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 RNGCHN 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 interferometry synthetic aperture radar (IntSAR) 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 subsidng ground surface above the oilfield. IntSAR 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 IntSAR 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 IntSAR 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 IntSAR measurements will be combined with well records on fluid extraction and injection to separate the delayed response from the immediate reponse 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 Jonsson,** Stanford University

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 × 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 modelling 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 misfits 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 parameters. We show that the use of ascending and descending interferograms together, a few well-place GPS displacement measurements or seismic data can greatly improve the reliability of source parameters. Without these data, solutions based on a single interferogram should be treated with caution.

G31B-0143 0830h POSTER

Imaging Fault Structure of the 1995 Kozani-Grevena Earthquake Sequence, Greece Using High Precision Aftershock Locations.

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The May 13, 1995 Kozani-Grevena earthquake (Mw=6.5) is a natural laboratory for studying crustal normal fault systems. The event and its aftershocks have been well observed geodetically, seismically, and geologically, providing an opportunity to integrate data sets to create a detailed subsurface fault model and investigate triggering and deformation associated with a large normal fault earthquake. Previous modeling of the earthquake has focused primarily on single geodetic data sets (e.g. inSAR - Meyer et al, 1996, GPS - Clarke et al., 1997) and has led to conflicting subsurface fault interpretations. In order to better model the subsurface fault geometry we have relocated aftershocks and use the interpretation of multiple complementary data sets to constrain a 3D boundary-element model of the earthquake sequence.

Using the Double-Difference earthquake location algorithm (Ellsworth and Wauldhauser, 2000) we have reduced the hypocentral location error by a factor of ~10, obtaining high-precision aftershock locations for 650 events recorded by a local network (Hatzfeld et al., 1997). Relocated aftershocks cluster into a system of planar structures that reveal the fine structure of faults that were active during the earthquake sequence. The master normal fault dips 45° north from 6-14 km depth and extends over a length of ~12 km, consistent with the Harvard CMT solution. Two south-dipping antithetic faults extend from the western half of the master fault, one located at the up-dip tip extending from 4-6 km depth, and the second located at approximately the mid-point of the master fault in cross section from 6-9 km depth. These antithetic faults dip 45° and 35° respectively. At the western end of the rupture is a system of strike-slip faults in an orientation consistent with slip-transfer or segment linking structures.

Fault patterns interpreted from the aftershock distribution form the basis of a 3D boundary element model using Poly3D. This code uses a mesh of contiguous triangular dislocation elements to capture the essential features of complex fault geometry in an idealized elastic half space. The mechanical model allows us to test the consistency of fault interpretations based on aftershock locations against surface geodetic and geologic data as well as to understand the mechanics of triggering and strain accommodation associated with the earthquake sequence. An improved fault model for the Kozani-Grevena earthquake is important for assessing seismic hazard and for understanding the mechanics of normal fault earthquakes and normal fault systems.

G31B-0144 0830h POSTER

Slip History of the 1999, October 16, Mw=7.1, Hector Mine Earthquake (California) Inferred From the Joint Inversion of InSAR and Teleseismic Data

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During the last decade the advent of satellite radar interferometry (InSAR) as well as a greater number of near source instrumentation, has provided an opportunity to study complex earthquake ruptures in greater detail with better resolution through joint inversions of seismic and geodetic data sets. The desertic environment of the Hector Mine earthquake provides excellent conditions for ERS1/2 radar satellite measurements, as was the case for the 1992 Landers event. In order to obtain the most accurate spatial and temporal resolution of the slip patches on a fault plane, we combine independent near-field differential interferometric data and far-field teleseismic data sets. The joint inversion of such data is required to compute the most realistic rupture models. We constrain the geometry of faulting by the ERS1/2 differential InSAR data and by the measured surface rupture, and finally we address the question of the proper fault segmentation for this event. Since InSAR measures only a change in range along the look direction, we combine the InSAR data from the ascending and the descending tracks in the joint inversion. Since the number of usable points in an interferogram is too large, we explore the effects of using undersampled interferogram data sets on the fault slip models. Resolution tests are performed that allow us to characterize the accuracy of our rupture models resulting from the inversions of both the individual and combined data sets.

