

Geodesy

G51A MCC: Hall C Friday 0830h

Geophysical Constraints on the Role of Fluids in the Crust Posters (joint with H, S, T)

Presiding: D Schmidt, Stanford University; M Saar, University of California, Berkeley

G51A-0940 0830h INVITED POSTER

A Mechanism for Seismically Induced Pore Pressure Changes Inferred from High Frequency Water Well Data

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Earthquakes can produce water level changes in certain distant wells orders of magnitude larger than can be explained by static stress changes. The redistribution of pore pressure can generate crustal deformation and perhaps even trigger seismicity. Some studies suggest that earthquakes induce permeability increases or other aquifer property changes. Standard hydrogeological methods do not continuously measure aquifer properties therefore it is difficult to monitor the inferred variations. We developed a new method to measure aquifer properties over short times by combining high-sample rate water level data (1 sps) and seismic data for a site near Grants Pass Oregon. The new method motivates a new model in which the seismic waves remove transient barriers of sediment in a fracture.

Pumping test data for the site is well-modeled by a single, infinitesimally thin square planar fracture embedded in a unbounded, homogeneous and isotropic confined aquifer. For this geometry, the amplification factor χ , defined as the ratio of the water level amplitude to the ground velocity, as a function of frequency f is

$$\chi = A(\nu, c)\Gamma \left[1 - \frac{4\pi^2 H f^2}{g} + \frac{\pi r^2}{2 L^2} \sqrt{\frac{\pi f}{K S_s}} (1+i) \right]^{-1}$$

where $A(\nu, c)$ is the ratio of the dilatational strain to the vertical ground velocity which is a function of the Poisson's ratio ν and the seismic phase velocity c , Γ is the ratio of the confined aquifer fluid pressure to changes in the dilatational static strain as inferred from the tidal response, K is the hydraulic conductivity, L is the fracture length, r is the wellbore radius and H is the water column height. Since the well geometry is known and S_s is measured by the tidal response, we use Eq. 1 to infer time-dependent conductivity and fracture length. Normally, the fracture length is 130 m. Immediately prior to the Sept. 30, 1999 $M_w=7.4$ Oaxaca, Mexico earthquake, the effective fracture length was 30 m. During the passage of the seismic waves, the effective length returned to 130 m. Simultaneously, the water level dropped 11 cm.

Based on these observations we infer that the seismic waves cleared a transient barrier from the fracture. Water pumped from deep in the aquifer contains 4×10^7 micron-size aluminosilicate particles/l. If the normal Darcy velocity through the fracture is 5 m/d, 0.3 mm thick barriers of densely-packed colloids can be deposited in two years. Dense clay floes have conductivities comparable to the wallrock (7×10^{-8} m/s) and thus effectively end the fracture. When floes form, the fluid pressure on the upstream side of the low-permeability barrier in steady state increases and the head drop across the barrier is 0.25 m (2.5 kPa pressure). If the farfield head is constant, when the barrier is removed the upstream side returns to the initial pressure by dropping by half the head difference, or 13 cm.

Seismically-induced pore pressure steps can occur by this mechanism in any hydrogeological system that

has: (1) low matrix specific storage, (2) fractures or faults and (3) a source of material for clogging. In geothermal areas precipitation rates can be 15x greater than modeled above resulting in pressure changes of 4×10^{-2} MPa which is sufficient to trigger earthquakes according to static stress studies.

G51A-0941 0830h POSTER

Groundwater Level Changes in a Deep Well in Response to an Intrusion Event on the Summit of Kilauea Volcano, Hawaii

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We analyzed groundwater level changes in the NSF well located on the summit of Kilauea Volcano, Hawaii in response to the May 21, 2001 intrusion event. The 10 hours preceding the intrusion event were characterized by extension recorded on three borehole strainmeters located up to 58 km from the summit, and deflation of the summit region recorded on tiltmeters. This probably occurred in response to a volume/pressure increase of a deep source extending at least 40 km beneath Kilauea. On May 21 at approximately 02:20 (UT) tilt and strain reversed directions. In the following hour compressional strain (up to 2 strain in the NSF well) and inflation of the summit (up to 5 radians) were recorded, as well as three shallow earthquakes ($ML=1.9-2.3$; $d<3.2$ km) in the summit region. Surface deformation was modeled as a shallow (0.5-2 km) pressure source (dike intrusion) feeding into the east rift zone conduit system. At about 03:30, strain and tilt reversed again and returned to near pre-event values during the next 20 hours. Water levels (between 490.7 m and 493.3 m in the past two years) were recorded every 10 minutes by two pressure transducers with a resolution of 0.05 cm, and indicate a small response to barometric pressure and Earth tides. On May 21 between 02:30 and 03:30 water level in the well dropped by 6.5 cm, an unexpected mode of change for compressive strain in uniform material. The water level decline indicates that pore-pressure diffusion in response to dike intrusion did not contribute to the observed summit inflation. Water levels gradually recovered back to normal level after about one day. A model that reconciles the coeval compressional strain and the water level drop in the well is that the compression induced by the intrusion caused instantaneous dilation of horizontal fractures or basaltic interflows that transect the well, which in turn caused water to drain out of the well, resulting in a water level drop. The volume of water drained from the well was approximately 1.5 liters, so that a dilatation of 1.5 mm on one horizontal fracture with dimensions of 1 m² could have drained all the fluid during the event. Once the stress was relaxed cracks contracted and the water level recovered. The proposed model does not exclude the possibility of large water pressure pulses propagating through newly opened fractures. However, the small response to barometric pressure and earth tides and the lack of water level changes in response to a ML 4.6 earthquake less than 3 km north of the well on April 26 2001 suggest that rapid propagation of large fluid-pressure pulses is unlikely.

