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POTENTIAL FOR TRIGGERING OF EARTHQUAKES BY STIMULATION OF DRY ROCK GEOTHERMAL FIELDS

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Stimulation of dry geothermal fields requires the injection of very large volumes of fluid, probably at pressures in excess of the least principal stress in the rocks. The high fluid pressure, if transmitted along faults under shear stress would reduce σ_n, the effective normal stress, and hence the frictional resistance to sliding along the fault. This mechanism has been responsible for earthquakes triggered by water flooding in the Rangely oil field in Colorado [1]. Therefore, the potential exists for triggering of earthquakes by fluid injection for geothermal power.

Ideally, where the rock has no matrix permeability or joints intersecting the induced hydraulic fracture, no earthquakes would be triggered. A hydraulic fracture is perpendicular to the least principal stress and is, therefore, a principal plane with no shear stress on it. However, leak-off into other fractures will occur even in rocks of very low matrix permeability and will be pressurized to some degree by the introduced fluid.

For earthquakes to be triggered, the effective normal stress would have to be reduced to about 1.2 τ, where τ is the shear stress on the fracture. If the stresses could be measured and the orientation of the fault be determined, as at Rangely, the fluid pressure which would be required to trigger earthquakes could be calculated. The stresses may be estimated from hydraulic fracture tests [2]. However, in general, the fluid pressure may not be subject to the operator's control due to the requirements of efficient geothermal power production.

Two techniques for circulation of fluid through the induced fractures require that the fluid pressure exceed the normal stress across the crack. The huff and puff method of inflating the crack with fluid and allowing it to relax as the heated fluid flows back, introduces fluid at $p_f > S_3$, the least principal compressive stress. However, the fluid pressure is reduced again, and some control over the undesirable pressurization of nearby shear fractures can be exerted by varying the time allowed for the fluid to leak back in the relaxation phase of the cycle. The other technique involves continuous circulation of fluid through a crack distended by the fluid pressure. In this case, nearby fractures will gradually become pressurized by fluid at or near the least stress, S_3, uncontrolled by the operator except by shutdown of the system.

One can easily calculate the conditions required for slip where some part of the shear fracture contains fluid at $p_f = S_3$ given the assumption that $S_1 > S_2 = S_3$. This is equivalent to having S_2 parallel to the fracture surface and, consequently, of no influence on the initiation of fracture. In these cases,

$$\tau = \frac{\sigma_1 - \sigma_3}{2} \cdot [\sin \; 2\alpha]$$

$$\sigma_n = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} \cdot [\cos \; 2\alpha]$$

and, as

$$S_3 = \sigma_3 + p_f$$

and

$$p_f = S_3, \; \sigma_3 = 0.$$

Therefore,

$$\tau/\sigma_n = \tan \; \alpha = \mu_s$$

where α is the angle between σ_1 and the normal to the fracture surface, and μ_s is the static frictional coefficient, about 0.8 for most rocks. Therefore, when tan α exceeds 0.8 ($\alpha \geq 39°$) slip along the fracture surface will occur in the absence of any cohesive strength, τ_o, for the rock. In other words, for this conservative set of assumptions ($S_1 > S_2 = S_3$; $p_f = S_3; \tau_o = o$) earthquakes will be triggered on all fractures at angles of less than about 50° to the maximum principal compressive stress direction. More sophisticated calculations show that for reasonable value of stress expected in the earth's crust, raising the fluid pressure to be equivalent to the magnitude of the least principal stress will result in triggering of earthquakes. At Rangely, for example, $S_1 \sim 2S_3$, a ratio reported fairly commonly from other areas. The fluid pressure, when raised by injection into a pre-existing fault to $0.9S_3$, triggered earthquakes. Below that value of the fluid pressure, the earthquakes stopped.

It is significant that the Rangely earthquakes remained small throughout the injection period. The largest were two events of $M_L = 4.0$ in April, 1970. The earthquakes apparently owed their small magnitude to the limited area over which the fluid pressure was sufficient to overcome the static friction. Fluid withdrawal within 500 meters of the line of injection wells served to limit the extent of the fault under high fluid pressure. Artifically induced earthquakes are not necessarily hazardous, then, except in areas where a large earthquake might be expected regardless of fluid injection or where a long section of a fault is gradually and nearly uniformly pressurized by fluid to the critical value.

If the fluid pressure gradient along a fault extending away from the injection well is steep, then earthquakes will first occur in the limited region under high pressure. As the earthquakes occur, the shear stress will drop, and higher fluid pressure is required to further reduce the static friction and trigger yet more earthquakes. As the pressure front advances to progressively greater distance along the fault but maintaining its steep gradient the zone of seismic activity will follow, leaving in its wake a much diminished frequency of earthquakes. The fluid pressure, if raised gradually along a gentle gradient, will trigger earthquakes more nearly simultaneously over a long front and offer the possibility of rupture over the entire section.

Calculations, based on numerical solutions to the coupled changes in fluid pressure in cracks and stress in the solid matrix, have been carried out by Paul Witherspoon and his associates at UC Berkeley. Their results suggests that for cases where the fluid pressure, P_f, is less than S_3, the pressure gradient away from the point of injection will be very steep. The unknown parameters of crack opening and stiffness have a large influence on the results, however, and application of their methods to the specific case would be required.

Conclusion

Earthquakes are likely to be triggered by fluid injection to stimulate geothermal energy production where the injection pressure is at or near the magnitude of the least principal stress. The earthquakes need not be cause for very great concern provided 1) some attempt to determine the in-situ stress is made to estimate the likelihood for triggering a major fault rupture initiated by a local slip. Is the region already at stresses very near the failure strength? If so, then, 2) monitoring of seismic activity should be conducted to track the migration of seismic activity, if any, away from the injection point. If, for example, the earthquakes occur over a broad front along what could reasonably be assumed to be a fault zone, then the system could be shut down. Some set of criteria for shutdown could be established based on the potential for a large earthquake and the degree of risk attendant upon its occurrence.