G31B-0145 0830h POSTER

Using Landsat 7 Images to Detect Co-Seismic Surface Displacements

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We attempt to measure earthquake-induced surface displacements using images from the panchromatic band of the ETM+ sensor of the Landsat 7 satellite. *Crippen* [1992] and *Puymbroek et al.* [2000] demonstrate the use of spacecraft based optical imagery to measure surface displacements, using images from the French SPOT satellite. One estimates horizontal displacements by finding the offsets that maximize the correlation between small patches from two images spanning the time of the earthquake. We expect accuracies in the estimates of the displacements of less than 1/10 of a pixel [*Puymbroek et al.*]. This data is thus complimentary to InSAR data which measures the near vertical component of the displacement field.

The Landsat 7 satellite records images of most of the Earth's land surface once every 16 days. Each scene has a spatial coverage of about 183 km by 170 km and a spatial resolution for the panchromatic band of 15 m per pixel . We use images recorded before and after the 1999, M_w 7.1 Hector Mine earthquake as a test case, since we can compare estimated displacements with those obtained from GPS and InSAR. Preliminary results show that the displacements associated with the earthquake are clearly visible in the offset field. However the offset field has large amplitude artifacts associated with difficulties in calibrating the alignment between scan lines. The sensor acquires data by scanning in a direction perpendicular to the orbital track, 32 lines for each of the left-going and right-going scans. This causes sets of 32 lines to be offset by a few pixels relative to each other. Due to nonlinear effects in the sensor, the shifts are not constant across the lines. The shifts are corrected for in the geometric correction scheme applied at the USGS EROS data center. However, we detect residual shifts up to a third of a pixel. The magnitude of the residuals is thus comparable to the signal we want to measure. We are currently working on an improved calibration for the line shifts which is essential for future use of the Landsat 7 to measure earthquake-induced surface displacements.

G31B-0146 0830h POSTER

Estimating Fault Displacement from the 1999 Hector Mine Earthquake Using LIDAR

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The 1999 Hector Mine Earthquake generated visible surface faulting along almost 60km of sparsely vegetated, undeveloped desert terrain. Six months after the earthquake, the entire length of the Hector Mine fault zone was mapped with a scanning laser altimeter as part of a joint experiment between the U.S. Geological Survey, the Southern California Earthquake Center and the commercial firm, Aerotec LLC. This data set has recently been recalibrated and validated with respect to GPS-measured ground control to provide a high-resolution, geodetic-quality digital elevation model (DEM) that can be used for applications requiring precise knowledge of the faulted terrain within a half-kilometer swath along the Hector Mine surface rupture. We show the various methods of calibration used and the improvements to the DEM that result. We then use this recalibrated DEM to estimate vertical and horizontal displacement at several diagnostic locations along the fault. Having a quantitative representation of the post-earthquake faulted terrain allows us to bring signal-processing techniques to bear on this problem, and we compare our results to those made by the USGS using conventional surveying techniques and to recently published Hector Mine displacement estimates from InSAR.

G31B-0147 0830h POSTER

The May 10, 1997 Ardekul (Zirkuh) earthquake in Iran: Crustal deformation constrained by Interferometric Synthetic Aperture Radar and inversions for fault slip, geometry, and elastic parameters.