G51A-0942 0830h INVITED POSTER

Fluid Pressure Increases in Hydrothermal Systems Induced by Seismic Waves: Possible Triggers of Earthquakes and Volcanic Eruptions

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That seismic waves trigger microseismicity in hydrothermal settings hundreds of km from the epicenter is plausibly linked to seismic-wave-induced fluid pressure changes at these distances. Although fluid pressure decreases have been observed in diverse settings, in the hydrothermal system at Long Valley, California, that seismic waves from earthquakes increase fluid pressure or discharge. Other published data, from thermal springs in Japan, Yellowstone, and Klamath Falls, Oregon, support the idea that seismic waves have induced pressure and discharge changes and that, in hydrothermal systems, these changes are usually increases. Temperature increases in seafloor hydrothermal vents within days after earthquakes as distant as 220 km imply, moreover, that seismic waves enhance conductance of vertical fluid flow pathways.

The influence of seismic waves (wavelengths of km), on hot, fluid-filled subsurface fractures (apertures of mm to cm) could proceed by several mechanisms. Local fluid flow induced at crack walls could remove mineral seals. Spatially uniform acceleration can move gas bubbles relative to denser liquid and solid phases. Thermal

expansion can elevate pressure around hot fluid that has penetrated upward.

By lowering effective stress and directly weakening faults that are themselves flow paths, seismic waves could initiate processes leading to volcanic eruptions or other earthquakes where sufficient subsurface magma or elastic strain energy have previously accumulated. This type of earthquake-volcano linkage could explain why volcanoes statistically erupt more frequently up to 5 years after $M>7$ earthquakes hundreds of km distant. For example, 11 months elapsed after the M_s 7.8 Luzon (Philippines) earthquake before Mount Pinatubo erupted on June 15, 1991, 100 km away. Steam emission and 3 M_4+ earthquakes in the Pinatubo area followed within days of the Luzon event, however, and a hydrothermal explosion on April 2 started the continuous unrest that built to the eruption. Seismic waves acting on Pinatubo's hydrothermal system could have initiated vertical path-clearing that led, after 11 months, to magmatic eruption.

At the base of the seismogenic zone for crustal earthquakes (8-12 km depth), expected temperatures (200-300°C) are close to those of hydrothermal systems at 0-3 km depth, and effective confining pressure may also be similar if fluid pressures exceed hydrostatic. Seismic waves may, therefore, facilitate upward movement of hot fluid into steeply dipping faults at depths where tectonic earthquakes originate. Triggered microseismicity and progressive fault weakening could lead to delayed larger events, such as the M_s 5.4 Little Skull Mountain earthquake 20 hours after, and 280 km from, the M_w 7.3 Landers, California, earthquake in 1992.

Intensified geophysical and hydrologic monitoring after major seismic events could test the hypothesis that seismic waves trigger earthquakes and volcanic eruptions by acting on hydrothermal environments.

G51A-0943 0830h POSTER

Numerical Analysis of Gravity Flow and Overpressure Development: Implications for Liquefaction Susceptibility in the New Madrid Seismic Zone

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We used mathematical modeling techniques to evaluate relations involving topographic-driven flow, overpressure development, and susceptibility to seismically-induced liquefaction in the Mississippi Embayment. The mathematical model assumes that the magnitude of excess pore pressure in the discharge area is determined by a basin's geometry and the distribution of hydraulic conductivity. The numerical simulations show the development of both shallow and deep groundwater flow (< 2 km) that discharges toward the Mississippi River near the New Madrid seismic zone (NMSZ). The modeling results indicate that excess pore pressures up to 7 atmospheric pressures could be sustained in a wide discharge area of the NMSZ by gravity flow. The predicted magnitude of excess pressures is generally consistent with the observed elevation heads (10-20 m) of artesian wells that penetrate the Upper Cretaceous aquifer in the study area. Numerical simulations examine the degree of overpressure downgradient in the discharge area. The high pore fluid pressure reduces effective stress, or the stress borne by the aquifer skeleton through grain to grain contacts. A drop in effective stress and a change in shear strength in matrix can influence strong ground motion in areas with water-saturated sediments. The prevailing overpressure conditions in the shallow NMSZ may result in a degree of ground shaking that is different than that expected under hydrostatic conditions. Reconstruction of the hydrology and overpressures of the deep seismic zone is difficult because critical hydrologic data of crustal rocks and faults are not available. Further theoretical modeling is needed to assess the overpressure conditions resulting from large-scale compressive stress in the crust of the NMSZ. We argue that ambient pore pressure distribution may be an important, but often ignored, component of earthquake and liquefaction studies in the NMSZ and elsewhere.

