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Recent high-resolution GPS observations of crustal movements revealed that silent slip events occurred in and below the deeper part of the seismogenic zone. For example, Ozawa et al. (2001) detected a silent thrust slip event in the deeper part of the Tokai subduction zone, which is a well-known seismic gap along the Suruga-Nankai trough. This event started from the beginning of 2001 and is migrating at the speed of about 20 km/year. Slip velocity of silent events is roughly estimated to be 10^{-8} - 10^{-9} m/s that is little larger than the velocity of relative plate motion.

To investigate the mechanism of silent slip events, we simulate the earthquake generation processes of a thrust fault in 3-D elastic half-space. First, we use the ordinal Dieterich/Ruina rate- and state-dependent friction law with cut-off velocity to the rate-dependence. We give depth distribution of constitutive law parameters based on experimental studies. Below the depth of the unstable-stable transition, critical weakening displacement begins to increase due to an increase of plastic deformation between micro-asperities. Around the transition zone, slow slip events are expected to occur due to large critical weakening displacement and small stress drop. The results of numerical simulations show that stationary slips proceed at the deeper part of the fault region, and then, they proceed gradually upward due to the stress concentration along the unstable-stable transition zone. In some cases, eventual silent slips occur at the deeper part of the seismogenic fault 10-50 years before instability. The slip velocity of this event is 10^{-9} m/s that is close to the observed value of slip velocity. A few years before instability, slip acceleration occurs along the transition zone. In some cases, silent slip events migrate horizontally along unstable-stable transition zone at the speed of about 10 km/year. Finally slip is localized into a narrow area at the deeper part of the seismogenic fault. Silent slip events can be interpreted as events caused by the stress concentration along the unstable-stable transition zone and the transitional behavior of the friction law.

Around the unstable-stable transition zone, actual frictional behavior is thought to be very complex. Shimamoto (1986) performed experiments using Halite to investigate frictional behavior around the unstable-stable transition. The results show the complex behavior where strength depends on strain rate: at a very low strain rate, strain rate strengthening occurs, at an intermediate strain rate, strain rate weakening occurs, and, at a high strain rate, strain rate strengthening occurs. These results suggest that at a very low strain rate, flow law is at work, at an intermediate strain rate, frictional instability can occur, and, at a high strain rate, strong viscous dissipation is at work. Using a spring and slider block system, we can reproduce slow slip events with this kind of friction law.

G61A-0977 0830h POSTER

Characterization of slow faulting with subdaily GPS positioning

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Over the last several years, data from continuously operating GPS stations have been used to detect transient deformation associated with large subduction zone earthquakes. Most recently, the Mw=8.4 June 23, 2001 Peru earthquake ruptured the Nazca-South American plate interface to become the largest event in the last 30 years. The mainshock was followed by a vigorous aftershock sequence, including three events with moment magnitudes of Mw=6.7, 6.5, and on July 7, an Mw=7.6 event. Two-hour position estimates from a continuous GPS station located at Arequipa, Peru, document transient deformation at time scales from hours to days. These signals are obscured by daily position estimates highlighting the need for utilizing sub-daily positioning to increase our ability to detect transient aseismic faulting. Station positions are estimated as stochastic processes with white noise resets every 2 hours using 24-hour data arcs. By applying stochastic resets to the coordinates only, the geometric strength of the 24-hour data arc for estimating carrier phase biases and atmospheric delays is retained. Station position estimates are thus obtained at a higher rate without significant systematic artifacts associated with higher frequency error sources. While modeling station positions as a white noise process may produce a time series that is noisier than a random walk model, it is a more conservative approach to identifying transient deformation. With this estimation scheme, subsequent position estimates remain uncorrelated in time, which is not the case with random walks. Moreover, the white-noise approach side steps the need to establish an a priori rate of random walk process noise which neither suppresses a true signal nor introduces erroneous deformation artifacts.

G61A-0978 0830h POSTER

Interplate coupling changes in the Tokai region, Japan, estimated from the vertical movements by leveling and tide gauge during 1960-2002

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The large earthquakes of more than magnitude 7.8 have repeatedly occurred along the Nankai-Suruga trough with an interval of 100-150 years. Since the last events of the 1944 Tonankai and 1946 Nankai earthquakes, it has passed more than 50 years. Recent findings of the 2001 slow slip event in the Tokai region by GPS dense continuous network led us to re-examine the possibility of slow slip events from the 1960s to the present in the Tokai region. We discuss the spatial changes of interplate coupling to make clear. Tide gauge measurements have continuously recorded at four sites since the 1960s and the precise leveling has repeated every year or every two year since the 1970s in the Tokai region by GSI. We estimated the changes of interplate coupling from these vertical movements. Characteristics of the interplate coupling are; 1) interplate coupling area apparently reached just beneath the Mikawa bay, which is located 30km depth of plate boundary, and 2) main area of the interplate coupling does not limited to the shallow plate boundary of coast area, but it extends to the in-land area. Sagiya (1999) already discusses the interplate coupling model from GPS measurements, respectively. However there are some differences between the observation and model calculation. Especially Sagiya's model could not explain exactly the subsidence at Omaezaki and the uplift at Oodaka, which is 100km west of Omaezaki. Moreover the convergence rate of the Philippine Sea plate is estimated to be about 2 cm/yr from the GPS measurements at the Suruga trough whereas those are 4 to 5 cm/yr at the Nankai trough (Heki and Miyazaki, 2001). The interplate coupling in the 1960s shows the subsidence rate at Omaezaki was less than 5mm/yr and it was about a half in 197s-1990s. It is suggested that interplate coupling is not full beneath Omaezaki in 1960s. Moreover the uplift is not detected at the inland area (Ise Bay) in 1960s. It could also suggest that the interplate coupling might have been weak in the eastern part of the Tokai region, suggesting the effects of afterslip due to the 1944 Tonankai earthquake. We also conclude that the intraplate coupling along the Suruga-Nankai Trough has changed episodically.

