response leads to an accelerated creep which terminates in an instability when the slope reaches the unrelaxed unloading stiffness of the surroundings. The model describes time-dependent processes leading to large scale rupture and the associated fault slip.

S 193

ON THE STRESSING OF THE LITHOSPHERE IN AN EARTHQUAKE CYCLE

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Victor C.F. Li (Division of Engineering, Brown University, Providence, RI 02912)

The large-scale response of an elastic lithosphere riding on a viscoelastic asthenosphere to periodic slip at a transform or subduction-type plate boundary has been described by an appropriate limit cycle solution for the generalized Elsasser-type plate model introduced and analyzed previously by Rice (1980) and Lehner et al. (1980). The periodic behavior of displacements and stress, their decay away from the plate boundary, and a resolution into co-seismic and post-seismic stress alterations have been obtained and their dependence on plate velocity, recurrence time, and a characteristic relaxation time investigated. Post-seismic stress alterations of equal sign as co-seismic stress jumps appear gradually at distances beyond one lithosphere thickness and become progressively more important than the latter. They are followed by a much slower post-seismic stress recovery, extending typically over 80% of the cycle length. The results of this study should provide aid in interpreting data from monitoring stations with a view on discovering potential long term precursory trends.

S 194

DISLOCATIONS AND DISCLINATIONS IN FAULTS

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A crack or fault is modeled as a combination of dislocations and disclinations. The body of the crack is due to translational displacements and is equivalent to the dislocation density field. The crack tip is due to rotational displacements and is equivalent to the disclination density field. The fundamental relationships governing these fields and their interaction have been derived for continuous distributions and specialised to discrete line cracks. These results are applied to various types of faults and explain why strike-slip faults end in thrust/normal faults yielding the associated echelon patterns.

Geothermal Systems
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Friday PM
Keiiti Aki (MIT), Presiding

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SEISMICITY INDUCED BY STEAM PRODUCTION AT THE GEYSERS STEAM FIELD IN NORTHERN CALIFORNIA

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Earthquakes in the vicinity of The Geysers steam reservoir are highly concentrated within the depleted volume of the steam reservoir. About two earthquakes/day have been recorded in the magnitude range 1-3.5 from 1975-1979. The earthquake activity is remarkably continuous in time and continuously reproduces the same spatial pattern. This pattern has a mushroom shape with two stems, and coincides with the zone of pore pressure decline, fluid withdrawal, and negative reservoir dilatation. Focal mechanisms for reservoir earthquakes are consistent with the regional tectonic right lateral shear, but the reservoir strain is primarily a contraction in all dimensions. Reservoir well, geodetic, and seismic data combined with previous seismicity records suggest that steam production triggers the small earthquakes. The two most likely triggering mechanisms probably relate to water boiling out of the fractures or fracture walls in the reservoir. They are (1) strain induced local increases in shear stress, and (2) thermoelastic reduction in normal stress. The second proposed mechanism modifies purely mechanical concepts of effective stress to include the effects of temperature in a non-isothermal environment. The Geysers data suggest that temperature gradients may be at least as important as pore pressure gradients in changing effective stress.

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GROUND MOTION IN THE NEAR-FIELD OF A FLUID-DRIVEN CRACK AND ITS INTERPRETATION IN THE STUDY OF SHALLOW VOLCANIC TREMOR

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We present a study of the motion of the ground in the near-field of a fluid-driven tensile crack embedded in a layered half-space. The source that we consider is the jerky opening of a channel connecting two fluid-filled cracks and the cause of the opening is excess pressure of fluid in one of the cracks. We make a complete representation of the three components of ground motion in the space, time and frequency domains and analyze the effects of fluid compressibility, source depth and medium structure on the ground response. Using this model, we view an episode of volcanic tremor as a continuous sequence produced by numerous jerky openings of channels occurring randomly in time along a chain of cracks. Our results are applied to the October 5-6, 1963 east rift eruption of Kilauea volcano, Hawaii, for which a wealth of seismic data is available. The tremor observed during that eruption suggests an area of 1 by 1 km for individual cracks and a rate of jerky opening of 1 per second, each involving an increase in cavity volume of 40 m^2, a pressure drop of 0.004 bar, and a seismic moment of 10^{19} dyne cm. The total moment integrated over the entire duration of tremor for the eruption is $0.5.10^{24}$ dyne cm, roughly equivalent to a single magnitude M5 earthquake. The seismic source parameters and other field observations offer constraints on the process of mass transport and are compatible with the excess pressure and viscosity of magma in the range of 40 to 50 bar and about 10^2 poise, respectively.