G51A-0944 0830h POSTER

Seismicity Induced by Groundwater Recharge at Mt. Hood, Oregon, and its Implications for Hydrogeologic Properties.

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Earthquakes induced by human-caused changes in fluid pressure have been documented for many years. Examples include seismicity induced by filling reservoirs and by fluid injection or extraction. Less well-documented are seismic events that potentially are triggered by natural variations in groundwater recharge rates (e.g., Wolf et al., BSSA, 1997; Jimenez and Garcia-Fernandez, JVGR, 2000; Audin et al., GRL, 2002). Large groundwater recharge rates can occur in Volcanic Arcs such as the Oregon Cascades where annual precipitation is > 2 m of which $> 50\%$ infiltrates the ground mostly during snowmelt in spring. As a result, infiltration rates of > 1 m per year concentrated during a few months can occur. Near-surface porosities are about 5-10%. Thus, groundwater levels may fluctuate annually by about 10-20 m resulting in seasonal pore fluid pressure variations of about $1-2 \times 10^5$ Pa. Such large-amplitude, narrow-duration fluid pressure signals may allow investigation of seismicity induced by pore fluid pressure diffusion without the influence of engineered systems such as reservoirs. This kind of in-situ study of natural systems over large representative elementary volumes may allow determination of hydrologic parameters at spatial and temporal scales that are relevant for regional hydrogeology. Furthermore, natural hydrologic triggering of earthquakes that persist for decades provides insight into the state of stress in the crust and suggest long-term near-critical failure conditions.

Here, we approximate the temporal variations in groundwater recharge with discharge in runoff-dominated streams at high elevations that show a peak in discharge during snow melt. Seismicity is evaluated as time series of daily number of earthquakes and seismic moments. Both stream discharge and seismicity are compared at equivalent frequency bands by applying segmented least-squares polynomial fits to the data. We find statistically significant correlation between groundwater recharge and seismicity at Mt. Hood, Oregon. We can use the time lag of about 120 days between the two records to estimate the regional hydraulic diffusivity ($1 \text{ m}^2/\text{s}$) and other hydrogeologic parameters (permeability $\approx 10^{-13} \text{ m}^2$, vertical matrix compressibility $\approx 10^{-10} \text{ m}^2/\text{N}$). These values are comparable with our results from coupled heat and groundwater flow studies that are based on bore hole temperature data at Mt. Hood.

G51A-0945 0830h POSTER

Analysis of the Seismicity Induced by Massive Fluid Injection in the HDR Geothermal Site of Soultz-sous-Forets (France)

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In July 2000 a stimulation experiment was performed at the Hot Dry Rock geothermal site of Soultz-sous-Forts (Alsace, France). During one week, a total of 23000 m³ of fluids were injected at 30, 40 and 50 l/s in a hot, fractured granitic massif at 5 km depth in order to enhance the fracture network. Induced microseismic events were recorded by both a surface and a downhole seismicological network. About 7200 events have been located precisely using both seismic networks. They form an elliptic-shaped microseismic cloud trending N30W, which grows northwards until the shut-in of injections and then increases to the South. A local tomography shows a slight raise of the velocities in the granite during the experiment until the last increase of injection rate (40 l/s to 50 l/s) which seems to be associated with a sudden decrease of the velocities. These observations could correspond to a change in the hydro-mechanical behaviour of the geothermal reservoir during the stimulation. We also determine several hundreds of focal mechanisms using polarities of P-waves. They reveal a dominant normal-faulting, in agreement with the stress regime in the Northern part of the Rhine Graben.

G51A-0946 0830h POSTER

Origin of postseismic streamflow changes inferred from baseflow recession and magnitude-distance relations

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One common hydrologic response to earthquakes is an increase in stream discharge. Discharge increases appear to be coseismic, typically peaking within a few days to weeks of the earthquake. The "excess" streamflow (the difference between the actual discharge and an estimate of what discharge would have been in the absence of an earthquake) may persist for months to years.