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The tectonic style of northeastern Iran is dominated by N-S right lateral and E-W left lateral faults which partially accommodate the convergence between Arabia and Eurasia. The M_W 7.2 Ardekul (Zirkuh) earthquake of May 10, 1997, occurred in eastern Iran near the Afghanistan border. We produce a map of the co-seismic deformation using Interferometric Synthetic Aperture Radar (InSAR) data from one ascending and two descending orbital tracks. The different line of sight components provided by the different tracks enable us to constrain two components of deformation over many portions of the coseismic displacement field. We invert this data for a model of the fault geometry and for the slip distribution on the fault plane. The top of the fault is constrained by the location of surface rupture. We use a constrained least squares inversion scheme combined with a grid search to describe the complete parameter space associated with this earthquake, including variations in fault geometry, multiple fault segments, and depth dependent elastic parameters. Our inversion results agree with the surface offsets of up to 2 m measured in the field by Berberian et al. (1999).

G31B-0148 0830h POSTER

Coseismic Displacement of Permanent GPS Stations During the Lana (July 2001) Earthquake

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The Lana Earthquake occurred on July 17, 2001 at 15:06 15.6 UT. The epicenter was located at ϕ= 46.742 N and λ = 11.368 E, in Northern Italy, by 40 seismic stations. Mw 4.7 (CSEM). Mo=1.2*10^{16} Nm (CSEM). At least two persons killed, one missing from rockslides, three people injured and minor damage in the Merano area. The quake was also felt in Germany and Switzerland. Several permanent GPS stations were tracking the GPS satellites with high accuracy in the area. Some of these stations are part of the fundamental European network, others contribute to its local densification. All are processed by independent Analysis Centers using state of the art software (Bernese 4.2)

and models of the observations. The changes in position of those stations in the time frame of the seismic event could be accurately reconstructed with time resolution of one week to fractions of one day. The high resolution GPS data show that about one half of the total coseismic displacement (approximately 25 mm) at at least one site took place one day before the epoch of the quake. Some displacement is evident also in the following days or weeks. We use this preliminary and very limited information to speculate on possible models which could describe the observed kinematics. We focus on a simple stick-slip mechanism, with two elastic, infinite half spaces sliding relative to each other, and examine the constraints on the depth of the crack and the total shear strain which the geodetic observations could put on the model.

G31B-0149 0830h POSTER

Average Strain Rate in the Italian Crust Inferred From a Permanent GPS Network

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We have computed time series of the horizontal coordinates of 30 permanent GPS stations in the Alpine Mediterranean area with the intent of estimating velocities and their uncertainties, on account of the detailed structure of their noise. The power spectral densities demonstrate that colored noise, mostly flicker phase and -more occasionally- random phase walk noise, can be present at low frequencies, typically below five cycles per year. At higher frequencies the spectrum tends to a regime of white noise. We use this statistical information to estimate the uncertainty of the velocities, in analogy with time series of frequency standards (two-samples Allan variance), as the 1σ probability of a change in the slope of two consecutive, equal length batches of a time series, as a function of the length of the batch. Taking into account the correct time correlation among the samples, the slope of each series is estimated by least squares. Stations with only one year tracking history and a standard least squares ('pure white noise') formal velocity error of 0.1 mm yr^{-1} have a velocity uncertainty, in the sense of Allan variance, of 2 - 3 mm yr^{-1}, which drops to 0.6 - 0.7 mm yr^{-1} with a five years tracking history. We use these velocity estimates to analyze the large scale intraplate kinematics of the area. This is characterized by a wide range of tectonic phenomena and is accompanied by a relatively intense volcanism and seismicity, which justify the expectation of small but theoretically measurable horizontal and vertical displacements. We show that the estimated strain rate is everywhere smaller than 50 10^{-9} yr^{-1} with a mean uncertainty between 13 and 20 10^{-9} yr^{-1} (1σ). The areas with largest strain rate are the Central Apennines and Eastern Alps, while in the Western Alps the estimated strain rate is smaller than 15 -20 10^{-9}) yr^{-1}, hence comparable with its uncertainty. The geodetic strain rate is compared with the co-seismic strain rate estimated from shallow earthquakes of M greater than 5 occurred in the past 400 years, using the Kostrov formula and the summation of the seismic moments over an area. We focus on the Eastern Alps, outer side of the northern Apennines, both under compression, and inner side of the North Central Apennines, under extension. We show that if the two strain rates are to coincide, then the seismogenetic area has an extension very nearly comparable with that containing the epicenters of the contributing earthquakes.

