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In our studies of simulated non-clay fault gouge, crushed Westerly granite with a median initial grain size of 100 μm was repeatedly cycled to its failure stress at constant effective confining pressure of 200 MPa and pore pressure of 50 MPa. The critical parameter controlling deformational behavior of this material was initial porosity, which was controlled between approximately 10 and 25 percent. Both peak stress and post-failure softening markedly increases with decreasing initial porosity.

Permeability, measured during the deformation experiment, decreased dramatically. From starting values at zero shear stress of about $10^{-15}m^2$, permeability decreased monotonically with shear strain, even though the sample dilated. As a result, values less than $10^{-18}m^2$ (1 microdarcy) were achieved for strains of around 45 percent, even though porosity was still about 15 percent. These low values have interesting implications for active fault zones in granitic rock. Physically, they imply a continuous decrease in pore size, and therefore grain size during shear.

T 146

PERMEABILITY OF FAULT GOUGES UNDER CONFINING PRESSURE AND SHEAR STRESS

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The permeabilities of 4 clay-rich San Andreas fault gouges (taken from surface and borehole depths to 408 m), a serpentinite fault gouge from San Francisco, and 2 pure clays were measured at confining pressures from 5 to 200 MPa and during shearing with shear displacement up to 9 mm at 200 MPa confining pressure. Samples consisted of 1 mm thick gouge layers placed between 30° sawcut surfaces of sandstone cylinders 25.4 mm in diameter and 63.5 mm in length. Permeability was strongly dependent on grain size distribution. Homogeneous, fine-grain San Andreas gouge (98.6% grain diameters < 0.075 mm) taken from borehole depth of 408 m, had a permeability < 1.0 nD at 200 MPa confining pressure, whereas the serpentinite gouge with mixed grain sizes (grain diameters ranged from 0.09 mm to 1 mm) was 2 orders of magnitude more permeable. Permeabilities for San Andreas gouges ranged from 2.1 to 22 nD at 50 MPa confining pressure and from 0.3 to 2.3 nD at 200 MPa. Only a fraction of the permeability (typically 50%) was recoverable upon unloading confining pressure. In addition, samples were deformed in steps and at each step permeability was measured in 2 ways: at constant differential stress and after unloading differential stress. The permeabilities obtained by these two methods were in close agreement with each other. In all cases, application of differential stress reduced permeability (23 to 87%). This reduction in permeability was primarily due to increased normal stress and was nearly independent of the amount of shearing. That is, most of the decrease in permeability occurred when differential stress was first applied and normal stress was increasing rapidly.

T 147

PORE VOLUME CHANGES ASSOCIATED WITH FRICTIONAL SLIDING OF FRACTURES AND SIMULATED JOINTS WITH AND WITHOUT GOUGE*

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Dilatancy is well established as accompanying the fracturing of intact rock in the laboratory, but few detailed experiments have been done at high pressure to determine if dilatancy occurs prior to and/or during frictional sliding of joints. Accordingly, the general problem of dilatancy associated with joint movement has been investigated in drained, triaxial compression, pore-pressure experiments of jointed specimens of Coconino sandstone. The jointed specimens consisted of right circular cylinders with either a single induced fracture at 28° to 31° to the cylinder axis, a sawcut at 35° to cylinder axis, or 35° sawcuts separated by simulated gouge of quartz sand. Tests were conducted at effective confining pressures to 90 MPa, an axial displacement rate of 5 x 10^{-5} cm/s and joint displacements up to 8 mm. Volume changes were measured by monitoring the adjustment in pore fluid (distilled water) volume required to maintain a constant pore pressure during the course of the test. For the fractured specimens and 35° precuts there was an initial compaction of the specimen upon application of the axial load. As the peak stress for the onset of slip was reached and sliding began, compaction decreased to zero and dilatancy occurred. The amount of dilatancy increased with increasing normal stress and increasing joint displacement. The dilatancy is correlated to observed microfracturing along the joint sliding surfaces. In sharp contrast the 35° precuts separated by quartz gouge showed only compaction prior to and during sliding at all stress and displacement conditions. Observational studies indicate that cataclasis and compaction of the gouge is the dominant deformational process.