G61A-0979 0830h POSTER

Interplate coupling model and slow slip events in the Tokai region, Japan

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During 2001 in the Tokai region, Japan, GPS network by GSI detects the abnormal horizontal movements with the steady convergence movements due to interplate coupling and these abnormal movements are apparently kept going at present. By using the time dependent analysis with the GPS data, slow slip events are clearly illustrated and showed that the source area are limited to rather narrow region around Hamana Lake, which is located 60km west of Omaezaki (Ozawa, et al., 2001). The analysis is based on the residual of the ground deformations subtracted from the general trend and seasonal variations estimated from the data for a few years before March, 2000. Yamamoto et al (2001) pointed out that there might exist the changes of the annual changes in the coordinates observed by GPS measurements, and concluded that the estimated slow slip events might affected by such annual changes. We re-examined the ground deformation by fixing the Gujo-Hachiman GPS site, which is located about 200km NW of Omaezaki and used by interplate coupling model by GPS measurements (Sagiya, 1999). We estimated the trend and annual displacements in each year from 1996. Characteristics of the obtained ground deformation are: 1) Convergent displacements at the Tokai region in the four years, are episodic since April 1996 to March 2000 and show the decrease of rate and their variations of up to 80 % in the period of April 1999 to March 2000. 2) Convergent displacements disappeared in the western Tokai region, from Mikawa bay to Hamana Lake since January 2001, and the southeastward displacements are observed in the western area of Omaezaki. Convergent rates do not decrease in the

northern area and west coast of Suruga Bay. These suggest source region of the slow slip would not limited to rather narrow region around Hamana Lake, but it might extend to the further northern area, at least 60 km NE of Hamana Lake. Vertical movements by precise leveling (GSI, 2002) indicate the migration of the uplift area toward the east from the Hamana Lake, suggesting the source region of the slow slip event could also migrate to the east- or northeast-ward in significant amount. We may conclude that the source region of the slow slip movements could migrate towards the deeper part of the strongly coupled plate boundary of the anticipated Tokai earthquake (the invasion of the asperity ?).

G61B MCC: Hall C Saturday 0830h

Geophysical Modeling Using Spaceborne InSAR Measurements I Posters (joint with S, T)

Presiding: H Zebker, Stanford University; B Minster, Scripps Institution of Oceanography

G61B-0980 0830h POSTER

InSAR and GPS Analysis of Ground Subsidence in Mexico City

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We describe the recent subsidence of Mexico City due to ground water withdrawal using a combination of Interferometric Synthetic Aperture Radar (InSAR) for high spatial resolution and Global Positioning System (GPS) data for calibration and improved temporal information. Groundwater extraction in the basin of Mexico exceeds recharge, lowering the water table by 0.1-1.5 m/yr, reducing pore fluid pressure in the aquifer and overlying aquitard, and leading to compaction of lacustrine shales and surface subsidence.

We used ERS-2 data for Interferometric SAR analysis. Results indicate land subsidence in Mexico City between February 1996 and January 2000 at rates as high as 378 mm/yr in the eastern metropolitan area. The downtown region shows rates up to 115 mm/yr. GPS data suggests that these rates have been steady at least since 1995 and are due to steady declines in the water table. Available well data indicate consistent water level drops over the last decade, concurrent to the near-constant subsidence rate measured by both GPS and InSAR. Static groundwater level define an approximate linear relation between water level drop and surface subsidence: Correlation of the InSAR fringe pattern with mapped stratigraphic units indicates that maximum subsidence is primarily controlled by unconsolidated Quaternary lacustrine clays and silts in the shallow sub-surface, marking ancient Lake Texcoco, now obscured by urban construction on the old lake bed.

G61B-0981 0830h POSTER

Prospecting for Horizontal Surface Displacements Accompanying Land Subsidence in Antelope Valley, CA Using InSAR

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Comparing InSAR-displacement maps derived from acquisitions on ascending and descending satellite passes over Antelope Valley, California we investigate the importance of horizontal surface displacements in a 3-year subsidence pattern with a maximum subsidence of ~6 cm. Horizontal displacements have generally been assumed to be negligible in studies of land subsidence over extended areas. This assumption has been justified with the large horizontal extent of the compacting subsurface units relative to their thickness and

the small spatial gradients of the stress changes causing the compaction. However, poroelastic theory predicts horizontal displacements even under these conditions and recent observations have shown significant horizontal displacement over a seasonally stressed aquifer system. Where significant horizontal displacements are neglected, estimates of the aquifer system storage derived from paired subsidence/drawdown observations may be severely biased. Moreover, where InSAR using only one look-direction is used to measure vertical surface displacements horizontal displacements can lead to an over- or underestimation of the vertical movements.

The differences between surface displacements derived for the two different satellite look directions are not significant, suggesting that horizontal displacements accompanying the long-term inelastic compaction process are small. Although errors due to atmospheric effects and phase noise prohibit the reliable detection of horizontal displacements of less than ~2 cm magnitude in most areas, the differences between the displacement maps are not correlated with the known subsidence areas, strongly suggesting that only insignificant horizontal displacements are accompanying the inelastic compaction process in Antelope Valley. Our results thus support the hypothesis that horizontal displacements in aquifer systems are limited to the elastically deforming aquifers.

URL: <http://pangea.stanford.edu/~joern/AGU2002/>

G61B-0982 0830h POSTER

Ground Surface Deformation Around Tehran due to Groundwater Recharge: InSAR Monitoring.

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Tehran is located on an active tectonic and seismic zone. The surface deformation monitoring provides a powerful tool for getting a better understanding of faults kinematics and mechanisms. Used in conjunction with GPS networks, InSAR (Interferometric Synthetic Aperture Radar) provides dense and precise deformation measurements which are essential for mapping complex heterogeneous deformation fields. Moreover, urban and arid areas preserve interferometric phase coherence.

