Robert J Mueller[1] (650 3294857; rmueller@usgs.gov)

[1]US Geol. Survey, 345 Middlefield Rd., MS977, Menlo Park, CA 94025, United States

[2]Berkeley Seismology Laboratory, University of California, Berkeley, CA 94720, United States

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

Frank K. Wyatt[1] (fwyatt@ucsd.edu)

Duncan Carr Agnew[1] (dagnew@ucsd.edu)

[1]IGPP/SIO, University of California, La Jolla, CA 92014, United States

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

David Schmidt[1] (541-346-3005; das@uoregon.edu)

Roland Bürgmann[2] (burgmann@seismo.berkeley.edu)

[1]University of Oregon, Geological Sciences, 1272 University of Oregon, Eugene, OR 97403-1272, United States

[2]University of California, Berkeley, Earth and Planetary Science, 307 McCone Hall, Berkeley, CA 94720-4767, United States

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

Charles Werner[1] (41-31-951-70-05; cw@gamma-rs.ch)

Zhong Lu[2] (605-594-6063; lu@usgs.gov)

Andreas Wiesmann[1] (41-31-951-70-05; wiesmann@gamma-rs.ch)

Urs Wegmuller[1] (41-31-951-70-05; wegmuller@gamma-rs.ch)

Tazio Tazio[1] (41-31-951-70-05; strozzi@gamma-rs.ch)

[1]Gamma Remote Sensing AG, Thunstrasse 130, Muri b. Bern CH-3074, Switzerland

[2]U.S. Geological Survey, EROS Data Center, SAIC, 47914 252nd Street, Sioux Falls, SD 57198, United States

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

G41A-03 0830h

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

Sandra McCarthy Warner[1] (540-231-2404; smwarner@vt.edu); Thomas J. Burbey[1] (540-231-6696; tjburbey@vt.edu); Geoff Blewitt[2] (gblewitt@unr.edu); John W. Bell[2] (jbell@unr.edu); Emma Hill[2] (emmahill@seismo.unr.edu); Michael Johnson[3] (702-346-5731; boomer@vvh2o.com)

[1]Virginia Tech Hydrogeosciences, 4404 Derring Hall, Blacksburg, VA 24061, United States

[2]Nevada Bureau of Mines and Geology, Mail Stop 178 University of Nevada, Reno, NV 89557, United States

[3]Virgin Valley Water District, 500 Riverside Rd, Mesquite, NV 89027, United States

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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.

G41A-04 0845h

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

Eric J Fielding[1] (1-818-354-9305; Eric.Fielding@jpl.nasa.gov)

James L Brink[2] (1-661-392-3808; JimBrink@chevrontexaco.com)

Tad W Patzek[3,4] (1-510-643-5834; patzek@patzek.berkeley.edu)

Dmitriy B Silin[4] (1-510-495-2215; DSilin@lbl.gov)

Ronald G Blom[1] (1-818-354-4681; Ronald.Blom@jpl.nasa.gov)

[1]Jet Propulsion Lab, Caltech, 4800 Oak Grove Dr., MS 300-233, Pasadena, CA 91109, United States

[2]Chevron U.S.A. Production Co., NAU SJVBU Business Unit, 15255 Lost Hills Rd., Lost Hills, CA 93249, United States

[3]Dept Civil and Environmental Engineering, UC Berkeley, 437 Davis Hall, Berkeley, CA 94720, United States

[4]Lawrence Berkeley National Lab, University of California, 1 Cyclotron Road, MS 90-1116, Berkeley, CA 94720, United States

SAR, GPS and LiDAR monitoring of the Lost Hills giant oil field in central California shows dramatic changes of subsidence over the last 15 years. Subsidence is caused by fluid withdrawal and subsequent compaction of the diatomite petroleum reservoir and in some areas has reached cumulative subsidence of 2 meters since 1989. Measurements of the surface elevation changes with semi-annual GPS surveys and SAR interferometry (using ERS-1 and ERS-2 satellite data) show subsidence rates exceeded 1 mm/day during 1995-1996 in the central part of the oil field. By 1999-2000, increased injection of water to replace the extracted fluids meant that no part of the Lost Hills field was subsiding faster than 0.5 mm/day and some areas that had extremely rapid subsidence before were slower than 0.2 mm/day. We increased the temporal resolution of the subsidence measurements for late 2002 and early 2003 by analyzing more frequent SAR acquisitions from the Radarsat-1 satellite to better understand the compaction response to changes in the oil field operations. The Radarsat-1 orbit-repeat period is 24 days but individual interferograms with short time intervals of only 24 days can have substantial errors due to atmospheric variations. Errors can be reduced by making interferograms with longer time intervals or by averaging multiple independent interferograms over a shorter interval. The Radarsat-1 satellite can image Lost Hills from up to six different tracks every 24-day cycle, potentially allowing six independent interferograms. *Part of this work was performed at the Jet Propulsion Lab, Caltech under contract with the National Aeronautics and Space Administration.

