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TITLE HYDRAULIC FRACTURING OF JOINTED FORMATIONS

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ABSTRACT

Measured by volume, North America's largest hydraulic fracturing operations have been conducted at Fenton Hill, New Mexico to create geothermal energy reservoirs. In the largest operation 21,000 m^3 of water were injected into jointed granitic rock at a depth of 3.5 km. Microearthquakes induced by this injection were measured with geophones placed in five wells drilled into, or very close, to the reservoir, as well as 11 surface seismometers. The large volume of rock over which the microearthquakes were distributed indicates a mechanism of hydraulic stimulation which is at odds with conventional fracturing theory, which predicts failure along a plane which is perpendicular to the least compressive earth stress. A coupled rock mechanics/fluid flow model provides much of the explanation. Shear slippage along pre-existing joints in the rock is more easily induced then conventional tensile failure, particularly when the difference between minimum and maximum earth stresses is large and the joints are oriented at angles between 30 and 60 degrees to the principal earth stresses, and a low viscosity fluid like water is injected. Shear slippage results in local redistribution of stresses, which allows a branching, or dendritic, stimulation pattern to evolve, in agreement with the patterns of microearthquake locations. These results are qualitatively similar to the controversial process known as "Kiel" fracturing, in which sequential injections and shut-ins are repeated to create dendritic fractures for enhanced oil and gas recovery. However, we believe that the explanation is shear slippage of pre-existing joints and stress redistribution, not proppant bridging and fluid blocking as suggested by Kiel.

INTRODUCTION

Most rock masses, particularly crystalline ones, contain pre-existing fractures, usually called joints. When fluid is injected into joints during hydraulic fracturing, several types of joint deformation can take place. At first the pressure rise in the joint is small enough that the joint does not actually open. Nevertheless, the effective closure stress, that is, the difference between the total earth stress acting normal to the joint plane and the fluid pressure, is reduced. If injection continues, the pressure can attain a value high enough that the effective closure stress no longer provides sufficient friction to resist shearing stresses acting parallel to the joint surface, and the joint will slip in a shear mode. If the slippage is sufficient, one rough surface asperity can ride over, or atop another, so that even if the pressure is suddenly reduced the joint opening and permeability are irreversibly increased. This is termed "shear stimulation." If fluid injection rates are modest shear stimulation may result in sufficient permeabilty that no further increase in pressure is attainable. If however the formation of void space by shearing is insufficient to accommodate the fluid volume injected into the rock joints, the pressure will continue to rise, and eventually attain a value equal to the earth stress acting normal to the joint. Then the opposing surfaces of the rock that meet at the joint will part. Because no actual rupturing of rock takes place during the parting, it is inappropriate to call this fracturing - we refer to this behavior as joint separation. If a proppant, either purposely injected with the fluid, or broken off the joint surfaces, is trapped in a joint following shut-in, the joint opening will again be irreversibly increased, and the joint thus "stimulated."

The kinematic argument for shear stimulation is made by referring to the Mohr diagram shown in Figure 1. For simplicity only a two dimensional stress state is depicted, in which the principal maximum and minimum compressive stresses are labeled σ_{min} and σ_{max} and the stresses on any other plane can be represented by the Mohr circle connecting the two principal stresses (Jaeger and Cook, 1979). In Figure 1 a fairly typical stress state is assumed, one in which σ_{max} is about twice σ_{min}. The effective closure stresses on a joint are reduced by the pressure, P, within the joint. Consequently separation occurs when the effective closure stress is zero, or $P = \sigma_{min}$. As shown in Figure 1, lift-off thus requires that the Mohr circle be moved so completely to the left that its left side is coincident with the origin. On the other hand,

References and illustrations at end of paper.

shearing requires only that the Mohr circle move left sufficiently to encounter the Coulomb-Mohr failure envelope. A mere touching is sufficient if a joint has the optimum orientation, but even if not optimally oriented most joints will shear-slip long before they separate.

Shear stimulation is rarely discussed in hydraulic fracturing theory. In fact, Lockner and Byerlee (1977), who demonstrated in rock mechanics laboratory experiments that slow pressurization could result in shear fracturing of intact, not just jointed, rock specimens, were moved to state that: "In the literature on hydraulic fracture the possibility of producing shear rather than tension fractures is surprisingly disregarded". Subsequently, several other papers (Hast, 1979, and Solberg, Lockner and Byerlee, 1980) have appeared which support the possibility of shear stimulation.