The archived acquisitions of ERS that span 9 months between September 1998 and June 1999 reveal wide areas of surface uplift (by as much as 9 cm). This vertical deformation (gradual in time) has probably no tectonic meaning but is rather the ground response to ground water recharge. These zones are all located downstream of large alluvial fans like the one of Karaj. The variation of effective stress caused by interstitial water draining could explain such surface deformation. It can also be noticed that some faults act as boundary for these deformation zones and fluid motion. The understanding of this deformation is relevant for groundwater monitoring and urban development management. It is also necessary for discriminating it from tectonic deformation that also occurs on this zone.

Due to the lack of attitude control of satellite ERS-2 since February 2001, the last images acquired could not be combined with the former acquisitions. Nevertheless, we expect to be able to enrich our set of images in order to map tectonic deformation on a longer period and to monitor in a more continuous way the deformation due to groundwater evolution. This would allow to quantify the permanent and reversible part of this signal.

G61B-0983 0830h POSTER

Magma Supply Dynamics at Westdahl Volcano, Alaska, Modeled from Satellite Radar Interferometry

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A series of ERS-1/ERS-2 satellite radar interferograms that span the time period from 1991 to 2000 show that Westdahl volcano, Alaska, deflated during its 1991-92 eruption and is re-inflating at a rate that could produce another eruption within several years. The rates of inflation and deflation are approximated by exponential decay functions with time constants of about 6 years and 2 days, respectively. This behavior is consistent with a deep, constant-pressure magma source connected to a shallow reservoir by a fluid-filled conduit. An elastic deformation model indicates that the reservoir is located about 6 km below sea level and beneath Westdahl Peak. We propose that the magma flow rate through the conduit is governed by the pressure gradient between the source and reservoir. The pressure gradient, and hence the flow rate, are greatest immediately after eruptions. Pressurization of the reservoir decreases both the pressure gradient and the flow rate, but eventually the reservoir ruptures and an eruption or intrusion ensues. The eruption rate is controlled partly by the pressure gradient between the reservoir and surface, and therefore it, too, decreases with time. When the supply of eruptible magma is exhausted the eruption stops, the reservoir begins to re-pressurize at a high rate, and the cycle repeats. This model might also be appropriate for other frequently active volcanoes with stable magma sources and relatively simple magma storage systems.

G61B-0984 0830h POSTER

Thermoelastic Contraction of a Pyroclastic Flow Deposit, Erupted From Augustine Volcano, Alaska, Observed With InSAR

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We construct a finite element model (FEM) of a pyroclastic flow deposit (PFD) on Augustine volcano, Alaska, to investigate deformation observed with interferometric synthetic aperture radar (InSAR) images. The PFD was emplaced during 1986 eruption of Augustine volcano. We generate 24 InSAR images, which span several intervals during 1992-1999, of the volcano to characterize transient deformation of the PFD. The three-dimensional problem domain of the FEM includes an elastic substrate overlain by a thermoelastic material representing the PFD. The geometry of the substrate is determined from a digital elevation model (DEM) and bathymetry data. The thickness of the PFD is determined from the difference between post- and pre-eruptive DEMs. The initial temperature of the PFD at the time of deposition, 400 degrees C, is estimated from the InSAR images via standard least-squares inverse methods, assuming a suite of thermoelastic material properties. Although the FEM predicts the major features of the observed transient deformation, systematic prediction errors are associated with the a priori PFD thickness distribution. We use an iterative FEM mesh adaptation method to optimize the PFD thickness distribution. We investigate a poroelastic deformational mechanism, caused by the decay of excess pore-fluid pressure in the substrate due to the gravitational load of the PFD, as an alternative to the thermoelastic model. However, the magnitude of the predicted poroelastic deformation is insufficient.

G61B-0985 0830h POSTER

Combining InSAR and Long-Period Seismic Waveform Modelling – the 1997 Manyi, Tibet Earthquake

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Elastic dislocation modelling using ground displacements measured with InSAR is a powerful tool for investigating the source parameters and slip distributions of shallow continental earthquakes. However, problems with tradeoffs between key source parameters (e.g. moment, fault dip and rake) can arise since often only data from a single satellite line-of-sight (LOS) are available. Subsequently the models based on such data can be ambiguous with some parameters poorly constrained. In this study we assess the potential improvements that can be made to earthquake source models derived from InSAR data by using long-period (135-150 s) seismic

waveform matching as an additional constraint. Long-period seismology is an effective technique for estimating the moment of an earthquake, and should therefore reduce the tradeoffs associated with it.

We use as an example the $M_w=7.5$ 8th November 1997 Manyi, Tibet earthquake. Six coseismic interferometric pairs were acquired spanning time intervals of up to eight months, and the topographic effects removed from the resulting interferograms using a digital elevation model constructed from ERS tandem pairs. We model the earthquake: a) as a series of rectangular elastic dislocations in an elastic halfspace, fitting the InSAR data alone; b) as an equal number of centroid moment tensors (CMTs), matching synthetic seismograms calculated for 49 GSN stations by the summation of over 5000 spheroidal and toroidal modes of oscillation of the Earth to the real data in a last squares sense; c) in a joint inversion where a CMT is calculated from the geometry of, and slip on, each dislocation, and the total misfit of both the InSAR and the seismic data is minimised.

The joint inversion scheme converges to a global minimum-misfit solution in fewer restarts than that required for the InSAR alone, and has a moment within 1% of that of the seismic solution, suggesting that a reduction has occurred in the tradeoffs related to the moment, and that the best-fitting fault geometry is compatible with the seismic data. This fault geometry requires a reversal of dip direction close to the mid-point of the mapped fault, and also a change in the rake; these factors may explain the apparent asymmetry across the fault observed in the interferogram.

