Measured at Mini-PBO Stations: Implications for PBO

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We report on 5 borehole stations installed in the San Francisco Bay area with strainmeters, seismometers, pore pressure monitors, tilt sensors, GPS, and high-frequency 24-bit recording systems. These "Mini-PBO" stations are part of an NSF-funded project to develop a pilot system for the study of transient plate boundary deformation from fractions of seconds to years in central California. We are currently resolving interaction problems, such as electical grounding, that are typically encountered during the hookup of such complex systems, and are in the initial stages of assessing the data quality of the instrumentation. The tensor strainmeters use the CIW hydraulic system to measure the volume change in 3 sensing volumes that form 120-degree sectors of an annulus, allowing the 3-component horizontal strain tensor to be determined. The tensor strainmeters, pore pressure monitors, and tiltmeters appear to reliably measure tidal strain, and local and teleseismic earthquake deformation. We will present studies of noise spectra and tidal calibration to better assess the performance of the strainmeters. We plan to add pre-amplifiers to the 3-component 2-Hz velocity borehole seismic packages to improve the signal at some of the stations where the microseismic noise peak around 0.1 Hz currently is not evident. The GPS antennas are mounted at the top of the borehole casings in an experimental approach to achieve inexpensive yet stable monuments. We will present noise studies that compare their stability with more conventional monuments. The lessons learned from the analysis and integration of the different data types produced by the Mini-PBO project should pave the way for users of the more extensive data sets that will be acquired through the dense instrumentation deployments planned under PBO.

G32B-06 1455h

Crustal Deformation in the Basin and Range: Recent Results from the BARGEN Network and Questions for the Future

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As late as the mid-1990's, our state of understanding of crustal deformation within the northern Basin and Range was quite poor. Prior space geodetic studies indicated that the integrated deformation across this ~1000-km-wide zone was 10–12 mm yr^{-1}, with only one site (ELY) near the center of the province. By 1998, however, continuous GPS had described the major features of the horizontal velocity deformation field near lat. 40° N, and by 2002 detailed horizontal velocity fields from both continuous and campaign GPS were available for both northern and central Basin and Range. Studies now focus on the physical mechanisms for both the broad-scale and detailed studies of deformation patterns as they relate to individual faults. These studies have highlighted a number of problems to be addressed by PBO, including: whether or not strain is localized along a small number of individual faults, versus evenly distributed across most Quaternary faults; the relationship between past and present strain and seismicity; the role of plate boundary forces versus gravitational forces in controlling the deformation field; and the contribution of historic earthquakes to the detailed deformation observed. With > 7 yrs of continuous data from the BARGEN network, we are now in a position to begin evaluating two important avenues of research, including transients or accelerations in site motion, and the vertical component of deformation. A subset of BARGEN sites now shows temporal variations in velocity that are as high as 0.4 mm yr^{-2}. Although we do not yet know whether these motions are related to tectonic processes, they have systematic properties, including regional coherence and displacements in accord with slip directions of nearby faults. Vertical velocities show a broad pattern of subsidence of ~1 mm yr^{-1} with coherent spatial variations of ±2 mm yr^{-1}. Even if the overall subsidence is in error on account of reference frame problems, the coherent variations of subsidence cannot be explained by any long-term, steady-state geophysical process such as thermal subsidence, erosion, or strain accumulation along faults.

G32B-07 1510h

Crustal Deformation of the Northern Basin and Range from Measurement with the Global Positioning System

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In northeast California, southern Oregon, and northwest Nevada the three major plate boundary elements of western North America interact, exhibiting a complex pattern of crustal deformation. Between latitudes 40 − 44°N, deformation associated with translation of the Sierra Nevada microplate, the Cascadia convergent margin, and the extending Basin and Range province overlap. Boundaries for geodetic domains associated with each of these tectonic elements are not well located, and as a result the contributions that each component has on the broad pattern of crustal motion are not well understood. To distinguish among various influences on crustal motion in the northwestern Basin and Range, a 700 km wide network of 86 geodetic sites was established and surveyed in September, 1999, and in June, 2003 with the Global Positioning System (GPS). The network provides a first look at the plate boundary scale deformation pattern of the northwest Basin and Range. We report geodetic velocities and strain rates inferred from the pattern of motion, and use their spatial characteristics to infer the dynamic sources of deformation. Locating the most rapidly deforming areas is necessary to guide the establishment of future sites in the extensional tectonics cluster of the nascent Plate Boundary Observatory. Results indicate that velocities in the eastern half of our network (between 114°W and 119°W longitude) are approximately 2-3 mm/yr westerly with respect to non-deforming North America. Strain rates between 114°W and 119°W are not resolvable, similar to GPS results obtained from campaign and permanent sites east of the Central Nevada Seismic Zone near latitude 39°N. West of 119.5°W the velocity magnitudes begin to increase and change to a more northwesterly azimuth, again similar to the transition between roughly non-deforming central Nevada and the Central Nevada Seismic Zone seen at 39°N. Velocities in the northernmost part of our network, near 43.5°N latitude, have a small eastward velocity component, possibly showing the influence of the Cascadia convergent margin at least as far east as longitude 120°W. Right lateral simple shear deformation is observed near the southwestern part of the network, and is most likely attributable to transform motion between the Sierra Nevada microplate and adjacent northeast California.

