variations from GPS derived site position time series

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Apparent seasonal site position variations are derived from 4.5 years of global continuous GPS time series and explored through the peering approach, i.e. depicting the contributions of the comparatively well-known seasonal sources to garner insight into the relatively poorly-known contributors. Contributions from pole tide, ocean tide loading, atmospheric loading, nontidal oceanic mass and ground water loading are evaluated. Our results show that about 40% of the power of the observed annual vertical variations in site positions can be explained by the joint contribution of these seasonal surface mass redistributions. After removing surface mass redistribution inferred seasonal effects from the observations, the potential contributions from unmodeled wet troposphere effects, bedrock thermal expansion, errors in phase center variation models and errors in orbital modeling are also investigated. A scaled sensitivity matrix analysis approach is proposed to assess the contributions from highly correlated parameters. The effects of employing different analysis strategies are investigated by comparing the solutions from different analysis centers. Comparison results indicate that current solutions of several GPS analysis centers are able to catch the seasonal signals but that the differences between these solutions are the main obstruction in further studying the residual seasonal effects. Potential implications for modeling seasonal variations in global site positions are explored, in particular as a way to improve the stability of the terrestrial reference frame on seasonal time scales.

G31A-0121 0830h POSTER

Seasonal Variation of Baseline Length Changes Observed in GEONET GPS Sites

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Murakami and Miyazaki [1999] reported that seasonal variation could be seen in the daily solutions of GEONET (the GPS Earth Observation NETWORK) GPS site coordinates. Hayashi et al. [2000] and Heki [2001] also reported seasonal variation in the baseline length changes. Especially, Heki [2001] investigated the seasonal variation of the baseline length change in Tohoku area, one of the most heavy snowfall areas in Japan, and concluded that the variation was due to snow loading and melting. These studies show that the existence of the seasonal variation is almost undoubted. However the previous studies employed relatively short period of GPS data (less than 3 years) or restricted the area of analysis, they have not revealed the characteristics or

the cause of the variation completely. Therefore, for the more detailed analysis, we employed all GEONET data and investigated the characteristics of the seasonal variation statistically.

First, we calculated all combinations of the baseline length changes from daily solutions of the GEONET GPS site coordinates, and then, using least squares method, we estimated secular trends, annual amplitudes and phases of the baseline length changes for every combination of the GEONET GPS sites. Finally, the estimated parameters (trends, amplitudes and phases) were employed to examine their regional or directional dependencies. The results are summarized as follows:

- (. The seasonal variation can be observed in almost all the baselines.
- (. Most of the large amplitudes of the seasonal variations are observed in N40W ~ N70W directions.
- (. The secular compressions are also observed in N40W ~ N70W directions.
- (. Most of the baselines expand in summer, and contract in winter.

The first result confirmed that the existence of the seasonal variations all over the Japan, and the last one was consistent with the Heki's interpretation: The snow loading causes the contraction and snow melting causes the expansion. However, his interpretation was not enough to explain the seasonal variations in no snowfall areas of the southwestern part of Japan. Further investigation of the seasonal variations, we selected the baselines with large amplitude of more than 4mm and plotted their distributions. A notable result is that the baselines that extend in summer are distributed almost all over Japan, however the baselines that extend in winter are distributed mainly in the southwestern part of Japan, especially across the mountains of the Japanese Alps. This result may help to consider the mechanism of the seasonal variation in the no snowfall areas, although we have not solved the problem yet.

G31A-0122 0830h POSTER

Migrating Crustal Deformation from GEONET Observations

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The Geographical Survey Institute of Japan (GSI) recently completed the installation of a continuous GPS observation network in Japan, which has enabled us to investigate real-time crustal movements. In this study, we attempt to detect migrating crustal deformations in Japan, using the horizontal components, which were observed at 900 GPS observation stations during the period from April, 1994 to February, 2001. These data include the effects of plate coupling, earthquakes, annual changes and noise at each station. In order to remove these effects, we modeled the time series as a linear combination of a constant term, linear term, trigonometric function whose period is 1 year, and offsets for episodic events (earthquakes). For the episodic events, we try to remove the effects of all earthquakes shallower than 30 km with magnitudes 5.0 or greater (221 events). To remove the noise, we use a Kalman filter which estimates the local trend at each station.

Our goal is to detect migrating crustal deformation across the Japanese Islands. We closely examine the crustal deformations which have these effects removed. We try to detect the migrating crustal deformation by a semblance analysis, which can detect the velocity, direction and epoch. Moreover, we use time series of the crustal deformation formed by stacking the GPS data from several stations.

We have detected some characteristic migrating crustal deformation, that have amplitudes which are much smaller than 1cm with rather fast velocities. The migrations we observe are much smaller in amplitude and have faster velocities than those reported by H. Ishii et al.(1980). Our observations may contain other factors, such as annual changes which are difficult to separate from tectonic movements.

G31A-0123 0830h POSTER

Space-Time Imaging of Aseismic Slip Transients on Subduction Zone Thrust Interfaces

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Dense arrays of GPS receivers have recently recorded aseismic slip events with durations ranging from days to months. We describe a time dependent inversion method for estimating the temporal and spatial distribution of fault slip, building on the concept of a Network Inversion Filter [Segall and Matthews, 1997, J.G.R.]. The NIF employs time-domain Kalman filtering, and allows for non-parametric descriptions of slip velocity, local benchmark motion, and measurement error. Recent advances include, explicit consideration of rotations and translations of the GPS reference frame, non-negativity constraints, and direct estimation of the spatial and temporal smoothing hyper-parameters.