G61B-0986 0830h POSTER

Crustal deformation of Iwojima volcano in Japan detected by SAR interferometry

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Iwojima volcano is one of the most active volcanoes in Japan. Large-scale crustal deformation is ongoing in the island. It is suggested that the island was uplifted about 40m during the recent 200 years (Kaizuka et al., 1985). The crustal deformations are believed to be of volcanic origin and are outstanding in terms of the magnitude and the complexity. It is important to understand the 3-dimensional evolution of the deformation field with time to understand the behavior of the volcanic sources. Although there are 2 permanent GPS sites in the island, they are not sufficient to monitor the extremely complex spatial and temporal patterns of the deformation. We here use JERS-1 SAR data to map the detailed surface displacement field associated with volcanic activity of the island. We processed up to 20 different pairs spanning 1992 to 1998. It is revealed that the rate of surface deformation was not constant but episodic. We also find that the displacements seem to consist of three different subsets of deformation pattern; i.e., Motoyama (north east of Iwojima), Chidorigahara (near an old crater), and Suribachi-yama mountain (south of Iwojima). The spatial pattern of the first subset is simpler than the others and explainable as an inflation and deflation of a spherical point-source. Source depth inferred from the pattern is smaller than 2 km. However, the rate of volume change is not constant and sometimes even changes the polarity, which suggests the complexity of the volcanic source structure and mechanism.

G61B-0987 0830h POSTER

Coseismic Deformation From the $M_w=7.8$ Kokoxili, Tibet Earthquake, From ERS InSAR Data.

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The 14 November 2000, $M_w=7.8$ Kokoxili earthquake ruptured more than 400 km of the western end of the left-lateral Kunlun fault, in Northern Tibet. We use ERS InSAR data, 1 m-resolution Ikonos images and

the 90 m-posting SRTM data to map the surface rupture and the displacement produced by the earthquake.

The surface break is clearly visible on Ikonos images. It is characterized by relatively simple, linear segments separated by more complex sections, involving en-echelon extensional cracks, pull-apart structures and pressure ridges. In some areas, the width of the rupture zone reaches several hundreds of meters, making the direct measurement of the coseismic displacement difficult. The InSAR data available to date show that the western end of the rupture reaches the extensional horsetail system at the western tip of the Kunlun fault, near the epicenter determined by the USGS. East of 91°E, the rupture follows the main trace of the Kunlun fault up to 93.6°E, where it bends southerly along the southern front of the Burhan Budai mountains, then ends near 95°E. The maximum surface slip is observed near 93.3°E and is about 7 m, less than half the value previously reported from field observations. Because of the poor coherence of the InSAR data near the fault and in the snow covered mountains, interferograms are unwrapped by pieces. We invert the interferometric maps using a constrained least-square inversion method. The fault is modeled with 10 km-long × 5 km-wide fault patches, following a simplified fault trace. We resolve (1) the horizontal component of slip on fault patches, (2) a linear ramp for each interferogram, and (3) an ambiguity constant for each piece of unwrapped phase. Fault dip is then locally adjusted to better fit the data and account for the fringe rate asymmetry between the two sides of the fault.

G61B-0988 0830h POSTER

Active Deformation at Canyonlands National Park: Distribution of Displacement Across Grabens Using InSAR

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The Needles District of Canyonlands National Park in southeastern Utah is a unique geologic region in which active extensional tectonics can be observed. The arcuate, northwest-trending system of faults that define the grabens region of the Needles District have simple stratigraphy and excellent exposure, therefore permitting the study of normal faults under relatively simple conditions. A 460 meter-thick sedimentary section is underlain by the Paradox evaporites, all of which sits within western flank of the Monument Uplift. It is generally accepted that once the adjacent Colorado River downcut into the Paradox Member, the sedimentary sequence became unbuttressed, and was consequently allowed to slide along the northwest dip of the Monument Uplifts western flank.

Using satellite radar interferometry (InSAR) and the Global Positioning System (GPS), we are monitoring recent deformation across the graben system. Prior to our study, knowledge of Canyonlands deformation rates was limited to long term geologic averages. We use synthetic aperture radar data collected by the ERS-1 and ERS-2 satellites encompassing a 7 year period of observation (1992-1999). We have produced 10 successful interferograms with short baselines (< 100 m) from both ascending and descending orbital trajectories. Preliminary results indicate regional subsidence within the graben system. The interferograms show surface deformation in the grabens as great as 3 mm/yr. In the look direction of the satellites, with greatest displacements occurring primarily in the northwestern portion of the region. InSAR derived rates are consistent with previously published results. Individual graben bounding faults can be resolved in many interferograms and we can resolve the spatial distribution of deformation across the graben system. Transects across the interferograms show a distribution of displacement rates that decreases to the east. Prior research has demonstrated that within the grabens there is a general eastward decrease in graben age and complexity, in addition to an increase in bounding fault asymmetry. Our work allows us to compare these observations with current displacement rates.

G61B-0989 0830h POSTER

Slip inversion on complex fault surfaces using angular elastic dislocations

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We present a new 3D slip-inversion method based on the analytical solution of an angular dislocation in a linear-elastic, homogeneous, isotropic, whole- or half-space. The approach uses a boundary element method (BEM) that employs planar triangular elements of constant displacement to model fault surfaces. Discretization of surfaces into triangular boundary elements allows the construction of complex 3D fault surfaces with irregular triplane and no overlaps or gaps. A damped least squares method is used to minimize the functional

$$\| \phi \cdot b - d \|^2 + \epsilon^2 \| \nabla \cdot b \|^2,$$

where b represents the slip distribution on the faults, ϕ the influence coefficient matrix and d the observed deformation data. ∇ is a discrete Laplacian operator for triangulated 2-manifolds, which serves as the measure of the roughness of the slip distribution, and ϵ represents the smoothing parameter. We have tested the method on synthetic forward elastic models using complex 3D fault geometry. Only one component of the computed displacement field (U_x , U_y , or U_z) was needed to constrain the inversion. Slip inversion results were used to refine initially simple models, developing more complex models that approached the fault geometry of the original forward model. We have also used the method to invert for fault slip on several natural examples employing a variety of observational data including: (i) field measurements of deformed stratigraphic layers, (ii) GPS and (iii) InSAR measurements of coseismic displacements.