* This work was supported by the U.S. Dept. of Energy (DOE) under Contract DE-AC04-76-DP00789.
**A U.S. DOE Facility.

T 148

STRENGTH OF SATURATED CLAYEY GOUGE, ITS DEPENDENCE ON STRAIN RATE AND PERMEABILITY

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The behavior of active faults is thought to be controlled in part by the mechanical properties of fault gouge. Experiments on clayey gouge in rock joints to approximate natural faults have been carried out under 2kb confining pressure to determine the relationship between shear strength, strain rates and drainage conditions. Permeability of clayey gouge is determined at pressures up to 250 bar. Experimental results show that: (1) at a given loading rate, a thinner clayey gouge sample is stronger than a thicker one; (2) in experiments in which drainage conditions vary, better drained samples support greater deviatoric stresses; and (3) permeability decreases with pressure, reaching 0.1 ninodarcy at about 250 bar.

In order to explain the differences in shear strength, numerical analysis based on a one-dimensional consolidation model is used to estimate the pore pressure in the clayey gouge as a function of loading rate and drainage condition. The observed differences in shear strength are interpreted in terms of the excess pore pressures generated in the clayey gouge under different loading rates and drainage conditions.

T 149

LARGE ANGULAR ROTATIONS OF BLOCKS ALONG STRIKE-SLIP ZONES AS SHALLOW DECOLLEMENT FEATURES

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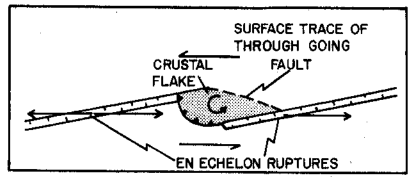
Large angular rotations of crustal blocks (90° or more) are often associated with major strike-slip zones and discrete strike-slip faults (e.g. western U.S. and Canadian Cordillera). Such rotations have been used in the past to reconstruct former positions of lithospheric blocks assumed to have been associated with the outcrops on which the rotations have been measured without evidence that the rotated block was indeed a lithospheric plate. We argue here, based on field, geophysical and experimental data that at least the largest portion of all such rotations are confined to shallow crustal flakes generated as a part of systematic shear zone evolution and in no way indicates a rotation of the lithospheric plate from which the flake was sliced off.

The initial stages of shear zone evolution may be characterized by the generation of en echelon ruptures which trend obliquely (10°-45°) to the general shear direction. Continued displacement along the shear zone results in oblique extension of the en echelon rupture segments and oblique compression of the material between them. Such compression results in folding and thrusting of shallow level crustal flakes which are synkinematically rotated in a sense compatible with the general sense of strike slip displacement.



T 150

PHOTOELASTIC AND ROCK MODEL STUDIES OF THE RAMP REGION OF THRUST FAULTS*

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The upper-plate deformation in the ramp regions of large-scale thrust faults is simulated in experiments using photoelastic models subjected to plane stress deformation and rock models (not scaled mechanically) deformed under confining pressure to 50 MPa. Both types of models basically consist of three unwelded layers with the middle layer containing a lubricated precut ramp inclined at angles of 20 to 35° to the layer interface. The photoelastic models provide a stress analysis of the ramp region up to the initiation of fault movement. The deformed rock models provide insight into the kinematics and deformation mechanisms associated with thrust sheet migration through the ramp region. Accordingly, the rock models indicate that the primary mechanism by which the thrust sheet bends in the lower hinge to move up the ramp is by the formation of reverse faults (back-thrusts) that dip opposite to the ramp. The back thrusts initiate at the lower hinge of the ramp and propagate toward the overlying layer interface. The photoelastic models show a large compressive stress concentration with a radial stress distribution in the lower hinge where the back-thrust initiates. Correlations with the rock models suggest that a back-thrust forms initially as an extension fracture parallel to the trajectory of the maximum principal compressive stress lying along the locus of maximum stress difference. As the material begins to move through the lower hinge, shear displacement occurs along the incipient extension fracture, producing the back-thrust. With continued displacement, the first-formed back-thrust is translated up the ramp as material behind it migrates through the lower hinge principally by the formation of additional back-thrusts.