While it thus appears that joints will shear slip at fluid pressures less than that required for separation, the joint opening, or dilation behavior for slippage and separation is quite different, as indicated in Figure 2. As pressure increases one again moves to the left on this diagram. At first the dilation is small, simply resulting from the decrease of effective closure stress, but then shear slippage ensues. As the joint surfaces continue to slip, they attain a state in which one large roughness asperity lies atop another, and further slippage would allow the largest asperity to slide over and down the other. Thus one expects a natural limit to the shear dilation. This maximum shear dilation is typically of the order of a fraction of a millimeter (Barton et al., 1985). If the joint pressure can be increased so that separation occurs, then the results of conventional hydraulic fracture theory (but taking the tensile strength of the jointed rock to be zero) indicate that the dilation is typically tens of millimeters (Perkins and Kern, 1961; and Daneshy, 1973), many times that of shear dilation. Thus as Lockner and Byerlee correctly foresaw, the key to understanding stimulation is not just rock mechanics, but also fluid dynamics. If a low viscosity fluid is injected into a joint at a low enough flow rate, the fluid volume can be accommodated within the small dilation afforded by shear slippage. Even though the joint opening and permeability are not increased as much as if by separation, the permeability increase could be sufficient to sustain low flow rates and low viscosity without large pressure gradients, and the pressure need not build up to separation requirements.

In an actual hydraulic fracturing operation it is likely that the entire spectrum of joint deformation can occur: near the injection well the flow passage area is limited, hence fluid velocities and pressure gradients are large and separation occurs. But near the tips of joints, far from the injection well, velocities and pressures are much reduced, and shear stimulation occurs. In the most common application of hydraulic fracturing, in petroleum reservoirs, very viscous fluids are normally used and injection rates are high. Consequently joint separation is dominant, and if few joints are present, as is often the case in petroleum formations, actual fracturing of intact rock occurs. However, in the geothermal reservoir fracturing described below, joints occur frequently, and high downhole temperatures render most viscosifying agents useless, so water is used as the fracturing fluid. Hence, shear stimulation dominates.

RESERVOIR STIMULATION EXPERIMENTS

Well instrumented hydraulic stimulation experiments have been conducted in two Hot Dry Rock (HDR) geothermal energy reservoirs. The first of these is located at Fenton Hill, on the west flank of the Valles caldera, a dormant volcanic complex in the Jemez Mountains of New Mexico, U.S.A. The second site is at Rosemanowes Quarry, in Cornwall, England. At both sites the reservoirs are jointed, granitic rock.

Hot Dry Rock geothermal energy reservoirs differ from the more familiar hydrothermal reservoirs in that in the former case, permeability and porosity must be induced, usually by hydraulic stimulation, whereas in the hydrothermal reservoir these attributes are already present, and in fact the existing porosity is usually saturated with water or steam, which, after drilling, can be used as the working fluid for energy extraction and electricity production. In HDR reservoirs essentially no water exists in-situ, and so must be supplied from an external source. The technical difficulties faced in HDR development are challenging. At least two wells must be drilled to depths where temperatures are 200 to 300°C, suitable for electricity generation. Even in regions with favorable geothermal gradients such temperatures are found at great depths, 3 to 5 km, where the minimum principal component of the in-situ earth stress is likely to be 35 to 100 MPa (5000 to 15000 psi). One must then stimulate the rock formation to hydraulically link the wells, and hold open the joints so that the permeability remains high and flow resistance is low. Furthermore, large areas of hot rock must be adequately bathed with flowing water to obtain high heat production for long periods.

Initial HDR feasibility was proven in early testing at the Fenton Hill site. Two wells were drilled to 3 km, linked via hydraulic stimulation, and during intermittent testing from 1978 to 1980, 3 to 5 MW of thermal power were produced for periods as long as nine months. The flow resistance was low enough that the pumping power required to force the water down one well, through the reservoir, and up the other well was less than 2% of the thermal power produced. The produced water was of high quality, low in dissolved solids compared to most geothermal fluids; and even during fracturing, the largest detected earthquake registered only 1.5 on the Richter scale. Further details are provided by Dash et al. (1983).