G61B-0990 0830h POSTER

Interferometric Synthetic Aperture Radar (InSAR) Analysis of Current Deformation Along the Arava Valley, Dead Sea Transform, Israel

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The Dead Sea transform (DST) is a left-lateral strike-slip plate boundary between the Arabian plate and the Israel-Sinai sub-plate. We present here results of an Interferometric Synthetic Aperture Radar (InSAR) analysis of recent ground displacements in the Arava Valley (AV), which is a 160km long depression in the DST between the Dead Sea basin in the north and the Gulf of Elat (Aqaba) in the south. The general structure of the AV is of NNE-striking en-echelon segments, a few tens km long each, enclosing small extensional and compressional structures in the major step zones. The current slip rate along the DST is poorly constrained and there are some indications that the AV segments are locked. For example, paleoseismic data indicate decrease in earthquake magnitude since Late Pleistocene, and a low seismicity level has been measured during the past 15 years. Using a hybrid approach of topographic phase construction (combining a DEM and a suitable ERS-1 to ERS-2 tandem pair) we analyzed five ERS frames of both descending and ascending tracks. Interferograms were generated from almost every possible pair and span periods of 2-74 months between 1995 and 2001.

We identified two regions in the AV with systematic ground displacement: (1) an area about 35 km long and 20 km wide, north of Elat, that includes the playas of Yotvata and Avrona, and the coastal sabkha of Elat, and (2) an area about 10 km long and 5 km wide in the central AV (east of Zofar) where the major Transform is observed at the surface and traced by seismic lines at the subsurface. In both regions the dominant displacement is vertical. The Yotvata playa exhibits continuous uplift at a rate of 85 mm/y between 3/1995 and 11/1995, and 15 mm/y between 5/1996 and 11/1998. The linear southeastern border of the uplifted area coincides with a right-step in the major fault, suggesting that uplift is related to local compression due to the change in the fault strike. The Avrona playa and the Elat sabkha show alternating uplift and subsidence that are synchronized with fluctuations in the local groundwater levels. This suggests that processes within the aquifer system are the cause for the observed surface displacements. In the Zofar area, interferograms of ascending and descending tracks reveal two separate phases of subsidence: 5-10 mm between 5/98 and 2/99, and 25-30 mm between 4/99 and 2/01. The association between the linear borders of the subsiding area and active faults suggests that the observed subsidence reflects slip along these faults. Our results indicate that current tectonic activity in the Arava Valley is limited to stepping zones between segments of the DST. The relationship of these local deformation patterns to the general left-lateral slip of the Dead Sea transform is being investigated.

G61B-0991 0830h POSTER

Numerical Modeling of Large Scaled Flank Displacements at Mount Etna Revealed by SAR Interferometry.

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An interferometric study, based on the analysis of more than 400 interferograms, shows the occurrence of displacements on the south-eastern flank of Mount Etna between July-August 1996 and January-February 1998. Motions are localized in two main sectors. A southern sector is limited to the South by an active anticlinal ridge and an eastern sector, bounded by the Pernicana faults system to the north, by rift zones to the west and by the Mascalucia-Tremestieri-Trecastagni fault system (MTTFS) to the southeast, slides to the east.

Ascending and descending interferometric data allow us to evaluate the vertical and horizontal components of the displacement field. Displacements along the MTTFS are essentially dextral with a small normal component and vertical motions are prevailing along the anticlinal ridge.

The onset of sliding coincides with a new cycle of volcanic activity in July-August 1996. Field measurements confirm that these displacements started simultaneously to the volcanic activity.

We use numerical modeling in order to constrain the mechanics and boundaries of active tectonic processes at Etna. This modeling is based on a three-dimensional boundary elements methods, which takes the realistic topography of the volcanic edifice into account. Using forward modeling we investigate whether the displacement field is compatible with gravitational effects, regional stresses or intrusions in the rift zones. We define the geometry of the south-eastern faults and the detachment responsible for the southern anticline. We show that although a north-south compression can explain the uplift of the anticlinal ridge, it is not sufficient to create the dextral-normal motion along the MTTFS. This north-south compression is compatible with last phase of convergence of the Magrebo-Appennine chain over its foreland. On the contrary, gravitational spreading of the eastern sector is consistent with motions along the MTTFS, but can not explain the displacements along the anticlinal ridge. Thus, the displacement observed on the interferograms are caused by a complex stress regime which reflects gravitational effects and regional stresses.

G61B-0992 0830h POSTER

A Modification to Goldstein's Radar Interferogram Filter

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The application of SAR interferometry (InSAR) to digital elevation modeling and deformation monitoring encounters problems due to noise in the interferometric phase, caused by water vapor in the atmosphere, incoherent temporal changes of the observed terrain, and geometrical decorrelation. These factors dramatically reduce the capabilities of radar interferometry in many applications, for example compromising detection and analysis of small (spatial) scale deformations. The quality of digital elevation models and displacement maps can be improved by filtering the interferometric phase.

In this paper, we present a modification to the Goldstein phase filter [1]. This filter amplifies dominant frequencies in patches of the interferogram with a factor alpha, thus not affecting noisy areas, while enhancing interferometric fringes. The filter is modified by making the factor alpha dependent on coherence ie incoherent areas are filtered more strongly than coherent areas.

The proposed filter is compared with other filtering techniques in the spatial and frequency domain. The effectiveness of the different filtering algorithms is evaluated using synthetic phase patches merged with real InSAR data, thus allowing preservation of realistic noise characteristics but giving control over the extent, shape and density of the simulated interferometric fringes. Finally, results are presented from interferometry data from the West Australian outback.

[1] Richard M Goldstein and Charles L Werner. Radar interferogram filtering for geophysical applications. *Geophysical Research Letters*, 25(21): 4035-4038, November 1998.