From late 1996 to late 1997 aseismic slip on the Philippine Sea plate subduction interface beneath Kyushu and Shikoku islands produced large transient deformation signals which began as afterslip subsequent to two M_W 6.7 Hyuga-nada earthquakes. The afterslip was then followed by the Bungo Channel slow earthquake centered about 100 km further north [Hirose et al., 1999]. While these two events overlap in time, our inversion demonstrates that the afterslip and the Bungo Channel slow earthquake were separated by a 50 km long region of little to no slip. The peak slip in both events occurred between depths of 35 and 50 km. Peak slip rates were ~ 4 m/yr in the afterslip event and ~ 1.2 m/yr in the Bungo channel event. The Bungo Channel slow earthquake nucleated on the shallow portion of the thrust interface and propagated deeper.

In 1997 the Cascadia subduction interface beneath Seattle and Vancouver Island ruptured in an aseismic slip transient that lasted about 6 weeks [Dragert et al., 2001]. Inversion of the available GPS data demonstrates that the event nucleated at a depth of around 30 km and propagated initially to the south and then dominantly along-strike to the north as well as updip. The duration of slip at any point on the fault is much shorter than the Bungo Channel event, and peak slip rates were ~ 0.5 m/yr. The rupture velocity may have been spatially variable.

The differences between the Cascadia and Bungo Channel slow earthquakes in rise-time and rupture propagation, suggest that a rich variety of aseismic slip transients can occur on subduction zone thrust interfaces. The failure mechanism allows instabilities that accelerate to maximum slip-rates on the order of 1 m/yr.

G31A-0124 0830h POSTER

Aseismic Slip Event with M_w 6.6 Accompanying 2001 M 5.8 Earthquake off Fukushima, NE Japan

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In February 2001, earthquakes with M 5.8 and 5.4 occurred along the plate boundary off Fukushima, northeastern Japan. The focal area is located at one of the most seismically active regions in Japan: there occurred swarm activities including 3 major events with $M > 7$ in 1938, and those including 5 with $M > 6$ in 1987. After the 1987 activity, however, no large earthquakes with $M > 6$ have taken place in the region.

A continuous GPS station (OIP) was installed on a gas platform 40km off Fukushima in 1995. OIP had been displaced toward southwest in the ITRF97 coordinate system with about 2cm/yr. all through the period until January 2001. Then the westward displacement was vanished and recently shows eastward movement, slightly. The deviation from the trend of its steady-state displacement before 2001 amounts to about 10mm in July 2001. Permanent GPS stations on land operated by GSI, on the other hand, show no significant displacement larger than noise level in the same period. This means that the rate of displacement observed at the sites on land over that of OIP should be less than 0.3 if 3mm of noise level is assumed.

One possible model explaining the displacement rate is an aseismic slip event with a thrust type of mechanism occurring on the plate boundary, though the constraint on the model is very weak. The model fault is 20km by 40km along its strike and dip, respectively, and includes the focal area of the two major events around its upper edge. The aseismic slip from February to July amounts to about 25cm, which is equivalent to M_w 6.6.

The area of this aseismic faulting almost corresponds to the aftershock area of the M 5.8 events, which is large for the main shock magnitude. This suggests that many of the aftershocks are ruptures of small asperities caused by the aseismic slip on the plate boundary.

G31A-0125 0830h POSTER

Spatial and Temporal Variations in Strain Accumulation at the Sumatra Subduction Zone from Recent GPS Measurements

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An earlier analysis of 1989-1994 campaign-style GPS measurements estimated horizontal velocities, precise to within 3-4 mm/yr, that have begun to reveal the strain accumulation pattern above the Sumatra subduction zone. The horizontal deformation field measured by GPS is consistent with nearly full partitioning between arc-normal subduction and arc-parallel slip at the Sumatra fault. Deformation in the forearc appeared to be divided into two distinct regimes, to the NW and SE of the rupture boundary of two great (M 8+) 19th century subduction earthquakes. This segmentation of the forearc velocity field could be successfully modeled by elastic strain dislocation in which the subduction zone south of the Equator is fully coupled (locked) to a depth of 50 km, while north of the Equator the subduction zone interface is only about 50% coupled. However, there was no compelling underlying geodynamic process that would explain the change in coupling.

Using improved processing techniques, the ITRF97 reference frame, and refined satellite orbits derived from reprocessing data collected at global reference sites, we recently completed a reanalysis of all of our Sumatra data. The augmentation of the original 1989-94 regional data set by measurements from a few key sites observed in 1996 and from a 2001 reoccupation of a 26 station network that spanned almost all of the offshore forearc islands and of the Sumatra coastal sites leads not only to significantly smaller uncertainties (about 1 mm/yr) of site velocities but also to a more uniform forearc velocity field. The recent observations can be reconciled with our earlier work if we consider the strain segmentation detected previously as a short time transient event. This view is consistent with coral-based results obtained by other investigators for the northern segment of the forearc (zone of the 1861 great earthquake) which suggest that an aseismic event may have occurred between 1989 and 1993. An alternative scenario that has not yet been explored considers a spatially transient segmentation line that moves north-west and is now off our geodetic network observed in 2001.