G32B-08 1525h

Before PBO: What Do We Know About Ground Deformation in the Cascade Range?

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Three of thirteen active volcanic centers in the Cascade Range are known to be deforming and therefore are among the candidates for PBO instrument clusters (*i.e.*, concentrations of continuous GPS stations and borehole strainmeters to be installed as part of the Plate Boundary Observatory). At Three Sisters in central Oregon, a broad area of uplift centered 5 km west of South Sister volcano was discovered in April 2001 using satellite radar interferometry (InSAR). Subsequent InSAR, campaign GPS, continuous GPS, and tilt-leveling observations indicate that the inflation is centered near 6 km depth, began in 1997 or 1998, and has continued at a constant rate of 0.005±0.001 km^3/yr. The total volume increase through September 2002 was 0.027±0.005 km^3. Results of the most recent (September 2003) campaign GPS and tilt-leveling surveys will be reported at the meeting. Medicine Lake Volcano in northeast California is known from repeated geodetic leveling, campaign GPS, and InSAR observations to be subsiding 8±1 mm/yr at the summit. A leveling survey in June 2003 between Tionesta and Alturas east of the volcano suggests fault displacements of several centimeters at three sites along the route since the previous survey in 1940. At Mount St. Helens in southwest Washington, a 14-station Geodolite EDM network centered near the volcano and extending 30 km across and 90 km along the volcanic arc was established in 1982. All 26 line lengths were remeasured in 1991, and 10 line lengths between 7 central stations were recovered by GPS in 2000. Strain accumulation between 1982 and 1991 was dominated by areal dilatation (0.15±0.06 μstrain/yr) in the central part of the network around Mount St. Helens. No significant strain accumulation was observed in the same area between 1991 and 2000. A continuous GPS station (JRO1) located 9 km north of the volcano is moving 8±1 mm/yr north-northeast relative to interior North America, which is generally consistent with rigid rotation of coastal Oregon as determined from modeling of regional GPS-measured deformation. A dense 40-station campaign GPS network around Mount St. Helens was established in 2000 and remeasured in 2003. Preliminary results indicate no significant deformation of the volcano beyond the 1980-86 lava dome, part of which is subsiding 8 cm/yr. The source of apparent far-field deformation is not yet clear. InSAR observations show that thick 1980 deposits in the North Fork Toutle River valley north of the volcano are subsiding and presumably compacting a few cm/yr.

G32C MCC: 2010 Wednesday 1600h

Before PBO: What Do We Know? III

(joint with S, T)

Presiding: **R A Bennett,** Harvard-Smithsonian Center for Astrophysics**; K W Hudnut,** U.S. Geological Survey

G32C-01 1600h INVITED

The Resolving Power of the Current State of GPS Information in North America: Implications for PBO Planning

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We combine both permanent and campaign GPS data from mostly published work to infer a kinematic solution within western North America plate boundary zone. We interpolate 1603 GPS velocity vectors to infer the horizontal velocity gradient tensor field, which is important for both seismic hazards analysis and for constraints on the dynamics. The interpolation algorithm uses continuous bi-cubic splines on the surface of a sphere. The GPS vectors are matched by the model velocity field, in a specified reference frame, in a weighted least-squares inversion. The reference frames of each geodetic study are determined in the inversion procedure. That is, we seek angular velocities, one for each study, that rotate the vectors into one self-consistent frame of reference. The algorithm involves no a priori bias as to the location of fault zones or blocks. The a posteriori variance-covariance matrix of the model strain rates and rotation rates can be evaluated to determine where block behavior is statistically significant, where deformation rates are significant, as well as the significance of the style of inferred strain rates. These model results can be compared with active fault slip observations. The quantitative assessment of the strain rates and rotation rates can be compared with predictions from competing kinematic and dynamic models. Discrimination between such competing models takes into account the a posteriori uncertainties in the kinematic parameters. In cases where discrimination between competing models is not possible, due to large errors in the kinematic solution, then it is possible to investigate where an increased GPS coverage or accuracy is potentially critical in resolving differences between competing models.