* This work was supported by the U.S. Dept. of Energy (DOE) under Contract DE-AC04-76-DP00789.
**A U.S. DOE Facility.

T 151

SIMULATION OF CREEP EVENTS AND EARTHQUAKES ON A SPATIALLY VARIABLE MODEL

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Numerical simulations of slip on 1-D and 2-D fault models have been made assuming a fault zone constitutive law similar to those determined experimentally by A. Ruina (pers. comm.) and J. Dieterich (1980) for both clean and gouge-filled contacts. These constitutive laws are characterized by two competing effects: an instantaneous dependence of fault strength on velocity (strength increases with velocity); and also an inverse dependence of strength that takes full effect only after a finite amount of slip d has occurred. The models predict recurring rapid slip events followed by periods of strain accumulation. Slow stable (creep) events are favored by low pressure, large elastic stiffness and large d, and vice-versa for unstable events. In this study the pressure effect is emphasized. 2-D simulations in a plate, with increasing pressure with depth, show a pronounced damping of slip perturbations at shallow depths ranging downward to steady oscillations and downward further to unstable growth of perturbations. Comparison of results with creep events on the San Andreas fault suggests that surface creep events must be confined to approximately the upper 1-2 km of the fault; deeper events would tend to be unstable. In addition to the depth dependence, model results predict that normal stress will fluctuate with complications in fault geometry. In certain areas, the observed the reliability of near-surface tests in defining regional stress had not been established, we decided to remeasure the stresses at the same locations but at greater depths. We core-drilled 200 m vertical NX holes in three of the aforementioned quarries and carried out hydrofrac measurements at 15 or more depths in each. Owing to weak horizontal bedding planes many of the tests yielded information only on the vertical principal stress (consistently at 0.026-0.028 MPa/m depth). Sufficient tests, however, resulted in both vertical and horizontal hydrofractures and showed dual sut-in pressures, to enable the calculation of all three principal stresses. Within 40-160 m depth horizontal stresses in all 3 quarries appear to belong to a uniform regional stress field with σ_{Hmin}(MPa)= 5 + 0.0015xDepth(m) and σ_{Hmax}(MPa) = 11 + 0.005xDepth(m); the direction of σ_{Hmax} is uniformly at N70°E ± 15°. These results are in agreement with the prevailing stress regime in the Midwest and a large portion of Eastern U.S. The rotation of σ_{Hmax} direction at one of the quarries from 135° at 10 m depth, to 110° at 21 m, to 84° at 47 m, to 75° at 70 m, and stabilizing at 65° ± 15° within 70-160 m, helps explain the discrepancy between the near-surface and the deeper stress determinations.

T 132

TECTONIC STRESS NEAR THE SAN ANDREAS FAULT FROM STRAIN RELIEF MEASUREMENTS

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During the summer of 1980, 57 strain relief measurements were made up to depths of 29 m, at two sites near Palmdale, Ca., one 2 km SW of the San Andreas fault, and the other 18 km to the NE. At depths greater than 6 m, an orientation of N15-25°W was observed for the maximum compressive stress(σ_1), and is interpreted to represent the local tectonic stress field. This is in agreement with tectonic stress orientations inferred by others from hydrofracture measurements to depths of about 1 km near one site (Zoback, 1980), strain accumulation from trilateration surveys at Palmdale (Lisowksi and Savage, 1979), and a stress anomaly associated with the 1979 Lytle Creek earthquake south of the study area (Clark, 1979). A N15-25°W tectonic stress orientation is also in agreement with fault plane solutions from Southern California (Sbar et al., 1979). The magnitudes of σ_1 below 6 m were found to be 0.4-1 MPa near the fault and 1-6 MPa at the site 18 km from the fault.