G31A-0126 0830h POSTER

Repeated Occurrence of Slow Slip Events on the Subducting Plate Interface in the Tokai Region, Central Japan, the Focal Region of the Anticipated Tokai Earthquake ($M=8$)

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A slow slip event, which seemed to start around this March or earlier and is ongoing on the plate interface at the moment in August, 2001, has been detected by a dense GPS network, GEONET operated by GSI, Japan, in the Tokai region, central Japan (see Fujii et al., in this meeting). In this region, the so-called Tokai earthquake ($M=8$) was predicted 25 years ago and a variety of observations are still executed for predicting the earthquake. In this meeting three years ago, we reported that the spatio-temporal changes in the interplate coupling between the subducting Philippine Sea and the overriding plates in this region, based on the leveling and the EDM baseline length measurement data, which have been observed during these 25 years. Using a back-slip inversion technique (Yabuki and Matsuura, 1992), we obtained the average back slip rate of 3-4 cm/yr on the plate interface equal to the previous estimates. However, the back slip rate obtained during each divided period of 4 years greatly changes in time and the largest one amounts to 10 cm/yr in a period

of 1983-1987. This large rate may be an artifact due to the small and limited covering region of observed data. The on-going slow slip event recently detected by GPS inspires us to re-examine our data with a far longer observation period than the recent GPS and to search for the past slow slip events. In this study, we re-analyze the augmented data set and interpret the spatio-temporal changes in the interplate coupling in view of such a slow slip event. Close examination of temporal and spatial changes of the data, based on forward and constrained inverse modeling, leads us to conclude that such a slow slip event seems to repeatedly occur on the plate interface in this region. Namely, at least two slow slip events seemed to occur during the periods of 1978-1983 and 1987-1991 when the rates of vertical movements and of the contraction in baseline lengths are smaller comparing to those in other 25 periods. The spatial pattern of relative uplift and subsidence region requires that the slow slip region is located at least at a deep portion of the coupling region, hence narrowing the coupling region. Accordingly, the coupling region on the plate interface changes in time, narrowing and widening. The changing period seems to be 3-4 years from the past 25 years observations. Unfortunately, the limited spatial coverage of old observations could not resolve the slip region precisely. However, it is of much importance to monitor the spatio-temporal changes in the coupling region, caused by repeated slow slip events, towards the final break of the Tokai earthquake. Present dense GPS network will be able to catch the changes of the frictional state on the plate interface with high spatio-temporal resolution.

G31A-0127 0830h POSTER

Using Point Measurements from InSAR to Detect Transient Deformation

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Transient slip events at a wide range of time scales characterize the northern transition zone between the locked and creeping sections of the San Andreas Fault, near San Juan Bautista. Many small creep events and slow earthquakes were superimposed on a much longer slip rate increase in the years following the Loma Prieta Earthquake. Creepmeters and strainmeters, which have been the primary instruments to record these phenomena, provide excellent temporal resolution, but are too few in number to constrain rupture area or depth of a slip event with much precision. This study attempts to utilize the extensive spatial coverage of SAR to better constrain these parameters. InSAR has been shown to be capable of detecting small variations in fault slip, but the prevalence of vegetative cover in this area has made decorrelation noise a real problem. To improve on this, we analyzed 25 ERS 1 & 2 ascending and descending scenes (track 299 frame 2861 & track 478 frame 729) to isolate points that have consistently high amplitudes and that are distinct from their neighbors. These points are interpreted to be permanent structures; rock outcrops and buildings whose walls behave like corner reflectors. Similar to points selected by the Permanent Scatterer method, this allows them to reflect coherently even between scenes with large perpendicular baselines. Identifying these points allows us to construct a sparse grid of point measurements that is coherent over much longer time spans than is the whole scene. We compare this to data from a 23 station campaign GPS network with observations from 1989 to 2001. We present a combined data set with a time frame (1992-2001) spanning the occurrence of several creep events and a M_w 4.8 slow earthquake.

URL: <http://www.seismo.berkeley.edu/~burgmann>

G31A-0128 0830h POSTER

On-going Slow Slip Event at the Tokai Region, Central Japan

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On-going slow slip event started from March, 2001 or earlier is detected at the Tokai region by a dense GPS network, GEONET operated by Geophysical Survey

Institute (GSI), Japan. By subtracting a linear trend and annual variations from the GEONET data, a thrust type slip movement is occurring for at least half a year at deeper part of the anticipated fault zone of the "Tokai earthquake ($M > 8$)", although the model suggests that the slip region could be extending into the locked zone. As the maximum slip at the plate interface zone becomes a few centimeter and the estimated area extends from the eastern border of the 1944 Tonankai Earthquake fault zone to the middle of the "Tokai earthquake" fault zone. As the area becomes about 40km x 150km, the moment magnitude of this slow slip events becomes 6.5, which is similar to those previously found at the Bungo Channel (western edge of the Nankai subduction zone) event [Hirose, et al., 1999; Ozawa, et al., 2001] and the Cascadia event [Dragert et al., 2001]. The Tokai region, central Japan, is located at the eastern end of the Nankai trough (continued to the Suruga trough), where the Philippine Sea plate is subducting beneath the southwest part of Honshu in the NW direction at average rate of about 3 - 5 cm/yr.

Repeated occurrence of the temporal changes of the interplate coupling in the Tokai region are also suggested (see Kimata, et al., in this meeting) during 25 years using a back-slip inversion technique similar to Yabuki and MatsuOura [1992]. The data used are horizontal length changes by the EDM ranging at two lines and level changes between Hamanako and Shizuoka, where are located just above the lower part of the locked zone. Results seem to indicate at least two slow slip events during the periods of 1978-1983 and 1987-1991 when both of the subducting rate and direction changes from the average plate motion.

A variety of time scale of slow slip event could closely related with the fluctuation of plate motions and/or changes in friction characteristics at the plate. Slow slip processes at deeper part of the locked zone of the plate interface could obviously play a key role in the stress accumulation and nature of repeated occurrence of the plate interface earthquakes.