These early successes led to the decision to create a deeper, hotter, and larger reservoir at the Fenton Hill site. The objective of this larger reservoir is to establish the engineering practicality of HDR. Based upon the early experiences, which indicated that the zones of stimulation were nearly vertical, with a roughly North-South orientation, two new wells were drilled in segments. In the first segment, 0 to 2.5 km, both wells were nearly vertical, but in the deeper segment the boreholes were directionally drilled towards the East, at an angle from vertical which eventually built up to 35°. Figure 3 shows a perspective view.

The upper well, EE-3, which is the intended production well, lies 300 m above the lower injection well, EE-2, in the slanted interval. Temperatures varied from 200°C at 3 km to 325° at 4.4 km. Also shown in Figure 3 is a well drilled for the older reservoir which now contains a geophone sonde. This geophone, and others placed in other boreholes, detect and locate the microearthquakes triggered during hydraulic stimulation (House, et al., 1985).

First attempts to hydraulically connect the two new boreholes by stimulation were initiated near the bottom of the lower well but difficulties were encountered due to the high downhole pressure (90 MPa or 13,000 psi), and stress corrosion in the high temperature environment. Attention shifted uphole, and in December 1983 a massive hydraulic fracturing operation was conducted in which 21,000 cubic meters (5,600,000 gal) of water were injected at 3.5 km in the lower well at downhole pressure of 83 MPa and average flow rate of 0.1 cubic m/s (40 barrels/min). Details are provided by Dreesen and Nicholson (1985). Figure 4 shows the locations of some of the induced microearthquakes. The downhole geophones are extraordinarily sensitive, which enabled detection of events with extrapolated Richter body wave magnitudes as low as -5, but Figure 4 shows only the 850 high quality events with magnitudes from -3 to 0. Note that the microearthquakes do not suggest a single planar fracture as predicted by conventional hydraulic fracturing theory (Hubbert and Willis, 1957), but instead depict a zone of stimulation distributed throughout a rock volume that is about 0.8 km high, 0.8 km wide in the N-S direction, and about 0.25 km thick. The precision of microearthquake locationing is 30 m, so the width of the seismic volume, 250 m, is not an artifact of measurement uncertainty. The volume of the stimulated zone is 4000 times greater than the volume of water injected. House et al. (1985) also concluded that the first motions of the microearthquakes and fault plane solutions determined from a surface array of seismometers indicated a shear-slip motion, probably along pre-existing rock joints. This suggests that tensile fracturing, if it occurred at all, generated only very weak seismic signals that could not be detected by the surface seismic array.

The wave form of a typical microearthquake recorded by a downhole geophone is shown in Figure 5. Note that the amplitude of the shear wave is larger than that of the compressional wave, which would be consistent with a shear slip mechanism. Figure 6 presents a spectrum of the compressional wave of the seismogram in Figure 5. Note the flat trend at low frequencies, followed by a roll-off which declines with the cube of the frequency. This behavior is consistent with that observed for spectra of waveforms from usual tectonic earthquake mechanics, i.e., those in which shear slip occurs. Based upon the source mechanism model of Brune (1970) the characteristic dimension of the rock surface mobilized for each shear-slip event is of the order of 10 m, comparable to the spacing of the major joints observed in well surveys.

In summary, the above results indicate a fracturing mechanism which is inconsistent with conventional theories of hydraulic fracturing which predict the propagation of a single fracture caused by tensile failure of the rock. However our results are consistent with Lockner and Byerlee's observation of shear failure in rock specimens at low injection rate. Furthermore, our observations were confirmed at the British Hot Dry Rock reservoir in Cornwall where it was observed (Pine and Batchlor, 1984) that fracturing occurred as a zone of multiple fractures, and that shear slippage along existing joints was the dominant cause of seismicity.

MODELING SHEAR STIMULATION IN JOINTED ROCK

The unexpected stimulation results presented above suggested that further study required a model incorporating detailed fluid dynamics and rock mechanics within jointed rock masses. The Fluid Rock Interaction Program, based upon the calculation method developed by Cundall and Marti (1978), was adapted for this use. Pre-existing rock joints are deployed on a regular rectangular grid and the code permits interactive coupling of fluid dynamics with rock stresses and deformations. For example, an excess of pressure on a block during one computational cycle will result in compression of the block, and opening (dilation) of the joints next to it, resulting in additional permeability and a changed pressure distribution.