G61B-0993 0830h POSTER

On the Detectability of Ground Deformation for Monitoring CO₂ Sequestration in Underground Reservoirs Using InSAR and GPS

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We address the problem of detecting ground deformation patterns due to sequestration of CO₂ in subterranean reservoirs using Interferometric Synthetic Aperture Radar (InSAR). The detectability of deformation is dependent on the size of the deformation and level of phase noise present in the interferogram in the scene of interest. We distinguish two kinds of noise in InSAR deformation maps, namely that due to correlation of the SAR images forming the interferogram and additive phase noise due to atmospheric inhomogeneities. Based on a given expected deformation pattern, we set a decorrelation phase noise root-mean-square (rms) level and solve for InSAR system parameters such as sensor baseline and number of looks. Phase noise due to atmospheric inhomogeneities result from the interaction of the radar signal with the refractivity random field of the atmosphere, in particular the lower troposphere. We appeal to Kolmogorov turbulence theory to stochastically model this random field, the purpose of which is to compensate for atmosphere phase noise. To this end, we employ geostatistical techniques, such as kriging, to interpolate an approximation to the atmosphere signature using GPS zenith wet delay (ZWD) data as control points. The resulting model reduces overall rms of atmosphere phase noise by about 50%. We show that the expected deformation magnitude leads to a total phase noise rms level of 25.7° with 20 looks taken in the radar image.

G61B-0994 0830h POSTER

Co-Seismic Crustal Deformation of the 1996 Onikobe Earthquakes, Japan, Detected by InSAR

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Two earthquakes of magnitude 5.9 and 5.7 occurred at onikobe geothermal area, northeastern Japan, on 11 August 1996. On 13 August 1996, another earthquakes of magnitude 4.9 occurred on the southwestern extension of the M5.7 earthquakes. These three earthquakes caused significant disaster near the hypocentral region.

The hypocentral area locates at the southern edge of seismically active region in the Tohoku mountain arc. It is known that the lower limit of seismogenic layer is extremely shallow, which is possibly related to the local thermal structure [Hasegawa *et al.* 1998; Umino *et*

al. 1998]. Detecting the coseismic displacement by InSAR may provide another look into the structural properties beneath the region. We processed JERS-1 level 0 data and generated 22 interferograms that bracketed the earthquake occurrence. We could detect significant phase changes nearby the hypocenters. Processing other pairs that do not bracket the earthquake, we did not observe similar phase changes and confirmed that they were caused by the earthquakes.

Preliminary result of the expected fringes is based on a seismically derived earthquake fault model [Umino *et al.* 1998], and is largely consistent with the detected fringes. There are some obvious differences between them, however, and they might tell us some new insights on the crustal properties.

G61B-0995 0830h POSTER

Measurement of Instantaneous Sea Level by L-band Radar Interferometry

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The radar interferometric measurement on sea surface has not been considered feasible, but Alsord *et al.* (2000) recently demonstrated that interferometric phases of L-HH SAR were correlated with centimeter-scale changes in the height of water surfaces within flooded vegetation. We present the characteristics of the JERS-1 SAR interferometric phase on seawater around Kaduckdo, Korea, and propose a possible application of SAR to measuring instantaneous relative sea level. Coherent signals, caused by manmade oyster farm structures and comparable to those from land in terms of coherence, were observed. Using 21 interferograms produced from 11 JERS-1 SAR single look complex data sets, the instantaneous sea level changes were estimated for the first time. The absolute sea level changes could not properly be restored by interferometric phases alone because of the discontinuity of phase and the large sea level changes in the area of interest. The wrapped phases are limited to an estimation of -7.6~7.6 cm changes due to uncertainty of sign (up or down). The comparison of the radar measurements with the tide gauge data (OTT-R20) yielded a relatively low correlation coefficient, 0.57. The possible error sources included the tide gauge measurements, which was not on-site measurements but 5 km away from the test site, and phase noise error (1.8 cm). We have overcome the ambiguity problem to some extent by exploiting radar back-scattering intensity. The radar intensity from sea farms was normalized using the statistics of the intensities at seawater and urban land area. The normalized intensity was inversely proportional to the sea level with a correlation coefficient of -0.83. We could thus constrain the number of wrapping counts to one (13 pairs) or two (9 pairs) within 68% confidence interval. When the wrapping count was chosen through the proposed method, the correlation coefficient was improved to be 0.96 with an r.m.s. error of 6.0 cm. The results show a feasibility of radar interferometry combined with altimetry to sea level measurement.

G61B-0996 0830h POSTER

Observation and Interpretation of Mining Induced Subsidence With Permanent Scatterers

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Mining activities in hard coal areas lead to widespread surface subsidence in numerous areas. This effect is enforced by the continuous loss of matter in the underground because most of the excavated soil is stored on surface dumps and not restored in the mines. Subsidence occurs intensively under cropped area and leads to spatial and temporal influences of the environment. In brown coal areas the groundwater table has to be lowered below the surface mining level to provide mining of brown coal in opencast pits. This is guaranteed by using fountains that extract the groundwater around the mining area. The slow groundwater stream of the underground causes a total drawdown also resulting in depressions around the mining areas. Mining induced subsidences show significant amounts of motion with rates ranging from some millimetres to some decimetres per measure interval. The changes by drawdown occurred in a range of 10 years while the effects

of the underground mining show changes on surface in ranges less than one year.

The aim of our work is to investigate the subsidence in two broad German mining areas by means of remote sensing. The investigated areas are the Ruhr area where 80% of the German hard coal is mined and the brown coal surface mining in the Lower Rhine Embayment. Within this second area of investigation some faults occur which divide the underground in clods. As a result this region shows the strongest gradient of the so far ground measured motions as well in strike as in cross strike of the tectonic system.

Experientially, the acquisition of the ground changes has been gathered by ground based levelling which provide line information. The subsidences are now monitored as a large coherent area using remote sensing technologies, like SAR Interferometry and Permanent Scatterers. The Permanent Scatterer method is based on SAR Interferometry and is advanced at the German Aerospace Center. Ground measurements are used to validate the new Permanent Scatterer technique. In doing so first interferometric results show a great accordance to the ground measurements of the Regional Survey Authority. A net of ground levelling defines the quality of the satellite based monitoring approach in terms of a reference level. Concerning method estimation our project provides an accurately estimation and relativisation of the compared monitoring systems.

The tectonic interfaces are especially suited for investigating the time-spatial tendencies of motion processes. It is a matter of current research to assess the local and episodic procedure of the relative motions in respect of the interface structures. Remote sensing provides a practicable opportunity to observe the motion sequences on interfaces and different materials. Our approach might be able to deduct the recent motion sequences and consequently to deduce statistic and deterministic predications of the nature of relative motions as a function of mechanical properties.