G31A-0129 0830h POSTER

Heterogeneous Crustal Deformation Along the Northern Itoigawa-Shizuoka Tectonic Line, Central Japan: Implications for Deformation Process in the Deeper Extension of Active Faults

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The Itoigawa-Shizuoka Tectonic Line (ISTL) is a major tectonic boundary intersecting middle of the Japan Mainland in the north-south direction. Northern part of ISTL is recognized as an active fault system whose geological slip rate is estimated to be as large as 3-9 mm/yr. In order to investigate a loading process of the fault system as well as a significance of a local deformation to the island arc-scale deformation, we installed 11 continuous GPS stations around the East Matsumoto Basin Fault (EMBF) and the Gofukuji Fault, which constitute the northern ISTL. The Gofukuji Fault is estimated to have one of the largest slip rate known (8-9mm/yr) among inland active faults of Japan. Filling gaps among the existing nationwide GPS network (GEONET) sites, new GPS stations are linearly distributed with a minimum spacing of about 2km so that we can reveal a precise deformation profile across the faults.

Through 1.5-year observation with the new GPS sites, we obtained a concentrated deformation around EMBF. A high shortening rate (-0.4ppm/yr) is observed within a narrow (about 25km) zone across EMBF while deformation rate in the surrounding area is an order of magnitude smaller. On the other hand, strain rate at the Gofukuji Fault is much smaller compared with that of tectonically active regions in Japan. Difference between the large geological slip rate and a small strain accumulation is apparently paradoxical. However, deformation around the Gofukuji Fault is widely spread and a 100km-wide region around the Gofukuji Fault is being deformed rather uniformly. The total displacement rate across the wide region is consistent with the estimated slip rate. From these results, we can deduce that a strain energy related to the loading process of the Gofukuji Fault is stored in a much wider region than that of EMBF. This also implies that a steady slip may occur in the deeper extension of EMBF loading the fault toward a failure, and that the deeper extension of the Gofukuji Fault has been fully relaxed due to viscous flow since the last earthquake more than 1000 years ago.

G31A-0130 0830h POSTER

GPS Results in Mongolia, Post-Seismic Deformation, and Implications on Crust/Mantle Viscosity in Central Asia

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We present the results of GPS measurements carried out in Western Mongolia over the 1997 - 2001 period. We find that the western part of the Amurian-North China block is moving east to southeastward relative to Eurasia at velocities ranging from 4 to 10 mm/yr. Velocities in the Mongolian Altay reach 8 - 9 mm/yr in a northeastward azimuth.

Using a numerical model of viscoelastic relaxation, we find that the post-seismic effects of the large earthquakes of the century in Mongolia (Tsetserleg $M = 8.0$, 1905; Bolnai $M = 8.4$, 1905; Fu Yun $M = 8.0$, 1931; Bogd $M = 8.1$, 1957) can still account for up to 7 mm/yr of the present-day surface displacements at some of our GPS sites, depending on the earthquake source parameters and the rheology used in the models.

In order to better constrain the crust/mantle rheology, we model the observed GPS velocities as the sum of a secular rigid-body displacement, post-seismic displacements due to viscoelastic relaxation, and a constant N-S velocity gradient across a deforming zone from the Siberian platform to China. We compute the χ^2 statistics between observed and modeled velocities for a large number of crust/mantle viscosity ratios, using the GPS sites located in an area of similar tectonic regime.

The GPS velocity field fits much better when post-seismic relaxation is taken into account, and the misfit pattern suggests a weak mantle of viscosity 4 to 8.10¹⁸ Pa.s below Western Mongolia. This result is supported by heat flow data, gravity models, and seismic tomography results that show a low velocity zone in the upper mantle below Mongolia. A Coulomb stress analysis shows that the presence of a weak mantle under Western Mongolia may explain the clustering of large earthquakes in this century in that area.

G31A-0131 0830h POSTER

Rheological Properties of Lithospheric Extension from Postseismic GPS Observations of the 1959 $M=7.5$ Hebgen Lake, Montana, Earthquake

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The 1959 Hebgen Lake earthquake, the largest historic earthquake in the Intermountain Seismic Belt, simultaneously ruptured two normal faults centered 25 miles northwest of the Yellowstone caldera. The depth of the 90th percentile of earthquake foci approximates the depth of the brittle-ductile transition. This depth increases northwesterly from 7 to 11 km based on the relocated 1973-1997 background seismicity between the northwest caldera and the southeast end of the Hebgen Lake fault. Leveling surveys near Hebgen Lake (1923 to 1983) revealed 30 cm of postseismic uplift, where USGS trilateration data (1973 to 1987) yielded extensional strain rate of 0.266±0.014 μ strain/yr with an azimuth of N15°E ± 1°. The University of Utah, on the other hand, has conducted GPS surveys in the area between 1987 and 2000, and the data revealed an extensional strain rate of 0.159±0.044 μ strain/yr, in a direction of N28°E ± 9° which is approximately perpendicular to the Hebgen Lake fault scarp. The horizontal velocities across the fault are 4.0 and 2.4 mm/yr corresponding to the trilateration and GPS data, respectively. With the assumption that these two survey methods can give consistent results, the decreasing strain rates from 1973 to 2000 may reflect that the fault has been undergoing viscoelastic relaxation. With the constraint of the

focal depth of background seismicity and applying an 1-D viscoelastic methodology (Pollitz, 1997), we invert the geodetic observations for layered rheological models that can best explain the postseismic surface deformation in the Hebgen Lake area. This study will reveal time-dependent response due to rheological structures in different depth, and establish an insight into understanding the cycle of large earthquakes in extensional stress regime.