G31B-0150 0830h POSTER

Interseismic Strain Across the Altyn Tagh Fault System (Northern Tibet), Measured by SAR Interferometry.

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The 1800 km-long, sinistral, Altyn Tagh fault accomodates the eastward component of movement between Tibet, to the south, and the Tarim block, to the north. Long-term (geological) and short-term (geodetic) estimates of its slip rate differ by a factor of two to three. This suggests either along-strike variations of the rate, due to interaction with thrusts or other branches of the fault, or temporal variations of the near-field strain rate throughout the seismic cycle.

We use SAR interferometry data acquired by the European Space Agency ERS satellites to map the interseismic strain across the fault system. Preliminary analysis of interferometric pairs covering time intervals of up to five years shows displacement gradient across the main fault consistent with a left-lateral sense of movement. Horizontal motion along the strike-slip fault is combined in the radar line of sight with vertical motion associated with adjacent thrusts. 3-D deformation models taking into account both types of fault are used to constrain interseismic slip rates at depth. The main error in the radar displacement maps results from the large elevation difference between the high tibetan plateau and the Tarim basin, on either side of the fault. This elevation step tends to produce different tropospheric phase propagation delays north and south of the fault, corrupting the far field tectonic signal. Stacking multiple interferograms will help mitigating these tropospheric effects.

G31B-0151 0830h POSTER

Different Phases of Earthquake Cycle Reflected in GPS Measured Crustal Deformations along the Andes

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The South American Geodynamic Activities (SAGA) project was initiated in 1993 by the GeoForschungsZentrum together with host organizations in Argentina and Chile with the main objective of studying the kinematics and dynamics of present-day deformation processes along the central and southern Andes. Currently the SAGA network consists of 230 geodetic markers spanning more than 2000 km long distance from Peru/Chile border in the north to Cape Horn in the south.

The majority of the observed crustal deformation field is relatively homogenous: roughly parallel to the plate convergence direction and decreasing in magnitude away from the deformation front. This pattern is characteristic for the *inter-seismic* phase of earthquake deformation cycle and can be explained by the elastic strain accumulation due to locking of the thrust interface between the subducting Nazca and the overriding South America plates. However, in addition to the dominant inter-seismic signal, close examination of the observed velocity field also reveals significant spatial and temporal variations, contrary to the commonly used assumption of constant deformation rates. This variation is especially pronounced for the measurements in the vicinity of the 1995 M_w8.0 Antofagasta earthquake (22°S-26°S). Here, after capturing up to 1 meters of *co-seismic* displacements associated with this event, the analysis of data obtained during the three following field campaigns (1996-1999), reveals highly time dependent deformation pattern. This can be explained by the decreasing importance of *post-seismic* effects of the Antofagasta event relative to the increasing dominance of the inter-seismic phase of subduction. Perhaps, even more interesting time dependent observations have been detected in the southern part the SAGA network (38°S-43°S).Here, after 35 years of the occurrence of the 1960 M_w9.5 Chile earthquake, we still see the continuing post-seismic effects of this largest ever recorded earthquake on the earth.

To properly interpret given observations, we developed the fully 3D Andean Elastic Dislocation Model (AEDM), which is used to explain the dominant interseismic signal. The subtraction of the AEDM predicted deformation rates from the observations leads towards the "filtered" residual velocity field, that can be used to highlight, for example, the post-seismic deformation effects. Also, in the central section of the SAGA network, the residual velocity field indicates the existence of more long-term (i.e. geologic) deformations.

In summary, the changing spatial-temporal pattern of GPS measured crustal deformation rates along the central and southern Andes is governed by the relative importance of different phases of earthquake deformation cycle.