We analyze the effects of earthquakes on baseflow, the component of streamflow provided by groundwater, for streams that exhibit large coseismic increases in streamflow and discharge large volumes of excess water. Specifically we focus on the earthquakes and basins considered by Muir-Wood and King (JGR, 1993). Although discharge Q may increase rapidly, the rate of baseflow recession $d \log Q/dt$ is unchanged suggesting that the (horizontal) hydraulic conductivity of the groundwater system providing baseflow does not change. For at least the studied streams, the coseismic increase of discharge therefore requires increased hydraulic head gradients resulting from the rapid release of water from some source of storage. Possible mechanisms that can rapidly release water from storage include the enhancement of matrix hydraulic conductivity, an increase in vertical permeability of confining units, and changes of fluid pressure in matrix materials by transient dynamic strain (e.g., by liquefaction). The relationship between the response of streams, earthquake magnitude, and the distance of the drainage basin from the epicenter, is not inconsistent with subsurface liquefaction being the mechanism that increases head gradients.

We also analyzed the response of the Sespe Creek Watershed (near Ventura, California) to multiple earthquakes. We find that discharge changed after three earthquakes. The observed changes in discharge have the same character. We develop a simple one-dimensional groundwater flow model and show that the postseismic response can be explained in all three cases by the same groundwater flow model in which hydraulic heads increase coseismically in the same region of the aquifer. The magnitude of the head change does not appear to scale with dynamic strain, and static strains are probably too small to produce the observed responses.

G51A-0947 0830h POSTER

Constraints on Permeability of the Upper Crust

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What controls the permeability of the upper crust on continents? Here I examine the potential controls that recharge and state of stress play on the lower bounds of permeability in crustal materials capable of fracture. I test the hypothesis that the minimum permeability of the crust is significantly governed by local recharge and state of stress. I examine the expected variability in permeability for crustal materials in a state of incipient failure based upon estimates of variability in recharge and topography. I then examine the variability in permeability that can be expected based on shallow state of stress measurements available throughout the world. Finally I compare the expected permeability of a recharge and stress controlled crust with that observed in nature.

G51A-0948 0830h POSTER

Vertical Crustal Movement Correlated with Seismicity in the Eagle Oilfields, British Columbia: Application of the InSAR Coherent Scatterer Technique

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The Eagle oilfields, located 10 km northeast of Fort St. John, B.C., Canada experienced 37 earthquakes greater than $M = 2$ from 1984 to 1998. Fluid injection

to increase oil recovery was initiated in the 1980s at the Eagle oilfields. Since seismicity began a few years after fluid injection was initiated, fluid injection has long been considered as a possible cause of the seismicity. Oil and gas production and fluid injection can also induce movement of the ground surface. Mapping of such surface movements using spaceborne synthetic aperture radar (SAR) repeat-pass interferometry (InSAR) can provide important information on the temporal redistribution of sub-surface fluid pressure associated with fluid injection and extraction.

Nineteen scenes of ERS-1 and ERS-2 SAR data were selected over the period 1992 to 1997 and analyzed using the coherent scatterer approach (Ferretti et al., 1999). This approach involves the identification of points on the ground that do not suffer from the de-correlating effect associated with vegetation. These points are typically urban structures and bedrock exposures. Eighteen differential interferograms were generated and around 1700 coherent scatterers were identified over a 13 km by 14 km area in the vicinity of the Eagle oilfields. Each scatterer provides a relative elevation estimate at 18 epochs over a five year period, allowing a vertical crustal movement rate to be calculated for each scatterer. Individual scatterers were found to exhibit a high variability in vertical movement rate but this variability was suppressed by spatial averaging at each epoch.

Calculations of surface displacement rates based on fluid injection and extraction data and a simplified poro-elastic model predict about 1 mm/yr of subsidence in the eastern part of the oilfield. However, the spatially averaged vertical movement rates show a significant variability of around 4 mm/yr over the study area. Two areas of relative uplift coincide with the two areas of most active seismicity during the 1992 to 1997 period.

G51A-0949 0830h POSTER

The connection between crustal deformation related to large earthquakes and underground flow in Kamchatka (Russia)

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Since 1977, water discharge, water level, temperature and pH have been measured in wells and natural springs, in six different localities in southeastern Kamchatka. In addition, the chemical components Cl, HCO₃, SO₄, Na, K, Ca, H₃BO₃, H₄SiO₄, free and melted gases CH₄, N₂, O₂, CO₂, Ar, He, H₂ and hydrocarbonates C₂H₆, C₂H₄, C₃H₈, C₃H₆, C₄H₁₀, C₄H₁₀i were analysed in water samples every third day. The depth of the wells varied from a few hundred meters to a few thousand meters. During the observational period, 10 earthquakes with $M > 7.0$ occurred in the surrounding area (i.e., within 250 km). A few earthquakes in some wells show clear anomalies in chemical composition before earthquakes. All earthquakes produced strong postseismic variations in water discharge and chemical composition in natural springs and water level changed in some boreholes.

For the biggest earthquake (Dec. 05, 1997, $M_w = 7.8$), GPS observations indicated preseismic deformation started about one month to the main shock. In some boreholes, geochemical anomalies were detected before the main shock. Slow deformation before large earthquakes can create extra stress in surrounding medium and increase the circulation in subsurface hydrological systems along with changes in their chemical composition.