When a computation in which joints were aligned parallel to the principal earth stresses was studied, a process equivalent to classical hydraulic fracturing (but without the necessity of accounting for rock strength) was predicted: a single joint opened at a pressure equal to the minimum earth stress, and the aperture and shape of the opened joint agreed well with conventional hydraulic fracturing theory (Daneshy, 1973). However, when the orientations of the pre-existing joints were rotated 30° from the principal stress directions, and a low viscosity fluid like water was used for fracturing, two types of stimulation patterns occurred. In the first type, typified in Figure 7, which occurs when frictional resistance to shear slippage is low or when the maximum dilatancy due to shear is large, only a single joint is stimulated. The resolved stresses shown in Figure 7, and later in Figure 9, result from a principal earth stress of 2σ applied at an angle of 30° to the joints. For simplicity the subscript min has been deleted so σ is the minimum principal earth stress and it acts perpendicular to the maximum stress, 2σ.

In the second type of shear stimulation, corresponding to high shear resistance or small dilatancy, multiple joint stimulation occurs as shown in Figure 8. Shear slippage along the joints is accompanied by shear-stress drops, and the interaction of these stress drops with the acting earth stresses results in opening of joints more perpendicular to the maximum stress, so that a dendritic, or branched joint pattern occurs. This pattern of stimulated joints and the computed shear-stress drops offer an explanation as to why the previous microearthquake maps are not planar, but are elliptical in shape, and why the observed first motions of microearthquakes indicate a shear mechanism.

To better understand the multiple joint stimulation behavior, refer to Figure 9. The main joint has slipped in shear and the joint surfaces have separated. When the surfaces are no longer in contact there is no friction to support the initial shear stress, so a stress drop occurs and the y-direction normal compressive stress in the region midway between the center and the tip of the main joint is altered as shown on the top and bottom of Figure 9. The original normal stress, 1.75σ, is reduced to as low as 1.25 σ in the upper right and lower left quadrants, which is now low enough for separation of the lateral joints to occur. These lateral joints then allow easy flow of the water into joints immediately adjacent and parallel to the main one. These parallel joints begin to open, and this cycle repeats itself, until eventually the stimulated joint pattern takes on the elliptical shape predicted in Figure 8, which reasonably approximates the pattern of microearthquake locations in Figure 4.

In contrast, when the shear resistance is low and shear dilation is high, as was the case for the single joint stimulation of Figure 7, the fluid is so easily accomodated by the rapidly dilating single joint that the pressure does not build up sufficiently to stimulate lateral joints.

DISCUSSION

The dendritic stimulation pattern depicted in Figure 8 has important implications in reservoir engineering. As suggested in Figure 10, volume drainage, whether it be of hydrocarbons or geothermal fluids, is more efficient than areal drainage. Dendritic fracturing was previously proposed by Kiel (1977), whose "Kiel Process" remains controversial to this day. The proposal seems to be based upon observed productivity increases in oil and gas fields. In this process a well is repetitively fractured with a proppant-bearing fluid, shut-in, and vented. In describing the mechanism Kiel explains that the first cycle of pressurization results in spalling and self-propping of the main fracture. In subsequent cycles the proppant purposely introduced in the fracturing fluid bridges the spall-proppants so the pressure rises and lateral fractures are propagated perpendicular to the first one. While such a mechanism may possibly work when the principal stresses in two directions are nearly the same, the model results presented here indicate that it is unlikely to work when the stresses differ considerably, as they so often do in situ. In this case the pressure rise in the blocked main fracture would simply result in further lift-off of the main fracture, overcoming the temporary blockage, and the main fracture would continue to propagate.

The key to dendritic fracturing overlooked by Kiel is shear - this allows the necessary reduction of the earth stress parallel to the main fracture to permit opening of lateral joints. While disagreeing with Kiel's explanation of mechanism, the present calculations do support his hypothesis - dendritic stimulation can occur under certain conditions, these being that the major joints not be parallel to the principal earth stresses, and that the flow rate and fluid viscosity within the joints be low enough that shear dilation is still sufficient to transmit the fluid rate without excessive pressure gradients.