G32C-02 1615h

Expected Performance of the Proposed PBO Network From Numerical Simulations

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With the recent funding approval of EarthScope, the scientific community is poised to begin the installation phase of the proposed Plate Boundary Observatory (PBO). GPS and strainmeters will soon be distributed across the western United States in a manner designed to target specific scientific objectives. While a blueprint for the placement of stations is already established, there exists a window of opportunity prior to the installation of instruments where the network geometry can be optimized. We perform numerical simulations to evaluate the performance of the proposed network. Three characteristic events are simulated: an aseismic transient on the central San Andreas fault, a slow earthquake on the Cascadia subduction interface, and a dike injection at Mount St. Helens. Results for transient source models describe the PBO network performance as a function of the magnitude and duration of an event and provide insight into the expected level of resolution. For each simulation, synthetic GPS and strainmeter data are created that include white noise and a random walk components. The Extended Network Inversion Filter (ENIF) [*McGuire and Segall,* 2003] is used to infer the original source parameters from synthetic time series given the proposed station distribution. The ENIF is an implementation of a Kalman filter that is well suited to extract a time-dependent signal from noisy data and is efficient at analyzing large time series. Resolution of the source process is evaluated by comparing the synthetic input model with the inferred source model estimated by the filter. We find that the proposed PBO network at Parkfield is nearly optimal compared to a network composed of random station positions. A discernible variation in source resolvability along the San Andreas fault is attributed to the along-strike variation in station density. For Cascadia, the slow earthquakes recently observed from existing GPS data appear to be at the lower threshold of resolvability for the proposed PBO network, but within the detection threshold. We also find that the proposed network for Mount St. Helens is currently optimized for deep source events and shallow deformation events (< 4 km in depth) are not well resolved.

G32C-03 1630h

Dynamic Global Plate Motion Model from Continuous GPS Observations to Support PBO Objectives

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We estimate a recent plate motion model for sixteen major and minor tectonic plates based solely on analysis of continuous data and metadata from 104 globally distributed permanent GPS stations analyzed operationally and consistently by the Scripps Orbit and Permanent Array Center (SOPAC), spanning the period from January 1991 to July 2003. Euler vectors for the North America, Pacific, and Eurasia plates are particularly well determined and form a sound basis for achieving PBO scientific goals. Site positions estimated from 24 hours of GPS phase and pseudorange data are aligned day-by-day to the IGS realization of the ITRF2000 reference frame using a seven-parameter similarity transformation, thereby ensuring that the ITRF2000 No-Net-Rotation Condition is preserved and that our plate motion model is absolute. Linear velocities of a carefully selected set of stations are estimated from the position time series, along with annual and semi-annual fluctuations and position offsets due to GPS instrument changes. A white noise plus flicker noise model is applied to estimate realistic uncertainties for the site velocities, which are then propagated into the derived plate motion model parameters. We also examine the vertical velocities of the sites in the site selection process to ensure long-term site stability, identify anomalous site motions, and to look for coherent motions within each of the rigid plates. The plate motion model is updated on a regular (monthly) basis (hence, dynamic) to improve its precision and reliability, as well as to detect possible anomalous changes due to seismic activity near active plate boundaries as postulated by several investigators.

URL: http://sopac.ucsd.edu

G32C-04 1645h

Current Development Status of an Integrated Tool for Modeling Quasi-static Deformation in the Solid Earth

