The recipients of this survey included oil and gas companies (32), utilities (27) and miscellaneous corporations such as chemical companies (53).

The owners and operators of injection wells have a legal and professional obligation to understand the risks inherent in operating such wells and to take reasonable action to minimize those risks. However, despite the extensive literature existing on injection-induced seismicity, we found an alarming number of errors and misinformation in the 42 responses we received. Only eight companies correctly reported that injection can occasionally induce earthquakes, while twelve contended quite clearly that injection cannot cause earthquakes. Seven companies claimed to have never heard of injection-induced earthquakes, while fifteen did not address the issue at all. Many companies blindly assumed that all potential risks could be avoided merely by following various state and federal regulations. In addition, numerous companies reported glaring fallacies including: • In California, water is injected into faults in order to lubricate them and reduce the seismic risk. • The idea that injection wells can cause earthquakes is a ploy by environmental groups to discredit deep well injection. • The only known instance of earthquakes induced by injection was near Denver, Colorado.

The survey demonstrates the inability of many companies to address environmental concerns raised by the public, and suggests a need for increased awareness of these issues. By educating professionals about the risks of induced earthquakes, the scientific community can help companies avoid potential liability by encouraging them to perform better site investigations, understand the benefits of seismic monitoring, and recognize when a potentially hazardous situation may develop.

S42D-7 1530h

Controlled Volumetric Source Studies of Induced Seismicity : A Comparison of Moment Tensor Techniques

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The determination of earthquake source parameters using inversion of waveform data has become a standard technique in seismology. In such studies the assumption that the event occurs by a process of pure double-couple failure (ie. a moment tensor with zero trace and zero determinant) and at a point source is often made in order to facilitate the processing. Some studies of the earthquakes induced by mining activity suggest that such assumptions are not valid, with significant non-double-couple and isotropic (volume change) components of failure.

Waveform data from events recorded around a tunnel excavation at the Atomic Energy of Canada Ltd's Underground Research Laboratory have been recorded on an array of 16 triaxial accelerometers designed to give optimal focal sphere coverage. These data have been processed using both an automatic processing technique, which assumes a shear failure mechanism, and with a method that makes no a priori assumptions about the mechanism. The results are compared and conclusions drawn about the benefits and pitfalls of the two methods.

The concept of extending the technique to include time dependence, where no a priori assumptions about a synchronous source are made, will also be discussed.

S42D-8 1545h

Relationship Between Velocity and Source Parameters of Natural and Induced Seismicity

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Several recent studies have shown an association between p-wave velocity structure and concentrations of events for both natural and induced seismicity. In order to further investigate this association, a detailed comparison between velocity and source parameters of both natural and excavation-induced seismic events was performed. Data from Parkfield and three sites of induced seismicity were analyzed, including a controlled experiment around a simple cylindrical tunnel where calculated stress change could be computed. The comparisons from all the sites showed that for the background seismicity, the largest events (as measured by magnitude, moment, or stress drop) corresponded to regions of intermediate velocity. Smaller events and higher b-values were observed at progressively higher and lower velocities. Lower velocities appear to correspond to weaker segments of the fault zones, incapable of storing substantial strain energy resulting in aseismic creep. Higher velocities appear to be asperities where the largest tremors occur including the 1966 earthquake at Parkfield. For the case of the controlled tunnel experiment, velocity variations were found to be induced by variations in normal stress. The fracture mechanics interpretation will be given, in addition to possible implications to Parkfield.

S42D-9 1600h

Small-Scale Mining-Induced Seismicity is Fractal

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Mining-induced, stope-scale microseismicity data collected by the U.S. Bureau of Mines in a hard rock mine were determined to have both a spatial and temporal fractal nature. The fractality extends over scales of 1 to 100 meters, and from minutes to days. On these scales, aftershock sequences typically last for less than a day. Small events are not confined to a single plane and cluster throughout the local rock mass. Over many months of mining, no long-term trend in the temporal or spatial fractality was apparent. No statistical difference was found in the fractal dimensions for aftershock sequences directly following production or de-stress blasts compared with other sequences following rock bursts. Furthermore, no statistical difference was found in the fractal dimensions when comparing two different stopes. These results suggest that the physical processes responsible for rock mass relaxation following a sudden stress change are the same, regardless of progenitor or location. Differences were found in other attributes that measure spatial extent, event rate, cumulative event numbers and energy. Therefore, the magnitude of the response, not the interactions of forces and local structure, distinguishes the aftershock sequences.

S51A MC: Hall D Fri 0830h
Lithospheric Structure Around the Mendocino Triple Junction Posters

Presiding: A Trehu, Oregon State Univ; S Schwartz, UCSC

S51A-1 0830h INVITED POSTER

The 94 Mendocino Triple Junction Seismic Experiment : Preliminary Results from the Transform System

[MENDOCINO 94 WORKING GROUP *] (ph. ; e-mail:); (ph. e-mail:)

In June 1994, a second phase of data acquisition added 6 marine multichannel seismic (MCS) profiles and wide-aperture recordings offshore and along coastal California to data collected onshore last year. Our objective is to image the crust and upper mantle in the newly formed transform margin south of the Mendocino Triple Junction.

Fourteen seconds of MCS data were collected using an 8300 cubic inch airgun array and a 4.2 km streamer. CMP gathers are nominally 10 fold with midpoints spaced every 12.5 m. The airgun shots were recorded by 10 ocean bottom seismometers deployed along two of the MCS profiles, and 180 REFTEK receivers located onshore. The REFTEK receivers were distributed as 2-D linear arrays along two transects and as a 3-1 areal array. The data set collected this June extends into the offshore region, a wide-aperture explosive profile located at 39°30'N. The combined data set results in a 300 km profile extending from the base of slope offshore, eastward to the Sierra Nevadas crossing the boundary between the Pacific and North American plates and the proposed 'slab less' window beneath North America. The MCS data provide structural images while the large aperture data sets provide velocity control on deep crustal reflectors and in addition, because of the dense shot spacing allow for wide-aperture imaging, and tomographic inversion.