Within the top 6 m, considerable scatter was observed in both the magnitude and orientation of σ_1. Comparison of this data with previous overcore data suggests that shallow measurements (< 6 m) may be unreliable for predicting tectonic stress in this region, perhaps due to thermal stresses in the upper few m associated with large seasonal temperature variations.

T 133

READING STRESS FROM CATACLASTIC ROCKS

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Intrafault material having grain diameters d < 4 mm which was produced by the brittle fracture of granite in a triaxial pressure vessel is shown to have a log normal particle size distribution. The grain diameter <d> at the mean of this distribution is shown to decrease with increasing fracture stress σ_f as $\log \langle d \rangle = -A\sigma_f + B$. For dry samples $A = 2.8 \times 10^{-3}$ MPa^{-1} and $B = 7.9 \times 10^{-2}$. Samples which were saturated with water and held at $\sigma_1 > 0.5\sigma_f$ for several hours prior to fracture produced coarser particle distributions than the dry samples. These wet samples were characterized by $A = 3.6 \times 10^{-3}$ MPa^{-1} and $B = 4.8 \times 10^{-1}$. Wet samples which were held at $\sigma_1 \simeq 0.1\sigma_f$ produced even coarser particle distributions, suggesting that the grain size distribution depends on the stress history of the sample. The trends defined by the above equation are shown to be consistent with <d> observed for gouge and cataclasite from the San Andreas and San Gabriel fault zones, where σ_f was deduced from the lithostatic confining pressure at the inferred depth of burial at the time of rupture.

T 134

CHANGES IN PRESSURE ON BART TUNNEL LINING--AN EARTHQUAKE PRECURSOR

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The Bay Area Rapid Transit Berkeley Hills tunnels cross the Hayward Fault zone near the western portal. Since construction in 1967, slow slippage along an active trace of the Hayward Fault has cracked the reinforced concrete lining, and shifted the track right laterally. Total displacement is about 52 mm. During construction, pressure cells were installed between the lining and the surrounding ground, and readings have been taken at irregular intervals over a period of 13 years. Passive pressures have increased with time due to right lateral slippage. Superimposed on this trend, there are periods when significant pressure changes occur over a short period of time. When these data are compared with the seismic record for the Hayward Fault, there appears to be a pressure decrease that occurs prior to an increase in seismicity.

T 135

HAVE LARGE-SCALE MAGNETIC CHANGES OF CRUSTAL ORIGIN OCCURRED WITHIN THE SAN ANDREAS FAULT SYSTEM, 1974-1980?

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M. J. S. Johnston

Synchronized total magnetic field measurements of high precision have been made throughout California since 1973. An analysis of these data indicates that localized anomalies with amplitudes of more than one nT occur at both ends of the creeping zone of the San Andreas fault in central California, the junction of the San Jacinto and San Andreas faults, and the region near the Mission Creek-Morongo Valley faults. A search for general regional differences between the mean data obtained from southern California sites and that from central California sites indicates that, after correction of the data for normal secular variation during the period 1974-1980, no mean field difference greater than 2 nT has occurred during this time in spite of the different tectonic regimes of these two areas. The secular variation rates were determined by least squares line fitting and ranged from 45 nT/yr near San Francisco to 55 nT/yr near the Salton Sea. The best fitting plane to these data has the form
$0.043X - 2.22Y + 123.18 - Z = 0$ where X is the decimal longitude, Y is the decimal latitude, and Z is the secular variation per year. This corresponds to a maximum spatial gradient of 1.5 ± 0.5 nT/100 km/yr.