URL: <http://www.mines.utah.edu/~rbsmith/RESEARCH/UUGPS.html>

G31A-0132 0830h POSTER

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

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The occurrence of the 1999 Hector Mine earthquake (M7.1) in the Mojave Desert has provided the scientific community with a wealth of data for analyzing time dependent deformation. A combination of survey mode GPS observations spanning from the time immediately following the earthquake up to July 2001, as well as continuous GPS stations from within the SCIGN network, provide us with a good spatial data density to observe patterns in post-seismic deformation. Inclusion of the SCIGN stations provides critical spatial and temporal data coverage for determining both horizontal and vertical deformation. Data were analyzed using the GIPSY processing software and the resulting deformation field is compared to post-seismic afterslip models. Modeled fault slip rates are estimated from GPS velocities from both the continuous and campaign mode GPS stations. It has been demonstrated that the horizontal data alone is not sufficient at distinguishing between afterslip and visco-elastic processes (Pollitz 2000). Comparisons of the GPS data, in particular the vertical, to afterslip models provide useful insight as to whether the post-seismic deformation field is the result of afterslip on the rupture plane or other time dependent processes in the lower crust.

G31A-0133 0830h POSTER

Postseismic Relaxation Time in the Near-Field of the Hector Mine Earthquake

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The collection of synthetic aperture radar data over the Hector Mine Earthquake region, by the European Space Agency satellite, ERS-2, has allowed for the creation of four postseismic interferograms since the October 16, 1999, event. Analysis of the interferograms (days 4-249, 39-144, 74-319, and 39-354), in particular the 39-354 day image, caused us to revise our original estimate that afterslip had a decay time of less than 40 days, and estimate a new, near-field exponential decay time of 94 +22/-16 days. To achieve this current estimate, we isolated a small section of each interferogram covering the high-low signal seen at the northern end of the fault rupture. A nonbiased linear regression method (i.e. functional analysis) was used to calculate the ratio of signal amplitudes between five pairs of interferograms. Uncertainties were estimated using a standard linear regression technique where the dependent variable was initially assigned all the variance. The technique was performed again, transferring the assumed uncertainty from the dependent variable to the independent variable. Assuming a single exponential decay time for this seismic event, these interferogram ratios and uncertainties were converted to decay time and uncertainty. From this, we arrived at the decay constant of 94 +22/-16 days. This constant compares well to the short-term relaxation time for the Landers Earthquake, 84 23 days, calculated by Savage and Svarc [1997] and somewhat less favorably to the time calculated by Shen, et al. [1994], of 38 days.

G31A-0134 0830h POSTER

Relating Measurements of Decaying Postseismic Surface Deformation to Viscoelastic Relaxation: This is no Time for Elsasser Time

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Techniques for measuring displacements of the Earth's surface have recently advanced to the point where the time-dependence of postseismic deformation (as well as its spatial patterns) can be characterized for large earthquakes. Given the availability of such data (and the promise of increasingly detailed measurements from future earthquakes), describing differences in early postseismic deformation from different rheological profiles of the lithosphere is no longer just a theoretical exercise. If postseismic deformation is due to stress relaxation in a viscoelastic crust or upper mantle layer below an effectively elastic upper crust of known thickness, the viscoelastic layer thickness and viscosity (η) may be determined independently using temporally detailed displacement observations (i.e., continuous GPS) from one or more locations. A related strategy of modeling postseismic displacements over a single time interval at several measurement points is currently used to estimate these parameters independently (e.g. Pollitz, 2001).

For models of an earthquake in an elastic layer of known thickness overlying a viscoelastic halfspace, η/Γ (Maxwell time, or T_m) is the rate-controlling parameter. In a given location relative to the fault, displacements produced by models with various Maxwell times may all be represented with one curve, provided displacement is plotted against time/ T_m . The time-dependence of postseismic surface deformation even for this simple model is complicated, but the same complicated response occurs for models with identical Maxwell times. This is not so for earthquake models incorporating viscoelastic layers, however: thicker viscoelastic layers yield faster postseismic velocities early in the earthquake cycle than thinner layers with the same Maxwell time (e.g. Pollitz, 1997; Cohen, 1984). Elsasser time (proportional to η/w , where w is viscoelastic layer thickness) is often posited as a reasonable rate-governing parameter for layered viscoelastic models because it has been proven to control time-dependent evolution of surface displacements in some cases (e.g., screw dislocation models for geometries in which variation of horizontal shear stress in the relaxing layer may be ignored, Rice, 1980). For near-field postseismic deformation following strike-slip earthquakes, however, thin viscoelastic layers yield faster postseismic velocities early in the earthquake cycle than thicker layers with the same Elsasser time (the opposite holds in some far-field locations). This means that for models with the same elastic plate thickness, η and w may be independently identified (theoretically) by modeling time-dependent surface displacement data from a single point. Such monitoring sites must be chosen carefully. If the observation point is adjacent to the rupture, relaxing layers with identical Maxwell times tend to produce similar time-dependent displacements. These data can provide an estimate of viscosity but not layer thickness. Models with the same Elsasser time can yield similar, time-dependent displacements in the far-field; data from these locations can constrain only η/w . I will present some descriptions of how ideal monitoring locations depend on model geometry, and will address how well displacement data from various locations relative to an earthquake rupture can bracket the width and viscosity of a relaxing layer. I will also show that for a range of reasonable lithosphere viscosity profiles, detailed displacement data from most locations between a few kilometers and 1-2 rupture lengths from the fault can contribute toward independent estimates of η and w .