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With the advent of projects such as the Plate Boundary Observatory and future InSAR missions, spatially dense geodetic data of high quality will provide an increasingly detailed picture of the movement of the earth′s surface. To interpret such information, powerful and easily accessible modeling tools are required. We are presently developing such a tool that we feel will meet many of the needs for evaluating quasi-static earth deformation. As a starting point, we begin with a modified version of the finite element code TECTON, which has been specifically designed to solve tectonic problems involving faulting and viscoelastic/plastic earth behavior. As our first priority, we are integrating the code into the GeoFramework, which is an extension of the Python-based Pyre modeling framework. The goal of this framework is to provide simplified user interfaces for powerful modeling codes, to provide easy access to utilities such as meshers and visualization tools, and to provide a tight integration between different modeling tools so they can interact with each other. The initial integration of the code into this framework is essentially complete, and a more thorough integration, where Python-based drivers control the entire solution, will be completed in the near future. We have an evolving set of priorities that we expect to solidify as we receive more input from the modeling community. Current priorities include the development of linear and quadratic tetrahedral elements, the development of a parallelized version of the code using the PETSc libraries, the addition of more complex rheologies, realistic fault friction models, adaptive time stepping, and spherical geometries. In this presentation we describe current progress toward our various priorities, briefly describe the structure of the code within the GeoFramework, and demonstrate some sample applications.

G32C-05 1700h

On Boreholes and PBO Borehole Strain

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Borehole tensor strainmeters (GTSM) installed in Australia and California have established a baseline of data spanning more than twenty years. The current baseline of data allows characterisation of a moderate number of instruments in a range of very different environments in a way which defines reasonable performance expectations for the upcoming PBO deployments. A generic understanding of effects which result from the process of installation of the instrument in a stressed rock mass emerges. This indicates that, provided due allowance is made for experimentally determined borehole recovery effects, the contribution of borehole strain meters more than adequately fills the observational gap between high stability/long term geodetic measurements of strain and strain rates and high resolution/high frequency seismic observations of earth deformation processes. The various strain relief processes associated with the installation procedures and borehole recovery effects associated with preexisting stress fields will be documented. Procedures for calibration of the total borehole inclusion and for progressive removal of effects due to rock anisotropy and visco-elastic creep of the grout and rock close to the borehole from far field tectonic effects will be defined and illustrated with examples. Observed deviations from these processes will be shown to be small and consistent with otherwise observed or implied fault motions. Full details of these borehole induced processes are, however, difficult to determine in the early years following installation, particularly if there is significant tectonic activity at the time. Once quantified for each site, the effects can be robustly removed from data streams.

G32C-06 1715h

When is the strain in the meter the same as that in the rock?

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Borehole strainmeters are a valuable tool for monitoring crustal deformation and an important component of the Plate Boundary Observatory (PBO). One type, the dilatometer, measures the volumetric strain; three component strainmeters measure the dilatation and two in-plane shear strains. Borehole strainmeters are emplaced in porous fluid saturated rock. Pore-fluid flow induces strain, however there is no fluid exchange with the strainmeter. Thus, the dilatation measured by the strainmeter is the same as that in the rock only when the rock remains undrained. Assuming that the rock is homogeneous and isotropic, the instrumental dilatation Δ^{inst} is given by $\Delta^{\mathrm{inst}} = C_1(\Delta^{\infty} - C_2 p^{\infty})$, where Δ^{∞} and p^{∞} are strain and pore pressure far from the borehole, and C_1 and C_2 depend on poroelastic rock properties; $C_1 = [1-(1+\alpha)\nu_u]/[1-(1+\alpha)\nu]$, $C_2 = [3(1+\alpha)(\nu_u-\nu)]/[2\mu B(1+\nu_u)]$, and ν, ν_u are the drained and undrained Poisson's ratios, μ is shear modulus, B is Skempton's coefficient, and α measures the vertical strain sensitivity of the instrument. This predicts that increases in pore-pressure, due for example to rainfall, cause a contractional strain. A large rainfall event in south Iceland raised water levels by 1-2 meters (10 - 20 kPa). Assuming $\nu_u = 0.33, \nu = 0.25, B = 0.7, \mu = 10^{10}$ Pa we predict contractions of order 180 nanostrain, in reasonable agreement with 4 of the 5 dilatometers in the area. Postseismic strain in the rock is expected to increase as the induced pore pressure gradients relax. However, a dilatometer ~ 3 km from a M_w 6.5 earthquake in the South Iceland Seismic Zone shows a postseismic strain change *opposite* in sign to the coseismic response. Rice and Cleary, Rev. Geophys., [1976] give the solution for two-dimensional edge dislocation in a poroelastic medium. From their results and the theory described above, we predict that the dilatation recorded by a strainmeter will be time invariant! This despite the fact that the mean stress, pore pressure, and dilatational strain in the rock all are time dependent. We conclude that the effects of drainage of a homogeneous, isotropic medium gives a correction of the observed sign, but can only partly explain the observed discrepancy. Fracture dominated poroelastic response, as described in the companion study, yields a qualitatively better explanation of the strainmeter data.