G31B-0152 0830h POSTER

Testing two Mountain Building Models Using Coseismic GPS Data

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Two distinct models have been advanced for the construction of mountain belts. In the decollement model, mountain belts are supposed to be critical wedges consisting of rock units that were thrust and multiplexed over a basal decollement under horizontal compression. In the thick-crust model, mountain belts are assumed to be a part of a compressed and thickened crust that rises under its own buoyancy. Here we examine the difference in coseismic response of the two models to earthquake faulting, using the coseismic GPS data collected during the 1999 Chi-Chi (Mw = 7.5) earthquake, Taiwan. Simulated surface deformation in the Chi-Chi earthquake for the two models are compared with the observed coseismic GPS data. Result for the thick-crust model shows good agreement with the observed deformation, i.e., the coseismic displacement in the upper plate decreases steeply with distance from the fault and the vertical component declines from an uplift near the fault to a subsidence at distances greater than 20 km. The decollement model, on the other hand, does not predict such pattern in the surface deformation.

G31B-0153 0830h POSTER

Spatio-temporal Patterns of In-elastic Strain Produced by Southern California Earthquakes

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We analyze spatial and temporal features of coseismic in-elastic deformation in the southern California crust. At present we examine results associated with approximately 100,000 earthquakes occurring between 1981 and 2000, and are in the process of expanding the research to include earlier events. Locations and fault plane solutions for the earthquakes are determined using the HYPOINVERSE and FPFIT computer codes. From the fault plane solutions and event magnitudes we calculate the potency tensors of the earthquakes, where the potency is the integral of the inelastic co-seismic strain over the deforming volume. Division by the involved rock volume would yield the strain tensors describing the co-seismic deformation. However, those rock volumes are not well constrained so we work with potency. Since the potency and strain tensors are proportional to each other, their principle axes have the same orientations and relative magnitudes.

The data are spatially and temporally binned, and summed in each bin to yield the cumulative potency tensors for given sub-regions and time periods. The eigenvectors and eigenvalues of the tensors are calculated, giving the orientation of the principle potency (and strain) axes. By comparing the plunges of the three axes, we estimate the expected style of faulting for each cumulative tensor. We compare the patterns of potency and faulting style at scales ranging from 2.5 km^2 columns of crust to all of southern California. We also examine changes in the pattern across year-long sub-catalogs covering the entire analyzed time period. Other examined features include (1) the relative prevalence and location of different faulting styles, (2) the percentage of bins with principle potency/strain axes that are significantly rotated out of the horizontal and vertical planes, and (3) the spatial correlation lengths of the orientation and magnitude of the potency tensors. Spatio-temporal patterns of these features and their relations to local fault geometry and large earthquake histories will be discussed in the meeting.

G31B-0154 0830h POSTER

A fault friction driven model of crustal stress in the Los Angeles region

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We are using models of the dynamic friction on faults during earthquakes to create a model of the

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crustal stress in the Los Angeles region. The goal is to increment the displacement along the edges of the domain and allow earthquakes to control the evolution of the stress field within the volume. A wide variety of seismological and geodetic observations constrain the level of stress, including (1) rupture behavior, such as rupture speed and distribution of slip, inferred from kinematic source inversions of earthquakes, (2) the lack of heat flow found in exposed fault zones, (3) GPS and InSAR observations of plate motion, and (4) the need to support variations in topography and mass density. Comparison of synthetic strong ground motions with recorded motions will also provide feedback into the dynamic friction models.

The model relies on two principle components. Dynamic rupture simulations of earthquakes provide a test bed for evaluating how well various friction models produce realistic rupture behavior and allow computation of the perturbations in the stress field caused by the slip on the fault. Static simulations produce estimates of the background stress field from gravity acting on topography and density variations, strain accumulation due to plate motion, and slip during prior earthquakes. Successive earthquakes within the region and subsequent earthquakes on a single fault will play an important role in discriminating between different friction models.