T 136

BREAKING THE 1/4 nT SEISMOMAGNETIC SENSITIVITY BARRIER

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Short baseline (<100m) magnetic gradient observations in Colorado using self-calibrating rubidium magnetometers (SCRs), accurate to 0.01 nT, showed 0.0023 nT rms (that's right, 2.3 pT) local stability for 1000 min. However, similar observations using several USGS proton magnetometers (PMs), with a 0.25 nT least count uncertainty, showed, at best, 018 nT rms. It therefore appears that the local gradient PM observations are dominated by instrument noise. For observations over longer baselines, which are commonly used in seismomagnetic research, the detection threshold for PMs may also be limited by instrumental noise, if noise reduction techniques are used to diminish non-seismic magnetic noise. For example, a stability of 0.03 nT rms for noise reduced 12 km gradients, observed by SCRs in Colorado, was previously reported. In view of the fact that no coseismic magnetic signals have been observed in California, even in several cases where large earthquakes occurred near operating PMs, and considering that coseismic signals should be the largest and most easily identified of all seismomagnetic events, the possibility for improving the sensitivity to seismomagnetic events in California (and other earthquake zones) should be investigated. It is important that the noise reduction techniques, which are applied to such high accuracy measurements in order to realize the best detection threshold, should include a method for reducing magnetic effects generated by ocean tidal currents. Fourier transforms of USGS PM gradients from central California were used to identify these tidal effects, which can be larger than the atmospheric magnetic noise, for site pairs near the ocean.

Constitutive and Kinematic Properties of Faults

Oregon/Nevada HI
Thursday AM
E. G. Bombolakis (Boston College), Presiding

T 137

DYNAMIC ANALYSIS OF THE HARTFORD DIKE LANDSLIDE

E.G. Bombolakis (Dept. of Geology and Geophysics, Boston College, Chestnut Hill, MA., 02167)

The Hartford Dike slide is well-documented. An understanding of this slide and other well-documented cases should help resolve some long-standing problems associated with overthrusts, descollements, earthquake-induced landslides, and several types of faulting. For this reason, a qualitative analysis of the Hartford Dike slide was presented previously, and a quantitative analysis now is presented here. This slide is a special case of a translational type that is not uncommon, and so the equations of sliding distance, travel time, and dynamic basal shear strength are derived in a form capable of being generalized.

An important feature of the Hartford Dike slide is that intense deformation did not extend any appreciable distance above or below the basal glide surface. This kind of observation has been a puzzle for many years with respect to a number of overthrusts and descollements. The explanation in the Hartford Dike case is that an instability mechanism caused a rapid reduction of the "internal angle of friction" along the glide zone. Data analysis indicates that the strength reduction was substantial: the "friction angle" was reduced to a value smaller than three or four degrees.

T 138

MECHANICS OF LOW-ANGLE NORMAL FAULTING IN THE MINERAL MOUNTAINS, UTAH

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M.R. Yusas (Utah 84112)

Roosevelt Hot Springs geothermal area is located in the Mineral Mountains of southern Utah. The geothermal reservoir was formed

EOS
TRANSACTIONS AMERICAN GEOPHYSICAL UNION
VOLUME 61 NUMBER 46 NOVEMBER 11, 1980

1980 AGU FALL MEETING

EOS

TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

EOS, Transactions, American Geophysical Union (ISSN 0096-3941) is published weekly by the American Geophysical Union from 2000 Florida Avenue, N.W., Washington, D. C. 20009. Subscription available on request. This issue $10.00. Second-class postage paid at Washington, D. C., and at additional mailing offices.

AGU FALL MEETING
Head for the Hills
San Francisco · Dec. 8-12

Section Luncheons

Geodesy	Tuesday, December 9 Casa de Cristal 1122 Post Street	12 noon
Hydrology	Wednesday, December 10 Casa de Cristal	11:50
Oceanography	Tuesday, December 9 Nikko Sukiyaki Van Ness and Pine	12:15
Seismology	Tuesday, December 9 '1906 Drinking Establishment' Holiday Inn Golden Gateway	11:30
Solar-Planetary Relationships	Wednesday, December 10 Nikko Sukiyaki	11:45

Space is limited—reserve early! All luncheons—$7.50.

See page 928.

Cover. The aurora, displayed in multiple bands and photographed near Fairbanks, Alaska, by Malcolm Lockwood. This is a reproduction of a color plate from *Majestic Lights—The Aurora in Science, History and the Arts,* by Robert H. Eather. This book is AGU's most recent release.