The MCS profiles image oceanic basement extending beneath the slope. Features along the profiles are somewhat unusual in comparison to similar profiles north of the triple junction where a prominent deformation front is marks active subduction of the Gorda plate beneath North America. Faults offsetting basement extend into and deform sediments in the Pt. Arena basin. Two of the profiles cross the mapped trace of the offshore extension of the San Andreas Fault. A 50 ms seafloor scarp is visible where the southernmost profile crosses the SAF.

(The Mendocino 94 working group includes representatives from Lehigh Un., Stanford Un., Rice Un., Oregon State Un., the USGS, WHOI, LDEO, IRIS, Humboldt St. Un., and IARC. Please address correspondence concerning this abstract to Anne Meltzer, Lehigh University, Bethlehem, PA, 18015, asm3@lehigh.edu.)

S51A-2 0830h POSTER

The Mendocino Triple Junction Seismic Experiment: The Transition from Transform to Subduction

Mendocino 94 Working Group *

The area in which the transition from a transform to a subduction continental margin occurs is the most complex to be studied in the Mendocino Triple Junction Seismic Experiment. This area has high recent seismicity, including a magnitude 6.9 earthquake at Petrolia in 1992. During June 1994 we carried out an experiment designed to give a detailed picture of this transition as well as to contrast the regions immediately to the north and the south. Two 100km long multi-channel seismic (MCS) profiles intersect immediately offshore Petrolia, one extending NW onto Gorda plate oceanic crust, the other SW onto the Pacific plate. The 4400 marine airgun shots were recorded onshore along two linear arrays of IRIS/PASSCAL seismographs totaling almost 500 channels. These instruments were deployed at distances of up to 150km from Cape Mendocino.

Initial examination suggests data quality is very good. The MCS data show complex shallow crustal structure to close onshore, and the land arrays recorded arrivals to ranges of over 200km. Techniques such as wave equation datuming and prestack depth migration will be required to improve our imaging of the region.

S42C-6 1515h

Induced Microseismicity Associated With Deep-Well Disposal of Brine at Paradox Valley, Colorado

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As part of an effort to reduce salinity in the Colorado River system, the US Bureau of Reclamation is conducting a program of shallow extraction and subsequent deep injection of brine in the Paradox Valley of southwestern Colorado. Between July 1991 and November 1993 six test periods of injection were conducted at various wellhead pressures and injection rates. Target wellhead pressures varied from 260 bars to 312 bars and injection rates varied from 9.5 to 28.4 liters/sec. Seismicity accompanied five of the six injection periods. More than 100 events were recorded in the immediate vicinity of the well; duration magnitudes varied from 0.0 to 2.0. No events had been detected within 3 km of the well in six years of monitoring prior to the beginning of injection.

The target horizon for injection in this well is the Mississippian Leadville Formation (limestone) at depths of 4.3 to 4.5 km. Analyses of subsurface oil exploration well and seismic reflection data indicate WNW-trending normal faults in the Leadville (subparallel to the surface strike of the valley). Preliminary evaluation of focal mechanisms from injection events are consistent with failure on WNW or NNE-trending fault planes. Both the trend and locations (deduced from one-dimensional velocity/hypocenter inversion) of the events are consistent with occurrence on the faults previously inferred to exist in the Leadville Formation.

Well logs of mechanical properties, pore-pressures and injection pressures were used to infer stresses at the bottom of the well. The results suggest that for hydrostatic conditions existing fault planes are stable. However, during the injection sequences, pressures at the well bottom were sufficient to promote failure on pre-existing faults as well as cause faulting in intact rock with a shear strength of ~140 bars (Fig. 1).

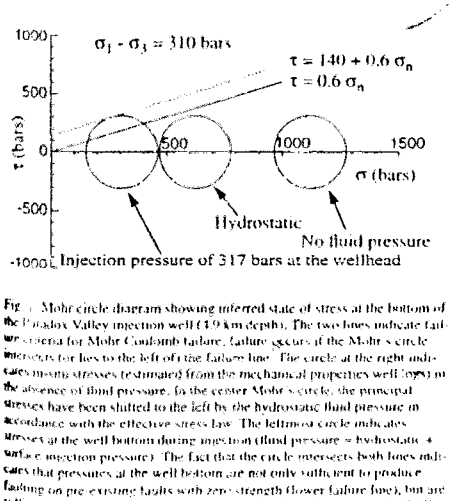

Fig. 1. Mohr circle diagram showing *inferred* state of stress at the bottom of the Paradox Valley injection well (4.9 km depth). The two lines indicate failure criteria for Mohr Coulomb failure; failure occurs if the Mohr's circle intersects (or lies to the left of the failure line). The circle at the right indicates in-situ stresses (estimated from the mechanical properties well logs) in the absence of fluid pressure. In the center Mohr's circle, the principal stresses have been shifted to the left by the hydrostatic fluid pressure in accordance with the effective stress law. The leftmost circle indicates stresses at the well bottom during injection (fluid pressure = hydrostatic + surface injection pressure). The fact that the circle intersects both lines indicates that pressures at the well bottom are not only sufficient to produce faulting on pre-existing faults with zero strength (lower failure line), but are sufficient to cause faulting even in intact rock with a shear strength of 140 bars (upper failure line).