G32C-07 1730h

Borehole Tensor Strain and Pore Pressure Noise from Mini-PBO Sites in the San Francisco Bay Area: Comparison with Parkfield Instruments

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Borehole strainmeters are an important component of the new Earthscope/PBO initiative. The first prototype cluster of five boreholes, usually termed Mini-PBO, was successfully installed along the San Andreas/Hayward fault system in the San Francisco Bay area from 2001-2003. Each 200m deep borehole was equiped with a tensor strainmeter, seismometer, pore pressure monitor, tiltmeter, GPS and temperature monitors. Records from the tensor strainmeters and pore pressure transducers are used to determine comparative noise spectra over nine decades of frequency (10E-7 to 100 Hz) at Mini-PBO locations with noise spectra from instruments at Parkfield. In particular, we compare the responses from the new Carnegie tensor strainmeters in the Mini-PBO sites with the Gladwin tensor strainmeters and Carnegie dilatometers at Parkfield. We also make the first measurements of pore pressure noise and determine the relations between pore pressure and strain, particularly during local and teleseismic earthquakes such as the November 3, 2002, M 7.9 Denali earthquake. The ten borehole strain instruments used are all installed at approximately 150-200 m depth. The general characteristics of power spectral density estimates obtained at all sites are similar with noise power decreasing with increasing frequency at roughly inverse frequency squared.Other than 10 dB microseismic noise peaks and 30 to 40 dB peaks at earth tidal frequencies, the spectra from the Parkfield instruments decrease from about -80 dB at a frequency of 10E-8 Hz to about -220 dB at a frequency of 100 Hz. Initial data from the Carnegie tensor strainmeters at the Mini-PBO sites appears to be about 10 dB noisier at frequencies between 10E-7 to 100 Hz. Pore pressure and compressional dilational strain are in phase and are highly coherent at short to intermediate periods.

G32C-08 1745h

Results From Long-Base Strainmeters in California: Implications for the PBO

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We have been making continuous measurements of strain using long-base instruments at various locations in southern California for some time: since 1974 at Piñon Flat, near the San Jacinto and San Andreas faults; since 1994 at Durmid Hill, very close to the southern termination of the San Andreas; and for the past year in Verdugo Canyon, at the northern edge of the Los Angeles basin. The first lesson learned from these measurements is that, even over baselines of hundreds of meters, the measurements must be made between points carefully anchored to depth; if this is done, the strain record can provide both very low noise at high frequencies (better than GPS by factors of 100 or more at periods of a week) and also long-term noise low enough to reliably measure secular strain accumulation. While the measurements have been made in only a few locations, these are in areas of active faulting, with secular deformation rates as high as in most areas along the plate boundary. We have observed coseismic signals from a number of earthquakes, and postseismic signals from a few: most notably a two-year signal from the 1992 Landers shock, and shorter-term deformations from the 1987 Superstition Hills and 1999 Hector Mine events. We have not observed any preseismic anomalies. The instrument at Durmid Hill has observed a number of short-term strain changes, and anomalous coseismic deformation from the Hector Mine earthquake; we attribute these effects to shallow creep on the San Andreas fault nearby. These high-quality data suggest that along the strike-slip boundary (and excepting creeping sections of fault zones) "strain events" are rare: rather, steady strain accumulation is punctuated only by occasional seismic events and relatively modest postseismic deformation. This picture is consistent with other data now available; installation by the PBO of many more instruments along the plate boundary will further test this idea.

G41A MCC: 3005 Thursday 0800h

Progress in Imaging and Understanding the Surface Deformation Field Above Reservoirs I

(joint with H)

Presiding: **D W Vasco,** Berkeley Laboratory, University of California, Berkeley**; H J Kuempel,** Leibniz Institute for Applied Geosciences