G61B-0997 0830h POSTER

Potential for Application of PSInSAR Data for Tectonic Modelling in Subduction Areas

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Interest has been increasing over the last few years in the use of satellite radar interferometry data (InSAR) for applications in seismology and tectonics. We report here on a new technique, PSInSAR, which relies on permanent scatterers and offers the possibility of measurements of ground displacements to a degree of accuracy, and over periods of time, previously unobtainable from conventional interferometry. This technique has been developed by TeleRilevamento Europa of the Politecnico di Milano in Italy. A permanent scatterer is any large, permanent angular object, such as building roofs, metallic structures, and even large boulders. Using these data, very accurate displacement histories can be obtained for the period 1991 to the present. Calibration with GPS data show good agreement, but the PSInSAR data are less noisy. The effect is akin to suddenly having a very dense GPS network retrospectively available for the last ten years in any moderately urbanised area in a region for which a satellite data archive exists (about 50 per cent of the globe). Data have been gathered for the area around Suruga Bay, Japan, which is expected to be the locus of a future great Tokai earthquake. Previous studies have used levelling or GPS data to model the locked part of the subduction plane in this area, using the Akaike Bayesian Information Criterion (ABIC) method. This method could be used with PSInSAR data, which would be likely to yield a better result on account of the greater density of data. Furthermore, there is now the potential to use the ABIC method in any subduction area, whether there exist GPS/levelling data or not, provided only that the area is sufficiently urbanised to yield adequate permanent scatterers as data points. This work results from a European Space Agency (ESA) 'Earth Observation Market Development' project entitled 'Developing markets for EO-derived land motion measurement products', involving, NPA (lead), the British Geological Survey (UK), Imperial College (UK), TeleRilevamento Europa (Italy), ImageONE (Japan), the Geographic Survey Institute (Japan), Oyo Corporation (Japan), Fugro (Netherlands) and SARCOM (ESA data distributing entity).

G61B-0998 0830h POSTER

Realistic Error Modelling for InSAR: Determination of Uncertainties in Earthquake Slip Distributions.

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The major source of error in InSAR measurements results from changes in tropospheric water vapour concentrations, creating phase delays that are unrelated to ground motion. These can be distributed over distances of tens of kilometres and, if interpreted as surface deformation, can cause errors in measurement as large as 10 cm. Here we present a simple modified Monte Carlo (MC) method for determining the impact of these errors on the accuracy of model parameters derived from InSAR data. In particular, we examine the reliability of InSAR-derived earthquake slip distributions.

Conventional MC bootstrap methods are often used for determining errors in model parameters derived from InSAR data. An ensemble of best-fit parameter estimates is found using different input data sets. Each of these data sets is derived from the original, but has its individual phase measurements randomly perturbed in a normal distribution about their original value using an a priori standard deviation. Errors in model parameter estimates are found from the distribution of best-fit solutions to each perturbed data set. For InSAR data, however, conventional MC fails to account for the spatial correlation of atmospheric errors between multiple sampled phase measurements. When the interferogram is sampled densely compared to the wavelength of atmospheric errors, conventional MC can grossly underestimate the errors of model parameter estimates.

To produce realistic error bars for parameter estimates, the interferograms variance-covariance matrix (VCM) must first be determined. A practical approach for this is to determine the mean covariance vs distance function (autocorrelation function), either spatially or from the interferograms power spectrum using the Wiener-Khinchine theorem (e.g. Hanssen, 2001). This must be done using a part of the interferogram away from the deformation, or, where this is not possible, after a first-pass model has been removed. Using the covariance vs distance function, an approximate VCM can be generated for the sampled points of the interferogram. It is then possible to synthesise an ensemble of perturbed data sets that will have this VCM. These perturbed data sets can be used to produce realistic errors for model parameter estimates.

We use this technique to examine the reliability of earthquake slip distributions derived from InSAR. Plots of the distribution of slip error on the fault plane are powerful tools for distinguishing those areas of the fault plane where slip patterns should be believed and those where they are spurious.

URL: <http://www.earth.ox.ac.uk/~timw>

G61B-0999 0830h POSTER

Application of Spaceborne Differential Radar Interferometry to Rockbursts, Mining Subsidence and Shallow Moderate Earthquakes

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We have processed ERS SAR scenes for several sites of rockbursts and mining subsidence, including South Africa (gold), Colorado (coal), the state of New York (salt), Germany (potash), and Poland (copper). We are also looking at JERS-1 scenes from a potash mine in the Ural mountains (Russia) for which no suitable ERS data exist. Sizeable mining-induced events have occurred at most of these sites: mb5.1 in April 1999, S. Africa; ML3.6 in March 1994, New York; ML4.8 in September 1996, Germany; mb4.9 in April 2000, Poland; and mb4.7 in January 1995, Urals. It is reasonable to expect detectable surface displacements from rockbursts, as they are rather shallow compared with tectonic earthquakes of similar size. Indeed, in the case of the 1999 S. African event differential InSAR detects up to 9-cm displacement away from the satellite, while the 1995 collapse in the Urals has resulted in up to 4.5-m surface subsidence. Some of the study rockbursts have occurred on the background of ongoing mining subsidence (e.g., Poland, Urals, New York), adding a detectable boost to the existing subsidence rate. In other cases, mining subsidence is planned and intermittent, without unexpected collapse (e.g., long-wall coal mining in Colorado).

We have applied deformation modeling using a 3D finite-difference code, focusing on the April 1999 event that was associated with a normal slip along the Dagbreek fault. Seismic events in this area (Welkom, S. Africa) are commonly associated with collapse of mined out volumes around west-dipping normal faults, but it is not clear how these faults contribute to the seismic and static displacements. The 1999 event provides an opportunity to address this ambiguity, as our InSAR measurements of surface displacements are complemented by local, regional, and teleseismic waveform records, as well as by measurements of displacements in the mine tunnels intersecting the Dagbreek fault. We are using these data to constrain the source and are investigating the use of 3D modeling methods in resolving discrepancies between seismically and geodetically based models.