Our preliminary results have focused on examining the behavior of ruptures with different friction models. We have found that (1) frictional sliding on fault surfaces is a highly nonlinear process that cannot be described by constant traction boundary conditions due to spatial and temporal variations in the magnitude and direction of the friction stress; (2) instantaneous healing of the fault upon termination of sliding accentuates the development of heterogeneity in the stress field and the distribution of slip; and (3) introducing rate-weakening behavior leads to pulse-like ruptures that tend to create stress fields and slip distributions with more heterogeneity for a given stress field than crack-like ruptures.

G31C MC: Hall D Wednesday 0830h

Surface Deformation Associated with Active Volcanism *(joint with T, V)*

Presiding: **F Amelung,** University of Hawaii**; S Owen,** University of Southern California

G31C-0155 0830h INVITED POSTER

Magmatic Activity Beneath the Quiescent Three Sisters Volcanic Center, Central Oregon Cascade Range, USA, Inferred from Satellite InSAR

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Images from satellite interferometric synthetic aperture radar (InSAR) reveal uplift of a broad ~10 km by 20 km area in the Three Sisters volcanic center of the central Oregon Cascade Range, ~130 km south of Mt. St. Helens. The uplift is centered ~5 km west of South Sister volcano, the youngest stratovolcano in the volcanic center. The center has been volcanically inactive since the last eruption ~1500 years ago. Multiple European Space Agency ERS-1 and 2 satellite images from 1992 through 2000, used in this study, were selected based on orbital separation and time of year. Summer and early autumn scenes were necessary to avoid decorrelation from snow cover. Interferograms generated from these images indicate that most if not all of ~100 mm of observed uplift occurred between September 1998 and October 2000. We interpret the uplift as inflation caused by an apparently ongoing episode of magma intrusion at a depth of ~6.5 km.

Geochemical (water chemistry) anomalies, first noted ~1990, coincide with the area of uplift and suggest the existence of a magma reservoir prior to the uplift. High chloride and sulfate concentrations, and a positive correlation between chloride concentration and spring temperature were found within the uplift area, with larger SO_4/Cl ratios in springs at higher elevations. These findings are indicative of a high-temperature hydrothermal system driven by magma intrusions.

The current inflation episode observed with InSAR may lead to an eruption, but the more persistent geochemical evidence suggests that the episode is likely the latest in a series of hitherto undetected magma intrusions. We do not yet know if the inflation has abated, is continuing, or has accelerated since October 2000–we only know that the highest rate of uplift occurred in the last year for which ERS-2 data was available (1999- 2000). In May of 2001, a continuous GPS receiver and seismometer were installed by the USGS within the Three Sisters Wilderness to monitor the uplift.

G31C-0156 0830h POSTER

Horizontal and Vertical Deformation Near Three Sisters Volcanic Center, Oregon, From Leveling, EDM, and GPS

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A broad zone of crustal uplift near the Three Sisters volcanic center, which was detected with SAR interferometry, has been interpreted to result from the accumulation of magma at a depth of 6.5 km during the interval 1998-2000. No useful SAR images of the deforming area have been acquired since late 2000, so it is not known whether the uplift is continuing. Possible ongoing deformation is being tracked by a continuous GPS station located 3.5 km north of the center of uplift, which was installed by the U.S. Geological Survey in June 2001. No significant deformation had been detected through mid-August, but the preliminary station velocity relative to a reference site 50 km to the east is similar to that predicted by inflation of a point source that fits the observed uplift. Several stations in a GPS profile extending north of the uplift along the Mackenzie Pass were resurveyed in August 2001 to determine the rate and pattern of deformation since 1999. These data will help determine corrections for secular tectonic deformation associated with subduction of the Juan de Fuca plate beneath North America. Recovery of four 300-m-long leveling arrays and a 21-station EDM network on nearby South Sister, planned for September 2001, will place limits on local tilt and strain since the initial observations in 1985. New campaign GPS stations will be installed and surveyed in September 2001 to improve spatial and temporal resolution of possible ongoing deformation.