G41A-01 0800h INVITED

Time-Dependent Land Uplift and Subsidence in the Santa Clara Valley, California

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We invert 115 differential interferograms derived from 47 synthetic aperture radar (SAR) scenes for a time-dependent deformation signal in the Santa Clara Valley, California. The time-dependent deformation is calculated by performing a linear inversion that solves for the incremental range change between SAR scene acquisitions. A nonlinear range-change signal is extracted from the ERS InSAR data without imposing a model of the expected deformation. In the Santa Clara valley, cumulative land uplift is observed during the period from 1992 to 2000 with a maximum uplift of 41±18 mm centered north of Sunnyvale. Uplift is also observed east of San Jose. Seasonal uplift and subsidence dominates west of the Silver Creek fault near San Jose with a maximum peak-to-trough amplitude of ∼35 mm. The long-term uplift is attributed to the gradual recharge of the aquifer over the 8-year period. It is assumed that the pumpage and redistribution of groundwater is responsible for the seasonal subsidence, although a direct correlation is still under investigation. The pattern of seasonal versus long-term uplift provides a qualitative constraint on the spatial and temporal characteristics of water bearing units within the aquifer. The Silver Creek fault partitions the uplift behavior of the basin, suggesting that it acts as a hydrologic barrier to ground water flow. While no tectonic creep is observed along the fault, the development of a low permeability barrier that bisects the alluvium suggests that the fault has been active since the deposition of Quaternary units.

G41A-02 0815h

SAR Interferometric Point Target Analysis for Long-Term Deformation Mapping

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Repeat-pass Interferometric SAR (InSAR) is a powerful technique for mapping land surface deformation at fine spatial resolution over large areas. The application of repeat-pass InSAR is limited due to temporal and geometric decorrelation and inhomogeneities in the tropospheric path delay. Interferometric Point Target Analysis (IPTA) utilizes the unique characteristics of the tropospheric path delay and SAR backscattering of certain ground targets to achieve higher accuracy deformation measurements than attainable with conventional InSAR. Over urban areas with numerous man-made structures or in areas where large rock outcroppings are visible, it is possible to identify point-like targets that remain phase coherent over time. These targets can be used as "natural" monuments to estimate the progressive deformation of the terrain at millimeter accuracy. Building upon conventional InSAR techniques, IPTA overcomes atmospheric delay anomalies and temporal and geometric decorrelation using multi-temporal interferograms by exploring the temporal and spatial characteristics of radar interferometric signatures collected from point targets. In this contribution the IPTA concept is introduced, including the point selection criteria, the phase model and the improvement of the model parameters. Intermediate and final results of IPTA examples using data acquired using ERS1, ERS2, and JERS confirm the validity of the concept for mapping subsidence related to the extraction of oil in Belridge, California and aseismic deformation along the Raymond fault in Pasadena, California.

URL: http://www.gamma-rs.ch

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Using GPS to Quantify Three Dimensional Storage and Aquifer Deformation in the Virgin River Valley, Nevada

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Quantifying aquifer storage is important in order to characterize aquifer response and optimize aquifer pumping in large well fields located in thick sedimentary basins like those in the arid southwestern United States. The majority of this water is released from storage because of aquifer-system compaction. Historically this compaction was assumed to occur only in the vertical direction. However, aquifer mechanics and related field investigations indicate that strain is three-dimensional and the amount of water released from storage by horizontal strain can be significant. The development of empirically-based analytical techniques that allow for accurate quantification of storage and an assessment of the strain components at various radii from the pumping well are needed. From May through August, 2003, field scale aquifer testing and land subsidence monitoring were performed in the Virgin River Valley at Mesquite, NV. The goals were to determine the usefulness of storage quantification methods at the field scale and developing an effective inexpensive method to monitor three-dimensional deformation patterns due to removal of water from storage. The ground movement was monitored using choke ring antennas and GPS receivers at 10 different locations at various distances from the pumping well for 100 days. The well was pumped for approximately 12 hours each day at a rate of about 18000 m3/d. Compared to pumping at a steady rate, pulsating pumping (i.e. on and off cycles) has been shown to concentrate vertical deformation closer to the pumping well. The effect of pulsed pumping on horizontal deformation is previously not well documented but can now be investigated. The GPS data and pumping data collected from the aquifer test will be used to quantify aquifer strain in three dimensions at various distances from the well and stages during pumping. These strain patterns will provide information about possible faults in the area that affect groundwater flow, provide information on subsidence prone areas, and yield information on the general behavior of groundwater flow in the region. Two modeling programs, the BIOT4 code and the Interbed Storage 1 package of MODFLOW will be used to evaluate whether these models can effectively simulate the horizontal and vertical deformation of a semi-confined aquifer from GPS measurements recorded at the land surface. In addition, the BIOT4 Code can be used to compare deformation in both the horizontal and vertical directions for the pulsed pumping scheme used in the field and at a steady pump rate.

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Monitoring Subsidence Changes over the Lost Hills Diatomite Oil Field, California*

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