Other than contributing to the mining practice, our InSAR results are relevant to the identification of ground truth to be compared with seismically determined epicenters. The 1999 S. African event is our best example in this respect, with an interferogram showing a clear fringe pattern that is easy to compare with existing seismic locations. For the purpose of ground truth, we have also examined ERS SAR scenes over sites of moderate tectonic earthquakes in Algeria (northern Africa). Due to the configuration of the existing seismic networks, these events are commonly located much too to the north. So far we have identified a possible signal (2 cm LOS) in the differential interferograms from descending and ascending interferometric pairs over the site of a December 1999 Mw5.6 earthquake, and are in the process of looking at additional SAR scenes over a site of a November 2000 Mw5.7 event.

Our results show that differential InSAR can be effective in providing detailed spatial coverage of surface changes associated with mining activities, as well as in establishing ground truth for the seismic locations of moderate tectonic earthquakes. The main limitation of the technique for such purposes is the insufficient temporal coverage of sites of interest by the ERS satellites, resulting in extensive decorrelation in some of the study cases. ENVISAT data are likely to be more effective in the future, especially if regular data collection is supplemented with ordering of data acquisitions on as-needed basis.

G61B-1000 0830h POSTER

Crustal Deformation Mapping with Satellite SAR Interferometry: Applied to 1999 Chi-Chi, Taiwan Earthquake

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The 1999 Mw=7.6 Chi-Chi earthquake was the largest inland earthquake of Taiwan in the twentieth century. We study with synthetic aperture radar interferometry (InSAR) the pre- and co-seismic surface deformations in an epicentral area of about 1500 km². Five radar images acquired by C-band SARs onboard the ERS-1/2 satellite are combined to create interferograms to map the sensor-to-ground displacements.

The co-seismic interferograms (1998-1999) have revealed significant crustal deformations. The arc-shaped fringe patterns (about 10 fringes) reflect uneven ground displacements produced by the major slip along the Chelungpu fault, a low-angle reverse fault. The interferometric results agree well with GPS measurements at 19 sites. Combining the co-seismic interferogram with the GPS data, it is found that the most significant deformations in the study area were around the Taichung city area where the subsidence ranged from 10 to 30 cm, and the southeastward horizontal motions ranged from 70 to 140 cm. The measurements are compared with the latest fault model derived for the earthquake. The results showed good agreement in general between the measurements and the model. Some disagreement at localized areas may indicate some minor geological structures.

The pre-seismic interferograms (1996-1999) have shown up to more than 1 fringe of crustal deformations. The measured deformations are considered having been governed by the general tectonic settings in Taiwan, i.e., east-west tectonic compression. The results also support the recent findings that the south-western coastal region belongs to the active deformation front, rather than to the stable foreland.

G62A MCC: 133 Saturday 1330h

Geophysical Modeling Using Spaceborne InSAR Measurements II (joint with S, T)

Presiding: H Zebker, Stanford University; B Minster, Scripps Institution of Oceanography

G62A-01 1330h INVITED

Co-seismic and post-seismic slip from multiple earthquakes in the northern Chilean subduction zone: Joint study using InSAR, GPS, and seismology

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Several large subduction zone earthquakes (Mw > 7) occurred in the region near Antofagasta, Chile between 1987-1998. Here, we investigate the spatial and temporal relationship between these events and any associated post-seismic slip. We use InSAR, GPS, and seismic data to constrain the distribution of slip on the subduction zone interface for the July 30, 1995, Mw 8.1 earthquake. Only InSAR and seismic observations are available for the Mw 7.1 earthquake on January 30, 1998. We find that the seismic data is particularly useful in providing spatial resolution of co-seismic slip for the 1998 earthquake. For earlier earthquakes in 1987 and 1988, only seismic data is available. Our current inversion, as well as previous results from others, suggest that there is little slip during the 1995 earthquake near a 1987 Mw 7.5 event. Our analysis further suggests that little moment from the 1995 slip distribution released near a 1988 Mw 7.2 event. According to our model for the 1995 event, the 1998 event occurred down-dip of the 1995 rupture. In other words, preliminary models indicate that these events do not overlap significantly and appear to be tilting up the slab interface.

Compared with other recent large subduction zone earthquakes (e.g., Jalisco, Mexico, 1995), post-seismic slip from the Mw 8.1 Antofagasta earthquake is small. The satellite line of sight displacements are of order a few cm, comparable to the noise. This signal strongly correlates with topography in most of our interferograms, suggesting a possible atmospheric origin. However, when the InSAR data from several tracks is combined with horizontal GPS displacements (Klotz et al., 2001), we are able to bound the magnitude and distribution of after-slip on the fault.

G62A-02 1345h INVITED

Melt Beneath the Siple Coast Ice Streams

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The Siple Coast ice streams flow over a well lubricated bed. With virtually no surface melt, basal melt is required to sustain a well lubricated bed. We used a recently derived InSAR map of the velocity of Siple Coast ice streams to estimate basal melting/freezing. Melt is determined, in part, by the basal temperature gradient. To obtain this gradient, we modeled ice temperature using the standard advection-diffusion equation for heat transport with the InSAR data used to determine the horizontal advection. Basal melt is also affected by the basal shear stress. We used both force-balance and control-method inversions of the InSAR velocity data to determine basal shear stress.

We find a wide range of melt conditions. Most of the melt occurs beneath the tributaries where larger basal shear stresses and thicker ice favors greater melt (e.g., 10-20 mm/yr). Basal freezing is predicted beneath much of the ice plains of Ice Stream C and Whillans Ice Stream. With a significantly higher basal shear stress, little or no freezing occurs beneath Ice Stream E. These findings are consistent with indications of variable flow over the last millennium in the section of the Ross Ice Shelf fed by Whillans Ice Stream and Ice Streams A and C and with relatively steady flow inferred for the region fed by Ice Streams D and E.