G31C-0157 0830h POSTER

InSAR studies of Hawaiian volcanoes: Initial results

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The Hawaiian volcanoes Kilauea and Mauna Loa are among the most active in the world. Kilauea is has been in near-continuous eruption since 1983 and Mauna Loa erupts on average every 15-30 years. The Hawaiian volcanoes are actively deforming due to transfer of magma into and out of the magma reservoirs, and due to movements along sub-horizontal decollements at the pre-volcano-seafloor. We discuss our JERS-1and ERS-2 InSAR observations which may help constrain this deformation.

A 1993-1998 JERS interferogram shows 22 cm of range decrease on the SE flank of Mauna Loa, roughly consistent with the 1993-1996 campaign GPS measurements. Flank motion has slowed down after this period as shown by 1998-2000 ERS interferograms. At Kilauea southflank deformation contributes only little to the observed range changes because of the viewing geometry of the ERS radar. The ERS intererograms show subsidence of 10 cm/yr in the summit area of Kilauea, consistent with leveling data. We discuss possible mechanisms for the observed subsidence including deflation of Kilaueas magma reservoir, deep dike inflation and degassing. Deformation due to shallow intrusions has also been detected

G31C-0158 0830h POSTER

Edm deformation monitoring at the Colima Volcano before and during the 1997-2000 activity

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The 1997-2000 activity at Colima Volcano began in November 1997 with a series of seismic swarms and deformations of the summit lava dome. This activity reached a climax on 20 November 1998 with the extrusion of lava, accompanied by pyroclastic flows. From 10 February 1999, the explosion activity began and continued up to the time of paper preparation. Summit deformation was detected by Electronic Distance Measurement (EDM) surveys using a single frequency distancemeter DI3000s mounted on a theodolite Wild T2. Distance measurements were carried out from three base stations utilizing nine reflectors located around the volcano edifice. Reflectors were located on three different altitudes at the volcano edifice (3250, 3450, 3850 m).. After the destruction of two summit reflectors in July 1998 we continued the EDM surveys mainly with five reflectors remaining on the north flank of the volcano. EDM distance measurements taken from November 1997 to July 1998 showed maximum cumulative distance change of 0.5 cm/day on the summit reflectors that was interpreted in terms of inflation of the volcanic edifice in response to magma movement towards the surface.. EDM variations recorded in August 1998 February 1999 from reflectors on the north flank of the volcano may reflect further inflation before extrusion of lava on 20 November 1998 and deflation after effusion ceased in February 1999.

G31C-0159 0830h POSTER

Deformation in Long Valley and the Hilton Block, Sierra Nevada, CA from GPS studies.

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Long Valley caldera, California, is a "natural laboratory" for the study of interaction between volcanism and tectonics. The Hilton Block area south of Long Valley caldera has been one of the most seismically active regions in California. The patterns of recent seismicity, however, are difficult to reconcile with the observed regional strain or with stress transfer calculated from simple elastic models of volcanic inflation. Understanding the connections between volcanism and tectonics in this region will require a better understanding of both the kinematics of the Hilton Block and the mechanics of stress transfer within the caldera system.

Annual GPS measurements have been made since 1999 on a growing network of ~35 sites designed to better characterize the both the regional strain rates and the strain rates within the Hilton Block. Our network includes data from 10 recently installed benchmarks and 10 benchmarks without a prior history of survey-mode GPS measurements. As indicated by the two-color EDM network run by the U.S.G.S., the resurgent dome has not inflated significantly during this time period. Therefore the strain measurements should be influenced primarily by the regional tectonics, not magmatic intrusion events. We will present preliminary results from this new network of GPS sites and also continuous GPS sites.

By developing a more detailed picture of the kinematics of the Long Valley region, we can advance our understanding of the mechanical interactions between