G41A-05 0900h INVITED

Inverse modeling of interbed storage parameters using land subsidence observations, Antelope Valley, California

Jörn Hoffmann[1] (+49 (8153) 28-3329; joern.hoffmann@dlr.de)

Devin L. Galloway[2] (+1 (916) 379-3737; dlgallow@usgs.gov)

Howard A. Zebker[3] (+1 (650) 723-8067; zebker@stanford.edu)

[1]German Aerospace Center (DLR), Remote Sensing Data Center, Oberpfaffenhofen, Wessling 82234, Germany

[2]United States Geological Survey, 7801 Folsom Blvd., Suite 325, Sacramento, CA 95826, United States

[3]Stanford University, Department of Geophysics, Mitchell Building, Stanford, CA 94305-2215, United States

Land subsidence above subsurface reservoirs has been observed in many locations all over the world. The observed surface displacements accompany reservoir pressure changes induced by the resource exploitation or management. In recent years satellite radar interferometry (InSAR) has increasingly complemented or replaced traditional methods for detecting and characterizing the surface displacement field above reservoirs. We have used land-subsidence observations from repeatedly surveyed benchmarks and InSAR in Antelope Valley, Mojave Desert, California to estimate interbed storage parameters controlling the subsidence in a previously calibrated regional ground-water flow and subsidence model (MODFLOW). Using the nonlinear parameter estimation program UCODE, we have estimated compaction time constants varying spatially from 3.8 to 285 years. A linear estimation of the inelastic skeletal storage coefficients yielded values between 0 and 0.09. We found that subsidence observations over long time periods were necessary to constrain the large compaction time constants in Antelope Valley. Because historical subsidence data cannot yet be provided by space-geodetic techniques such as InSAR the time-constant estimates in our model were constrained primarily by observations from benchmarks. Incorporating the resulting parameter estimates into the MODFLOW ground-water flow and subsidence model significantly improved the agreement between simulated and observed subsidence, whereas the model-simulated aquifer heads proved to be very insensitive to our modifications of the interbed storage parameters. Both the accuracy of the estimated parameters and the resulting models' ability to predict subsidence over short time periods is hampered by the fact that the simulated hydraulic heads are often not representative of the actual aquifer hydraulic heads. These errors constitute the primary limitation of the approach presented here.

G41A-06 0915h INVITED

Imaging and Analysis of Ground Surface Deformation using Tiltmeters for Reservoir Optimization

Eric Davis[1] (415-861-1097; eric.davis@pinntech.com); Chris Wright[1] (chris.wright@pinntech.com); Du Jing[1] (jing.du@pinntech.com); William Roadarmel[1] (william.roadarmel@pinntech.com); Dmitriy Astakhov[1] (dmitriy.astakhov@pinntech.com); Larry Griffin[1] (larry.griffin@pinntech.com)

[1]Pinnacle Technologies, 600 Townsend St. Suite 160W, San Francisco, CA 94103

Simultaneous injection into multiple wellbores inevitably raises questions about fluid distribution. One way to monitor both the injection and subsequent fluid withdrawal is with an array of surface tiltmeters. The tiltmeter data is used to produce a video of surface deformation, which enables quick visual assessment of the stimulated areas. The data is further analyzed when discreet events are noted. Some of these events include opening of new areas which previously received little fluid, changes in distribution caused by shut-ins and injection pressure changes, and breakthroughs into shallower zones. The geophysical inverse problem is solved using a combined volumetric and dislocation solution to quantitatively estimate the dimensions, depth, volume content and shear offset of an affected zone. The data generated by the monitoring system is used in the short term to alter injection strategies to aid production while preventing significant breakthrough into unwanted zones and in the long term to help optimize the field treatment strategy.

G41A-07 0930h

A Coupled Inversion of Pressure and Surface Displacement

D. W. Vasco[1] ((510) 486-5206; dwvasco@lbl.gov)

Kenzi Karasaki[1] (kkarasaki@lbl.gov)

kiyoshi Kishida[2] (kishida@toshi.kuciv.kyoto-u.ac,jp)

[1]Berkeley Laboratory, Earth Sciences Division/Bldg. 90 1 Cyclotron Road, Berkeley, CA 94720, United States

[2]Kyoto University, Department of Civil Engineering, Kyoto 606-8501, Japan

A coupled inversion of transient pressure observations and surface displacement measurements provides an efficient technique for estimating subsurface permeability variations. The methodology has the advantage of utilizing surface observations, which are typically much less expensive than measurements requiring boreholes. Furthermore, unlike many other geophysical observables, the relationship between surface deformation and reservoir pore fluid volume changes is relatively well understood. Our treatment enables us to partition the estimation problem into a sequence of three linear sub-problems. An application of the approach to a set of tilt and borehole pressure data from the Raymond field site in California illustrates it's efficiency and utility. The observations are associated with a well test in which fluid is withdrawn from a shallow fracture zone. During the test thirteen tiltmeters recorded the movement of the ground surface. Simultaneously, nine transducers measured pressure changes in boreholes intersecting the fracture system. We are able to image a high permeability, north trending channel located within the fracture zone. The existence and orientation of this high permeability feature is substantiated by a semi-quantitative analysis of some 4,000 transient pressure curves.