A good example of the sensitivity of the subsurface hydrological system is the response of the natural springs to extra stress in the medium, created by passing seismic waves from large earthquakes. Water discharge and the chemical composition critically change after every earthquake with $M > 5$ within a distance of 150 km. The size of the anomalies in chemical composition and water discharge depends on the distance from and the magnitude of the earthquakes. Preseismic and coseismic variations of the subsurface flow parameters connected with the variations of the stress in surrounding medium.

G51A-0950 0830h INVITED POSTER

Tomography of Coupled Poroelastic and Magma-intrusion Deformation Sources, Revealed by InSAR: Application to Segum Volcano

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Segum Island is located near the center of the Aleutian arc and consists of two calderas. Most of the historical eruptions emanated from the Pyre Peak caldera, which dominates the western half the island. The most recent eruptions occurred intermittently during December 1992 through August 1993. We generate 40 interferometric synthetic aperture radar (InSAR) images that span the interval 1993-2000 to characterize both the co- and post-eruptive deformation. The complexity of the images indicates deformation is caused by some combination of multiple transient sources and suggests coupling between shallow poroelastic sources and magma-intrusion at greater depths. We develop a method that allows for transient amorphous dilatation source distributions to simulate poroelastic deformation induced by magma-intrusion. The evolution of clusters within a three-dimensional array of dilating sources is estimated from multiple InSAR images using standard damped-least-squares inverse techniques. We impose additional constraints by minimizing the strain energy of the dilating source array using finite-difference methods. The quantity of data associated with the InSAR images is reduced with a quadtree algorithm to facilitate computation. Model predictions indicate the deformation of Pyre Peak is caused by a relatively shallow (poroelastic) contracting source that persists during the co- and post-eruptive phases. A substantial co-eruptive shallow (poroelastic) contracting source beneath the eastern caldera decays while a simultaneous dilating source (magma-intrusion) occurs much deeper during the post-eruptive phase.

G51A-0951 0830h POSTER

Preliminary InSAR Analysis of Lokbatan mud Volcano Near Baku, Azerbaijan

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Five ERS-1 and ERS-2 scenes from 1996 through 1999 centered near Baku Azerbaijan are analyzed using interferometric synthetic aperture radar (InSAR) in combination with optical satellite images (Advanced Spaceborne Thermal Emission and Reflection-ASTER) and ground truth data. We look for evidence of precursory surface deformation related to mud volcanism. The mud volcanoes of Azerbaijan are structures up to several hundred meters high with eruptions driven by high fluid and gas pressures at depths of a few kilometers (and are not related to magmatic activity). The primary target is the mud volcano Lokbatan, which erupted spectacularly with flaring natural gas and production of several thousand cubic meters of mud in October 2001. Initial InSAR processing used a digital elevation model (DEM) based on the combination of a global DEM with a high resolution DEM based on ASTER stereo optical data. This DEM was then refined with radar pairs possessing short temporal baselines. Correlation over the area was fair with the Lokbatan volcano showing moderate to low correlation over a time period of 2 years. Preliminary results show no clear indications of deformation with the available data (two years before the eruption). More data is currently being processed. A visit to the site suggest that considerable hydrocarbon production in the area along with rising ground water levels may also potentially create surface signals.

G51A-0952 0830h INVITED POSTER

Coupled Heat and Fluid Flow Modeling of the Earths Largest Zinc Ore Deposit at Red Dog, Alaska: Implications for Structurally-Focused, Free Convection in Submarine Sedimentary Basins

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Crustal heat flow can provide a strong mechanism for driving groundwater flow, particularly in submarine basins where other mechanisms for driving pore fluid flow such as topography, compaction and crustal deformation are too weak or too slow to have a significant effect on disturbing conductive heat flow. Fault zones appear to play a crucial role in focusing fluid migration in basins, as inferred in ancient rocks by many examples of hydrothermal deposits of sediment-hosted ores worldwide. Many rift-hosted deposits of lead, zinc, and barite ore appear to have formed at or near the seafloor by focused venting of hot basinal fluids and modified seawater, although the geophysical nature of these systems is not so well known. For example, the upper Kuna Formation, a finely laminated, black, organic-rich siliceous mudstone and shale in the Western Brooks Range of northwest Alaska, is host to the largest resources of zinc yet discovered in the Earths crust, containing ore reserves in excess of 175 Mt averaging about 16% Zn and 5% Pb. Although situated today in a highly-deformed series of structural allocthonous plates thrustured during the Jurassic to Cretaceous Brookian Orogeny, the stratiform ores are thought to have formed much earlier in the anoxic, mud-rich Carboniferous-age Kuna Basin when adjacent carbonate platforms were drowned by rifting and tectonic subsidence. Fluid inclusion studies of ore-stage sphalerite and gangue minerals indicate sub-seafloor mineralization temperatures less than 200°C and most likely between 120 to 150 °C, during a period of sediment diagenesis and extensional faulting.