G31A-0135 0830h POSTER

Fluid Pressure Changes in the Surprise Spring Basin Near Twenty-Nine Palms, California, Induced by the 1992 Landers and 1999 Hector Mine Earthquakes

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Pressure changes induced by the June 28, 1992 M7.3 Landers earthquake have been assumed to affect geodetic measurements as well as Coulomb stress changes. Groundwater levels measured manually by

the U.S. Geological Survey in and around the Surprise Spring basin, approximately between the fault ruptures of the Landers earthquake and the October 16, 1999 M7.1 Hector Mine earthquakes, show that strain-induced pressure changes in the alluvial basins can dissipate by vertical flow on a time scale of days within several hundred m of the surface, and that the spatial distribution and time variation of pressure changes reflects not only the coseismic strain field but also spatial variations in hydraulic conductivity.

The Landers earthquake imposed about 20×10^{-6} contractional volumetric strain on the Surprise Spring basin. Although fluid pressure in sedimentary rocks typically increases 20-50 cm of water per 10^{-6} contraction, groundwater level measurements in August, 1992, detected few changes that could be attributed to the earthquake. We argue that strain-induced pressure changes did occur, but had dissipated by vertical flow during the 60 days before water levels were measured. More specifically, because the wells are perforated 100 m or less below the water table, in rocks with vertical hydraulic diffusivities of $1-10 \text{ m}^2/\text{s}$, only 10-20% of the immediate post-earthquake fluid pressure changes would have remained at the time of the first post-Landers measurements.

In contrast to the expected monotonic decay of coseismic fluid pressure changes, water levels in eight wells rose 1-10 m between August and December, 1992, and remained elevated until at least 1996. Although lower pumping rates due to a post-earthquake population decline in 1992-1994 could have affected water levels in two wells near the town of Landers, other wells where this delayed response occurred are not influenced by pumping. The wells exhibiting this delayed and sustained pressure increase are generally closer to faults which may provide vertical connections to deeper zones where the coseismic fluid pressure increase had not dissipated.

The Hector Mine earthquake imposed strains similar in magnitude, but opposite in sign, to those imposed by Landers. Measurements within three days after the earthquake revealed that in two wells drilled since the Landers earthquake, water levels had dropped 10 m or more. Water levels in these wells continued to fall for several months following the Hector Mine earthquake, consistent with continuing strain imposed by afterslip. As of July, 2001, no other spatially coherent pattern of delayed water level changes has been observed for the Hector Mine earthquake.

G31A-0136 0830h POSTER

Subsidence, Compaction and Gravity-Sliding: Understanding Geodetic Strain Data Across Basin-Bounding Faults in Southern California

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High rates of geodetic shortening occur across the Los Angeles and Ventura basins. This deformation is inferred to represent a significant seismic hazard, and is presumed to be largely accommodated by active hanging-wall faulting, folding and tectonic uplift. In southern California, however, these deep subsiding basins are often bounded by oblique reverse faults that thrust early-Cenozoic and older rocks over young unconsolidated sediments. This suggests that footwall deformation, subsidence and compaction may play an important role in producing the apparent high strain rates. Even in the absence of active shortening, sediment compaction alone can produce surficial motions that mimic deep fault slip or elastic strain accumulation. Differential subsidence and compaction of footwall sediments relative to hanging-wall basement rocks can lead to increased vertical separation and fault rotation about horizontal axes. Such effects would contribute to net horizontal and vertical motions in both geologic and geodetic data. More importantly, subsidence and compaction can increase the potential for gravity-sliding towards the basin and the development of significant non-planar 3D fault geometry. A prime example occurs along the San Cayetano fault. Structure maps and cross sections derived from industry well data reveal a fault geometry reminiscent of thrust nappes in the western Alps. At shallow levels, a thin-skinned thrust sheet with low dip extends out in front of the deep, steeply-dipping fault segment by over 4 km, is nearly 2 km thick, and occupies over 60 cubic km. This geometry is strongly indicative of gravity-driven failure resulting from basinward tilt. Failure of this mega-slide off the hanging-wall block most likely occurred within the Rincon Formation, a 400-m thick ductile shale sequence that often accommodates detachment slip. Slide reactivation was likely augmented

by overpressured fluids trapped below the base of the slide. The thrust-nappe geometry of the San Cayetano fault has significant implications for how it and other basin-bounding faults may accommodate slip. If fault geometry is the result of an ancient gravity slide, the slide can be reactivated independently and/or aseismically. Observations of near-surface slip or large slip events at the toe of the slide may not be indicative of tectonic slip or large earthquakes at depth on the fault. Thus, in addition to the large contrast in elastic moduli, the observed high strain rates across basin-bounding faults may be the result of sedimentary, tectonic, and gravity-driven processes that all need to be thoroughly evaluated.

URL: <http://www.crustal.ucsb.edu/hopps/>

G31A-0137 0830h POSTER

Radar Interferometric Mapping and Numerical Simulation of Land Subsidence along the Dead Sea Shores, Israel and Jordan

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During the last decade, sinkholes and wide shallow subsidence features have become major problems along the Dead Sea shores in Israel and Jordan. Sinkholes are readily observed in the field, but their locations and timing are unpredictable. Wide shallow subsidence features are often difficult to observe in the field. However, once identified, they delineate zones of instability and increasing hazard. In this study we apply interferometric synthetic aperture radar (InSAR) measurements to map and calculate rates of vertical displacement phenomena in the Dead Sea basin. We analyze 27 SAR scenes acquired during the years 1992 to 2001 by the ERS-1 and ERS-2 satellites. The interferograms span periods of 2 to 103 months. Wide shallow subsidence features include circular and elongate coastal depressions (a few hundred meters to a few kilometers in length), depressions in ancient alluvial fans, and depressions along salt diapir margins. Phase differences measured in our interferograms correspond to subsidence rates generally in the range of 0-20 mm/year, with exceptional high rates that exceed 60 mm/year in two specific regions. During the study period, the level of the Dead Sea and of the associated groundwater has dropped by about 8 meters. This water level drop within an aquifer composed of fine-grained material has caused an aquifer system compaction resulting in gradual subsidence. Calculation of the expected compaction and comparison with the InSAR observations suggest that the observed subsidence along the Dead Sea shores occurred where the total thickness of the fine-grained marl layers is between 5 m and 20 m in the upper 30 m below the surface. Our observations also show that in certain locations subsidence appears to be structurally controlled by faults and salt domes. The temporal relationships between wide shallow subsidence features and sinkholes are still not fully resolved, excluding the use of gradual subsidence as a precursor to sinkholes.