S 197

SEISMIC MODEL OF A HYDRO-FRACTURED EARTH WITH SPECIAL REFERENCE TO THE HDR GEOTHERMAL ENERGY SOURCE

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Various passive and active seismic experiments have been carried out at the Fenton Hill Hot Dry Rock site by the Los Alamos Scientific Laboratories. Their results have been described in LASL HDR staff (1978) and Fehler (1979). In the present paper, we tried to synthesize their results to come up with a coherent picture of the fracture. For this purpose, we found it necessary to define the fracture as consisting of a system of large-scale cracks imbedded in a volume containing small-scale cracks. The large-scale cracks can be studied by deterministic methods using reflected and converted waves, but the volume containing small-scale cracks requires modelling by a random medium.

The radius of Fresnel zone is useful for interpreting data from experiments involving various wave-lengths and distances (source-reflector-receiver). For example, an important factor determining the amplitudes of reflected and converted waves from major cracks is the ratio of the size of Fresnel zone to the crack size. On the other hand, the random media parameters such as RMS velocity fluctuation and correlation distance are used to study the scattering and attenuation effect during the propagation through the heterogeneous volume containing small-scale cracks.

Comparison of seismic data for cases in which the fracture is pressurized and unpressurized greatly helps to give unique interpretation of data. Some results obtained here may be extended to larger-scale natural geothermal sources. For example, we found that the extent of a heterogeneous volume may be inferred from the observed shape of coda envelope.

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SEISMIC ACTIVITY ASSOCIATED WITH REGIONS OF POTENTIAL GEOTHERMAL RESOURCE IN WESTERN MEXICO

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A series of three earthquakes (estimated magnitude: 5.0) occurred within the Neovolcanic belt of western Mexico NW of Mexico City on Feb. 22, 26, and 28, 1979. These events and their aftershocks were recorded by a portable seismic network deployed as part of the ROSE experiment by the Hawaii Institute of Geophysics. The location of the main shocks and aftershocks is found to be concentrated near Los Azufres, a region thought to have one of the highest geothermal energy potentials in Mexico. The distribution of these earthquakes coincides with a region where Alverez (1979) found self-potential anomalies that he suggests define a potential geothermal field. Another concentration of seismic activity within the suspected region of geothermal potential is evident from our data; this suggests that local seismic activity could be used in this region to locate potential geothermal resources.

S 199

GEOTHERMAL EARTHQUAKES: TEMPORAL AND SPATIAL CHARACTERISTICS.

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Seismicity analysis of four known geothermal areas in California (Imperial Valley, Coso, Lassen, and Geysers) and one non-geothermal area (San Jacinto fault zone) reveal several similarities and certain notable differences which lead to a possible definition of a geothermal earthquake. By converting local micro-earthquake catalogs (average magnitude 1.75 to 2.5) into a time series and comparing the seismicity with a generalized Poisson distribution, it was determined that 75% of the earthquakes are clustered temporally within 18 hours and spatially within 10 km in the geothermal areas. The average clustering time in the non-geothermal area is 5 or more days and the average spatial seperation is greater than 10 km. The significant exception is the Geysers area in which no temporal clustering of earthquakes is observed. This contrasts to the Lassen area which is tightly clustered in time and is also a vapor dominated reservoir. The spatial and temporal pattern of earthquakes at Geysers suggests that the geothermal wells may affect the normal seismicity associated with the reservoir. At both Salton Sea and Coso, earthquake clusters tend to avoid regions of high heat-flow. The b-value within these two areas exceeds the regionally averaged value by 0.2 to 0.4.

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THE RELATIONSHIP BETWEEN HIGH PORE PRESSURES AND SEISMICITY AT THE FENTON HILL NEW MEXICO HOT DRY ROCK GEOTHERMAL SITE

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Low-level seismicity has been observed over the past four years during periods in which a HDR reservoir at Fenton Hill, NM was pressurized to create low impedance flow connections between wells. Activity usually started suddenly following injection of a critical volume of water (60% to 80% of the maximum volume previously injected under high pressure) and stopped soon after the cessation of pumping. The sudden commencement of seismic activity probably represents the initiation of fracture extension.

In three experiments occurring in March and October of 1979, we were able to locate several hundred seismic events using a single three-component geophone tool. During the first few hours seismic activity is confined to a narrow planar zone intersecting the injection well. Several days of injection caused activity to expand into a wide spherical volume

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