We have constructed fully-coupled numerical models of heat and fluid flow to test hydrologic theories for free convection, submarine venting and subsequent ore formation, as constrained by paleoheat flow and petrologic observations. A finite element grid was designed and adapted for a cross section of the Kuna Basin, geologically restored to latest Mississippian time. Hydrologically, the Kuna Basin was a 200-km wide, rifted asymmetric basin layered with calcareous turbidites, mudstones and carbonates overlying a thick conglomerate and sandstone aquifer, which likely was thickest and more faulted near Red Dog (Ikalukrok graben). Buoyancy-driven free convection cells drive fluid migration to km-depths in the submarine basin, at rates of about 5 m/yr within permeable normal faults, which are assumed to be conduits. Mostly lateral flow is predicted to occur in the deep clastic formations. The clastic aquifers appear to be the principal reservoir for metal-bearing brines that ultimately discharged near the seafloor within slightly permeable, highly porous and organic rich muds, where sulfate can be reduced to form massive zinc-lead sulfide ores. Basin-wide paleoheat flows of 150 to 160 mW/m² and focused fluid discharge along normal faults are required to explain the hot thermal venting recorded within these ore fields. This mineralized hydrothermal system provides a remarkable geophysical model for the role of faults, free convection and extensional basin heat flow in ore genesis.

G51A-0953 0830h POSTER

Heat Flow, Climate Change and Advective Heat Transfer Beneath Winnipeg, Canada

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Winnipeg, Canada is situated in an area of relatively low heat flow, occurring near the eastern edge of the Williston Basin. Temperatures in the carbonate sequence beneath the city are typically between 5.0 and 6.0°C, with geothermal gradients of approximately 0.008 to 0.015°C/m. However, temperatures as high

as 11.0°C have been found in the upper reaches of the bedrock beneath certain areas of Winnipeg. Associated with these elevated temperatures are negative geothermal gradients low as -0.060°C/m, indicating downward heat flow. This downward flow of heat has been found to penetrate as deep as 130 metres below ground surface.

Elevated temperatures in the bedrock beneath Winnipeg cannot be attributed to climate change alone due to the magnitude of the anomaly. Basement heating and injection of warm water into the aquifers underlying Winnipeg are likely responsible for the temperature anomaly along with mesoclimate change. Basement construction occurring over approximately the last 100 years has altered the heat loading at the surface and in many cases several metres below the surface. Temperatures beneath basements are held constant at approximately 15 to 20°C, rather than fluctuating about the mean annual temperature of 2.14°C. This has played a large role in altering the subsurface temperatures of the region. Temperature profiles beneath central Winnipeg show the greatest impacts of this loading of heat from the surface, with smooth temperature profile and geothermal gradients that increase linearly from the surface. Groundwater use practices have also played a large role in altering the heat flow beneath Winnipeg, Canada. Most groundwater use within the City of Winnipeg is for air conditioning and industrial cooling and much of this use is non-consumptive, with warm water being pumped back into the shallow carbonate rock aquifer, known locally as the Upper Carbonate Aquifer, to maintain aquifer pressures. These injection wells exist throughout the city but appear to have the greatest impacts in an industrial area in eastern Winnipeg and in an area with several large apartment buildings in western Winnipeg where the largest volumes of warm water are injected. Temperature profiles in areas where anomalous advective heat flow is prevalent are characterized by elevated temperatures occurring over discrete intervals, indicating transport through fractures and paleokarst features in the Upper Carbonate Aquifer.

The presence of elevated temperatures beneath Winnipeg indicate that the current practices of using groundwater for cooling may not be sustainable due to the current injections of warm water and basement construction. However, the increases in heat flow beneath Winnipeg make the use of geothermal energy by heat pumps an attractive alternative for space heating.

G51A-0954 0830h POSTER

Using Borehole Temperature Profiles to Constrain Regional Groundwater Flow

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Starting with regional geographic, geologic, hydrologic, geophysical, and meteorological data for the Tono area in Gifu, Japan, we develop a numerical model to simulate subsurface flow and transport in a 4 km by 6 km by 3 km thick fractured granite rock mass overlain by sedimentary layers. Individual fractures are not modeled explicitly. Rather, continuum permeability and porosity distributions are assigned stochastically, based on well-test data and fracture density measurements. The primary goal of the study is to simulate steady-state groundwater flow through the model, then calculate travel times to the model boundaries from specified monitoring points, to represent leakage from a hypothetical nuclear waste repository.

The lateral boundaries of the model follow topographic features such as ridgelines and rivers. Assigning lateral boundary conditions is a major point of uncertainty in model construction. One approach is to assume that the boundary conditions associated with surface features (closed boundaries along ridgelines, open boundaries along rivers) are appropriate for the entire thickness of the model. An alternative approach ignores the local surface features and assigns lateral boundary conditions based on larger-scale geographical features (flow from mountainous regions toward the coast). The first approach results in a mostly closed model while the second approach results in a mostly open model. The two models produce vastly different spatial distributions of groundwater flow, so we would like to find a means of choosing the more realistic model.