G31A-0138 0830h POSTER

Application of Differential InSAR to Mining

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In a NASA funded project we are applying differential InSAR to measure surface deformation associated with mining at depth. Surface displacement can be caused by rockbursts associated with mine collapse or mining-induced stress released on nearby tectonic features. The latter type of rockbursts are similar to tectonic earthquakes, but generally occur at shallower depths than non-induced events of similar size. Thus significant co-seismic surface changes may accompany

them. In addition, subsidence of a more gradual type may result from ongoing soft-rock (e.g., coal, potash, salt) mining. While such subsidence can accidentally occur above abandoned mines, it is most often planned as part of the ongoing ore extraction, especially in so-called long-wall mining. Predicting the amount and spatial extent of this subsidence is an aspect of mining engineering. It is important to compare these predictions with measurements of the actual deformation. Although mines use leveling and GPS measurements to monitor subsidence, these are generally performed with much smaller frequency (e.g., annually) and lower spatial resolution than repeat-pass differential InSAR can provide.

We are using ERS-1/2 raw SAR data provided by ESA and Eurimage, and the Gamma software for their processing. At present we are focused on the processing and modeling of data from two representative sites. By the end of the project we will have analyzed several more sites of subsidence and $M > 4.5$ rockbursts.

As an example of mining subsidence, we are currently analyzing data from the site of a coal mine in Colorado (USA), operating in a relatively flat and arid area. Numerous adjacent long-wall panels of extraction are used, some exceeding 5 km in length. A 600 to 750-m length of panel may be extracted per month, with a maximum subsidence of 1.5 to 1.8 m expected over each panel. The surface deformation can be monitored especially well during the summers of 1995 and 1996, when nine good-quality ERS-1/2 SAR scenes were gathered. Two of these scenes form a tandem pair to be used for topography. We are also making use of a 30-m DEM from USGS, maps of extraction panels, leveling data and microearthquake locations.

As an example of rockbursts, we are presently analyzing ERS-2 SAR data from the site of a M5.1 rockburst that occurred on April 22, 1999, in the gold fields of Welkom, South Africa. The event was induced on a fault transecting the mine and had a normal mechanism. Only two good-quality SAR scenes are available from this site, spanning about a year including the event. Thus the topography effect cannot be removed using interferometry. However, since flat surface and urban environment characterize this site, a clear fringe pattern is observed, apparently associated with the rockburst. This pattern suggests up to 9-cm subsidence. Its center is within 5 km from the seismically determined event location. Thus this rockburst represents an example of the capabilities of InSAR to provide ground truth locations for moderate shallow earthquakes.

To model the seismic source, we are using the RINGCHN software (Feigl and Dupre, 1999) based on analytic solutions for a homogeneous half-space. In order to model deformation in realistically complex crust, including layered structure and lateral heterogeneities, we are also developing a 3D finite-difference method of estimating deformation in a volume due to displacement on a fault surface. This method will be also used for the modeling of mining subsidence.

G31A-0139 0830h POSTER

Integrated GPS and SAR Interferometry to Measure Time-varying Surface Deformation Over a Giant Oilfield in California*

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We combine campaign GPS measurements with interferometric synthetic aperture radar (InSAR) images to map the deformation around and above the Lost Hills oilfield, one of the biggest fields in the USA. GPS at several dozen benchmarks every six months provides a long time series of total vertical and horizontal position change for monuments in the rapidly subsiding ground surface above the oilfield. InSAR maps using data from the ERS satellites measure relative changes at high spatial resolution with some moderate- to long-wavelength noise sources such as orbit error and atmospheric delays. The GPS data are used to model the moderate to long-wavelength surface deformation field so that the error contributions at those wavelengths in the InSAR images can be estimated and removed. The rapid subsidence (rates greater than 1 mm/day in 1995) and small size (roughly 3 km wide by 10 km long) require the use of short time intervals for the InSAR

pairs (between 35 days and 8 months), and also processing with the smallest possible sample spacing of 20 by 20 meters to resolve the extreme strain rates.

Previously published comparison of the tiltmeter measurements with well fluid extraction demonstrated both an immediate elastoplastic response to depletion and a time-dependent creep response. The high spatial and temporal resolution of the InSAR measurements will be combined with well records on fluid extraction and injection to separate the delayed response from the immediate response to better understand the processes of compaction in the oil reservoir rocks, extremely high-porosity diatomite. This will have direct relevance to the oilfield operations as the compaction can damage the wells and should be minimized. Surprisingly, in some parts of the oilfield, injecting more water to replace the pressure of the oil and gas extracted causes the subsidence rates to increase. Because the fluid input and output at the oilfield is measured, it provides an excellent test bed for understanding the response of the earths surface to fluid movements at depth.

* Work partially performed under contract with the National Aeronautics and Space Administration.