G41A-08 0945h INVITED

An efficient semi-analytical method for modeling strongly coupled diffusion and deformation processes in layered poroelastic media

Rongjiang Wang[1] (+49 (0)331 2881209; wang@gfz-potsdam.de)

Hans-Joachim Kuempel[2] (+49 (0)511 643 3496; kuempel@gga-hannover.de)

[1]GeoForschungsZentrum Potsdam, Telegrafenberg, Potsdam D-14473, Germany

[2]Leibniz Institute for Applied Geosciences, Stilleweg 2, Hannover D-30655, Germany

From poroelasticity theory we know that fluid diffusion will induce matrix deformation and vice versa. In practice, well known phenomena for such coupled processes are, for example, occurrence of seismotectonically induced groundwater fluctuations, land subsidence as a result of fluid extraction from subsurface reservoirs, production-induced surface strain near the vicinity of wells, reservoir- or injection-induced seismicity. Modeling of deformation and pore-pressure data that have been observed near the surface can help to image the dynamics and to assess the hydraulic properties of subsurface aquifers. We here present a semi-analytical Haskell propagator method to fully handle linear poroelastic problems in a multilayered half-space. Our method is a powerful tool for various reasons: (1) It is faster than traditional numerical schemes when respective discretization of the object region is chosen and solutions are sought for single locations only; (2) a problem is easily formulated, as only a set of five poroelastic parameters per layer plus the layers' thicknesses need to be specified; (3) the method is highly flexible, as forcing functions of point injection, single force (e.g., surface loading), double couple dislocation (earthquakes), etc. may be readily incorporated; (4) the so-called loss-of-precision problem of the original propagator algorithm has been fully overcome using the orthonormalization technique. The effectiveness of the new tool has been demonstrated by modeling pump-induced near-surface tilt data obtained at a test site near Sopron in western Hungary. The results show that the hydraulic diffusivity of the shallow subsurface aquifer can be assessed with an accuracy better than half an order of magnitude, if other elastic parameters and the geometry (depth and thickness) of the water-bearing formations are sufficiently known from, for example, bore-log records. Moreover, the present method can be applied to model induced seismicity based on the Coulomb failure criterion.

G41B MCC: Level 1 Thursday 0830h

Geodesy of Terrestrial Planets I Posters *(joint with P)*

Presiding: **D E Smith,** NASA Goddard Space Flight Center**; T Van Hoolst,** Royal Observatory of Belgium

G41B-0030 0830h POSTER

Solar Eclipses on Mars: Spatial and Temporal Patterns in the Motion of the Shadow of Phobos

Robert Comstock[1] ((858)534-8290; rcomstoc@ucsd.edu)

Bruce Bills[1,2] (bbills@ucsd.edu)

[1]UCSD/Scripps Institution of Oceanography, Institute for Geology and Planetary Physics, La Jolla, CA 92093-0225, United States

[2]NASA GSFC, Geodynamics Branch, Greenbelt, MD 20771, United States

The shadow cast by Phobos on the surface of Mars is small and moves rapidly, and can thus provide important relative position information. The size, shape, direction and speed of motion of the shadow evolve over a range of time scales determined by the orientations of Mars and Phobos orbits, and their relative orbital rates. We develop a simple geometric model for the temporal and spatial patterns of Phobos shadows on Mars, and comment on the possibility of using observations of the shadow of Phobos as a supplemental method for determining lander locations. The orbital parameters for the Mars-Phobos system are sufficiently different from the Earth-Moon system that terrestrial eclipse experience is a poor guide. The lunar orbit, with mean angular rate 13.33 deg/day, mean radius 60.2 Earth radii, and variable inclination (18-28 deg) to the equator plane, makes solar eclipses on Earth relatively rare. With an average of 2.38 eclipses per year, only a small fraction of the globe experiences a total eclipse in any given century. In contrast, the orbit of Phobos, with rapid mean motion of 1152 deg/day, small mean radius of 2.7 Mars radii, and negligible inclination of 1.1 deg, provides a favorable eclipse environment. Although the size and orbital distance of Phobos are such that total solar eclipses never occur on Mars, partial eclipses are common, with an average of 3.22 per day throughout most of each annual cycle. The Viking Lander 1 (VL1) camera system captured three Phobos eclipse events on 20, 24, 28, September 1977. On Earth, one would never see a series of eclipses at one location over such a short time scale. However, on Mars it is possible to see two eclipses in one day at a single location. A goal of the present study is to address the likelihood of observing a sequence of eclipses, similar to that observed by Viking 1, at a single site. A