Surface recharge is much larger for the closed model, but field recharge data are of too limited spatial extent to provide a definitive model constraint. Simulation of a long-term pumping test indicates that the pressure-transient response does not discriminate between the two models either, because the volume of water that can practically be pumped is small compared to natural groundwater flow. Temperature profiles in 16 boreholes show consistent trends with conduction-dominated (linear) temperature profiles below depths of 300 m. The open and closed models predict strongly different temperature versus depth profiles, with the closed model showing a strong convective signature produced by the large surface recharge. The open model shows more

linear temperature profiles, better agreeing with measurements from the field. Based on this data we can eliminate from consideration the closed model, at least in its present form in which surface recharge penetrates deep into the model.

G52A MCC: Hall C Friday 1330h

Advances in Geodetic Techniques Posters (joint with S)

Presiding: Y Bock, University of California, San Diego; **F Vernon**, University of California, San Diego

G52A-0955 1330h POSTER

Sea Level Variation in Seismic Normal Mode Band Observed With On-Ice GPS and On-Land SG at Syowa Station, Antarctica

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We analyze sea level variation data from a differential GPS and gravity data from a superconducting gravimeter (SG) at Syowa Station, East Antarctica (69.0°S, 39.6°E), in an eight month period of 1998. At frequencies between 0.2 and 2.5 mHz in seismic normal mode band we observe similar spectral peaks in both of the data. Power spectral densities of these peaks are about $5 \times 10^{-2} \text{m}^2/\text{Hz}$ in the GPS data and about $5 \times 10^{-17} (\text{ms}^{-2})^2/\text{Hz}$ in the SG data. We also observe high coherence and zero phase between the two data at frequencies of these peaks. Results of response analysis and simple mode calculation suggest that the observed peaks in the SG data are due to the effects of ocean water attraction and loading associated with the sea level variation, a possible cause of which is seiche in Lützow-Holm Bay around the station. Applying a transfer function method to both of the data, we can reduce the background noise due to the oceanic effects in the SG data.

G52A-0956 1330h INVITED POSTER

GPS Fault Slip Sensors in Earthquake Alert Systems

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The potential for issuing a warning of imminent strong shaking was initially proposed by J. D. Cooper in 1868. The idea has been further developed more recently (e.g., Heaton, T. H., *Science*, 1985), and early warning systems have now been developed and implemented (e.g., the UrEDAS system in Japan). Limitations in the robustness and trustworthiness of the systems, as well as costs, may explain why they are not more widespread. To our knowledge, before now, only seismic sensors have been considered in designing solutions to this problem. We describe, and expect to show test results from, the first deployment of a GPS-based augmentation to earthquake alert systems. GPS can be used to detect surface slip on a fault in real-time. Thus, adding GPS can improve response time and robustness of the system, and could decrease the chance that a small event (without surface rupture) is somehow interpreted by the seismic sensors as being a large event. Our system detects slip on a fault, in real-time, if slip exceeds a few centimeters. Where two So. Calif.

Integrated GPS Network (SCIGN) stations straddle the San Andreas fault near Gorman, the fault is not known to creep, so a detected displacement would be a clear indication that a large event is in progress. This could occur within seconds after a large event has begun, conceivably well before the seismic array data alone can yet be relied upon to assess whether the event is large or small. With this and several other specific cases where we are deploying this instrumentation, we feel that GPS data acquired and processed in real-time can significantly add to earthquake alert systems. The potential for providing earthquake information rapidly after future earthquakes, from a variety of real-time GPS systems, is considerable. The GPS slip sensor concept relies upon high sampling-rate data, acquired and processed in real-time. Preferably, the data would be from a braced array that is located close to, and spanning, the main strands of an active fault. Such arrays are not likely to be included in projects that are intended to study longer wavelength deformation of the crust, so may require special deployments along hazardous active faults. Furthermore, such arrays could someday provide unique observations of near-field dynamic and static motions that would be useful for understanding earthquake source physics.

URL: <http://pasadena.wr.usgs.gov/office/hudnut/slipsensor/>

G52A-0957 1330h INVITED POSTER

Combining Real-time Seismic and Geodetic Data to Improve Rapid Earthquake Information

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The Berkeley Seismological Laboratory operates seismic and geodetic stations in the San Francisco Bay area and northern California for earthquake and deformation monitoring. The seismic systems, part of the Berkeley Digital Seismic Network (BDSN), include strong motion and broadband sensors, and 24-bit dataloggers. The data from 20 GPS stations, part of the Bay Area Regional Deformation (BARD) network of more than 70 stations in northern California, are acquired in real-time.

We have developed methods to acquire GPS data at 12 stations that are collocated with the seismic systems using the seismic dataloggers, which have large on-site data buffer and storage capabilities, merge it with the seismic data stream in MiniSeed format, and continuously stream both data types using reliable frame relay and/or radio modem telemetry. Currently, the seismic data are incorporated into the Rapid Earthquake Data Integration (REDI) project to provide notification of earthquake magnitude, location, moment tensor, and strong motion information for hazard mitigation and emergency response activities.