G31B MC: Hall D Wednesday 0830h

Advances in Modeling of Deformation Due to Earthquakes I (joint with NG, S, T)

Presiding: M Simons, California

Institute of Technology; Y Fialko,

University of California San Diego; S

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G31B-0140 0830h POSTER

InSAR Covariance Estimation, Data Reduction, and Combination of Multiple Datasets in Deformation Modeling

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Modeling deformation using spatially-dense interferometric synthetic aperture radar (InSAR) data has provided many new insights into physics of earthquakes. However, in published InSAR deformation studies, data covariances have been ignored and InSAR data incorrectly treated as independent, leading to biased modeling results. Moreover, the data sets are so large ($> 10^7$ points) that numerical computations are all but impossible if the complete covariance matrix is to be incorporated. We present here an approach for both data volume reduction and use of full covariance information that permits a more optimal inverse solution from InSAR and GPS data.

We first reduce the InSAR data volume using a two-dimensional quantization algorithm that retains many data points in areas of high fringe variability where deformation signal is present, but few were no deformation is observed. The algorithm typically reduces the number of data points by 2-3 orders of magnitude. We then estimate the data covariance matrix for the reduced data set by analyzing the spatial correlation of observed tropospheric noise, obtained from interferogram regions that are not deforming. We assume that the data covariance function is isotropic, i.e., only dependent on distance between two points in the interferograms. We find InSAR data are uncorrelated at distances greater than 2-5 km, hence most of the matrix elements are zero. Hence, when we propagate the errors we only have to calculate and store one sparse matrix line at any given time.

We apply this InSAR modeling strategy to the 1999 Mw7.2 Hector Mine earthquake, a right-lateral strike-slip earthquake that occurred in Mojave Desert, southern California. In addition to InSAR data from both ascending and descending orbits, we also use radar amplitude image offset data (SARIO) for both ascending and descending azimuth directions and campaign GPS observations from 55 stations. Comparison of InSAR and GPS data shows a large RMS difference of 5 cm that is mainly caused by poor accuracy of the vertical GPS component. Comparison of SARIO and GPS data suggests that the accuracy of the SARIO data is about 15-20 cm. We derive a fairly complex fault geometry with 9 segments from the field-mapped fault rupture, the SARIO data, aftershock locations, and from non-linear inversion of the data. We solve for variable fault slip on 1.5 km \times 1.5 km patches using non-negative least squares. Our optimal model indicates a maximum slip just northwest of the epicenter (6.5 m strike slip

and 1 m of reverse faulting) with an estimated geodetic moment of 6.24×10^{19} Nm (Mw7.2), similar to seismological estimates. Our modeling results and the SARIO data suggest that field observations underestimated the magnitude and extent of the fault rupture.

G31B-0141 0830h POSTER

InSAR derived focal mechanism of the 1994, M5.9 Double Spring Flat, Nevada earthquake

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The M5.9 1994 Double Spring Flat (DSF) earthquake occurred in the Sierra Nevada-Basin and Range Transition Zone within a complex step-over region between the Genoa fault (the Sierra Nevada range front fault) and the Antelope Valley fault. It was the largest earthquake to struck Nevada in the past 30 years. Based on early aftershock locations the main event was placed on the NE-striking nodal plane (Ichinose et al., BSSA, 1998). However, the location of the epicenter near a major NNW-striking fault and NNW-oriented, co-seismic ground-cracks suggest that the NNW-striking nodal plane was the rupture plane. We discuss geodetic data derived from descending and ascending 1993-1995 ERS interferograms to better constrain the focal mechanism of this earthquake.

The InSAR data provide a hint about which fault ruptured during the earthquake. Elastic inverse modeling shows that models with both, the mainshock on the NNW-striking, and the mainshock on the NE-striking nodal planes can explain the data. Models with the mainshock on the NNW striking fault plane, however, are characterized by slightly smaller slips between model predictions and observations than models with the mainshock on the NE-striking plane. This favors the geologically more plausible NNW-striking nodal plane as the fault plane.

G31B-0142 0830h POSTER

The Reliability of Earthquake Source Parameters Derived from SAR Interferometry

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Since the coseismic interferogram of the 1992, Landers earthquake, SAR Interferometry (InSAR) has been used to map the surface deformation due to many earthquakes. InSAR data have two distinct advantages over other coseismic geodetic data: they are spatially continuous, with spatial resolution of better than 100 m, and they do not require field campaigns to collect. A variety of inversion techniques have been applied to these data in order to extract earthquake source parameters, including fault geometry and slip distributions. Here we address the question of reliability of earthquake source parameters derived from InSAR, particularly where only a single interferogram is available.

Coseismic interferograms for 3 Turkish earthquakes are analysed: Dinar (M~6.4; 1995), Düzce (M~7.1; 1999) and Orta-Çankiri (M~6.1; 2000). In each case, only a single interferogram is used and, except for the Düzce earthquake, these data are the only geodetic data available. Source parameters are determined using a downhill simplex inversion technique. Errors in fault parameters are investigated using a Monte-Carlo bootstrap approach, in which best-fit solutions to 100 perturbed input datasets are found. The analysis of errors reveals surprisingly large uncertainties in some fault parameters. For the Dinar and Düzce earthquakes, magnitude of slip on the fault plane and fault rake trade off against each other such that neither is well determined. This results in a significant uncertainty in seismic moment (up to 50%) unless additional constraints are used. Similarly, for the Orta-Çankiri earthquake, fault slip trades off against the depth extent of faulting, although seismic moment is well determined in this case.

These uncertainties largely arise because InSAR only samples a single component of the displacement vector. We advocate the use of additional data, where available, to further constrain the earthquake source