The geodetic measurements can provide complementary constraints on earthquake faulting, including the location and extent of the rupture plane, unambiguous resolution of the nodal plane, and distribution of slip on the fault plane, which can be used, for example, to refine strong motion shake maps. We are developing methods to rapidly process the geodetic data to monitor transient deformation, such as coseismic station displacements, and for combining this information with the seismic observations to improve finite-fault characterization of large earthquakes. The GPS data are currently processed at hourly intervals with 2-cm precision in horizontal position, and we are beginning a pilot project in the Bay Area in collaboration with the California Spatial Reference Center to do epoch-by-epoch processing with greater precision.

G52A-0958 1330h POSTER

Simultaneous Synthesis of Static and Dynamic Ground Motions Near a Finite Fault in a Layered Medium

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Recent development of geophysical observation instruments such as GPS have allowed us to obtain precise broadband data in wide dynamic and wide frequency ranges, including static displacements in a large

area. Since theoretical studies analyze dynamic motions and static displacements individually, this study attempts to synthesize not only dynamic motions but also static displacements simultaneously and estimate effects of a surface layer on displacements in a frequency range of 0 - 1.5 Hz.

When we represent seismic waves by the discrete wavenumber method, we face a difficulty in the choice of two factors to obtain accurate seismograms including static displacement: (1) the truncation number of wavenumber integration and (2) the representation of a potential in zero horizontal wavenumber. To find a suitable value of the truncation number of wavenumbers, we utilize a spatial domain solution using the analytic formulation for a homogeneous half space of Okada(1985) and estimate a wavenumber region in which the majority of energy is concentrated. For a finite rectangular fault buried in a half space, we find that a suitable value of the truncation number of wavenumber is 4 km^{-1} by comparing the analytical solution of Okada for static deformation. Secondly we find a new kind of singularities for a finite rectangular fault when both horizontal wavenumbers, k_x and k_y , go to zero, or in a case corresponding to VTSE (vertically traveling plane S-wave element). In order to deal with VTSE from a finite fault, a new S wave potential is introduced to obtain a displacement whose polarization is restricted on a horizontal plane. In order to remedy these singularities, we take an asymptotic solution for $k_x = k_y = 0$. These devices make it possible to simulate accurate seismograms, including dynamic and static components, for any fault configurations and station locations by our method. Moreover, we can apply our procedure to layered media to estimate the effect of a soft surface layer on static displacement. In the case of vertical strike slip fault, if a soft surface layer exists above a fault, static displacement at the surface is amplified by twice of in the half space case.

G52A-0959 1330h POSTER

Evaluation of Accuracy in Kinematic GPS Analyses Using a Precision Roving Antenna Platform

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Most tectonic plate boundaries and seismogenic zones of interplate earthquakes exist beneath the ocean and our knowledge on interplate coupling and on generation processes of those earthquakes remain limited. Seafloor geodesy will consequently play a very important role in improving our understanding of the physical process near plate boundaries. Seafloor positioning using a GPS/Acoustic technique is the one potential method to detect the displacement occurring at the ocean bottom. The accuracy of the technique depends on two parts: acoustic ranging in seawater, and kinematic GPS (KGPS) analysis. Accuracy of KGPS have evaluated with following way:

1) Static test: First, we carried out an experiment to confirm the capability of the KGPS analysis using GIPSY/OASIS-II for a long baseline of about 310 km. We used two GPS stations on land, one as a reference station in Sendai, and the other in Tokyo as a rover one, whose coordinate can vary from epoch to epoch. This baseline length is required for our project because the farthest seafloor transponder array is 280 km east of the nearest coastal GPS station. The 1 cm stability of the KGPS solution was achieved in the horizontal components of the 310-km baseline over the course of one day. The vertical component showed fluctuation probably due to parameters unmodeled in the analysis such as multipath and/or tropospheric delay.

2) Sea surface experiment: During cruise KT01-11 of the R/V Tansei-maru, Ocean Research Institute (ORI), University of Tokyo, around the Japan Trench in late July 2001, we deployed three precision acoustic transponders on both the Pacific plate (280 km from the coast, depth around 5450 m) and the landward slope (110 km from the coast, depth around 1600 m). We used a surface buoy with 3 GPS antennas, a motion sensor, a hydrophone, and a computer for data acquisition and control to make combined GPS/Acoustic observations. The buoy was towed about 80 m away from the R/V to reduce the impact of ship noise on the acoustic measurements. The position of each antenna on the buoy was estimated independently with respect to the reference station in Sendai. Time variations of inter-antenna baseline lengths demonstrate that the short-term repeatability of kinematic GPS analysis on a drifting buoy were stable to less than 10 mm of RMS. We also compared the coordinates of a GPS antenna on