CONCLUSIONS

Seismic monitoring provides a view of hydraulic stimulation which is unobtainable by any other means at the depths of interest here. The seismic observations reported here, supported by results in Britain as well as in rock mechanics experiments, indicate that injecting low viscosity fluid at low rate into jointed rock results in multiple joint stimulation caused by shear-slippage, not the single tensile fracture of conventional theory. These results were explained and verified by a coupled rock mechanics/fluid flow model, which further constrained dendritic fracturing to situations where the joints and principal earth stresses are not parallel.

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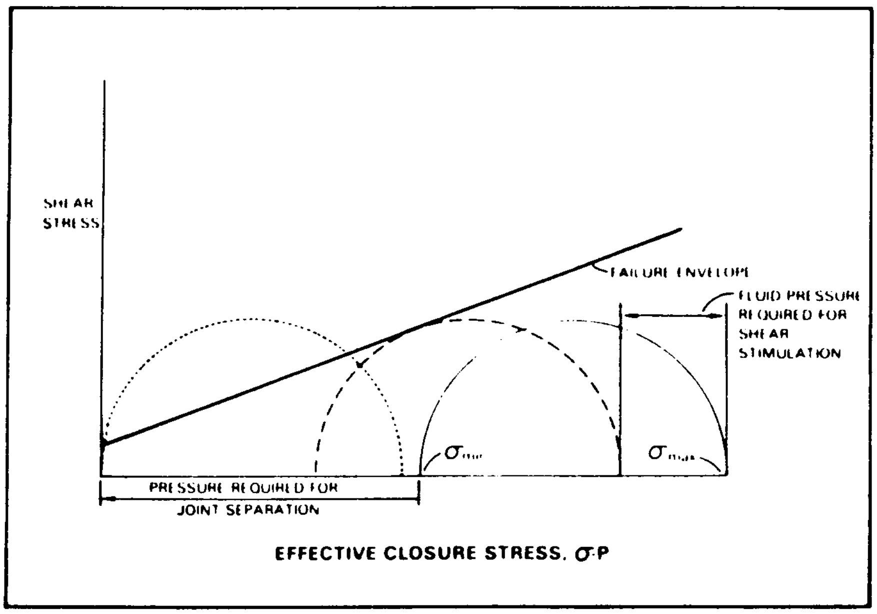


Figure 1. Mohr stress diagram illustrating that lower fluid pressure is required for shear stimulation compared to joint separation.

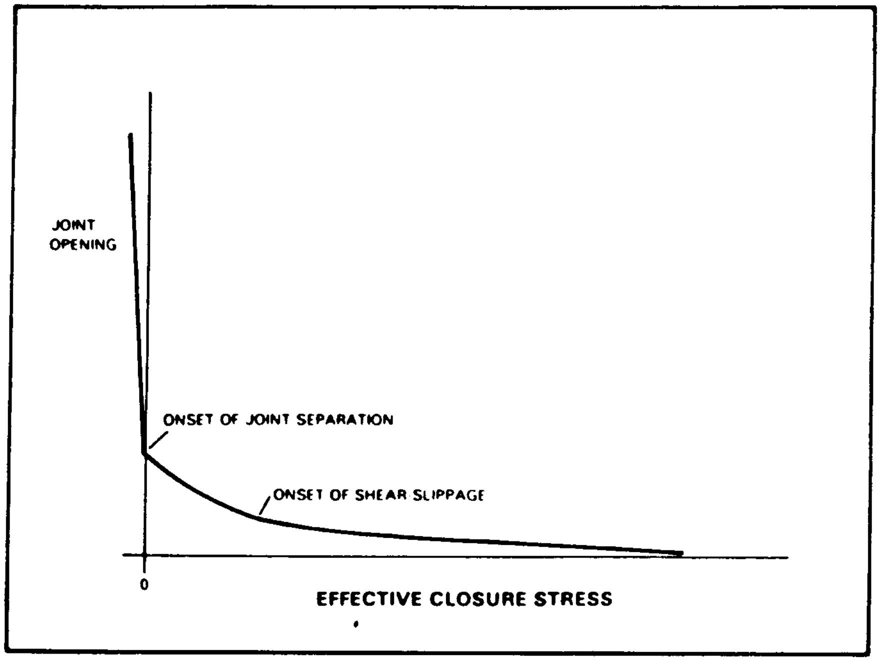


Figure 2. Joint dilation behavior.

Fig 3

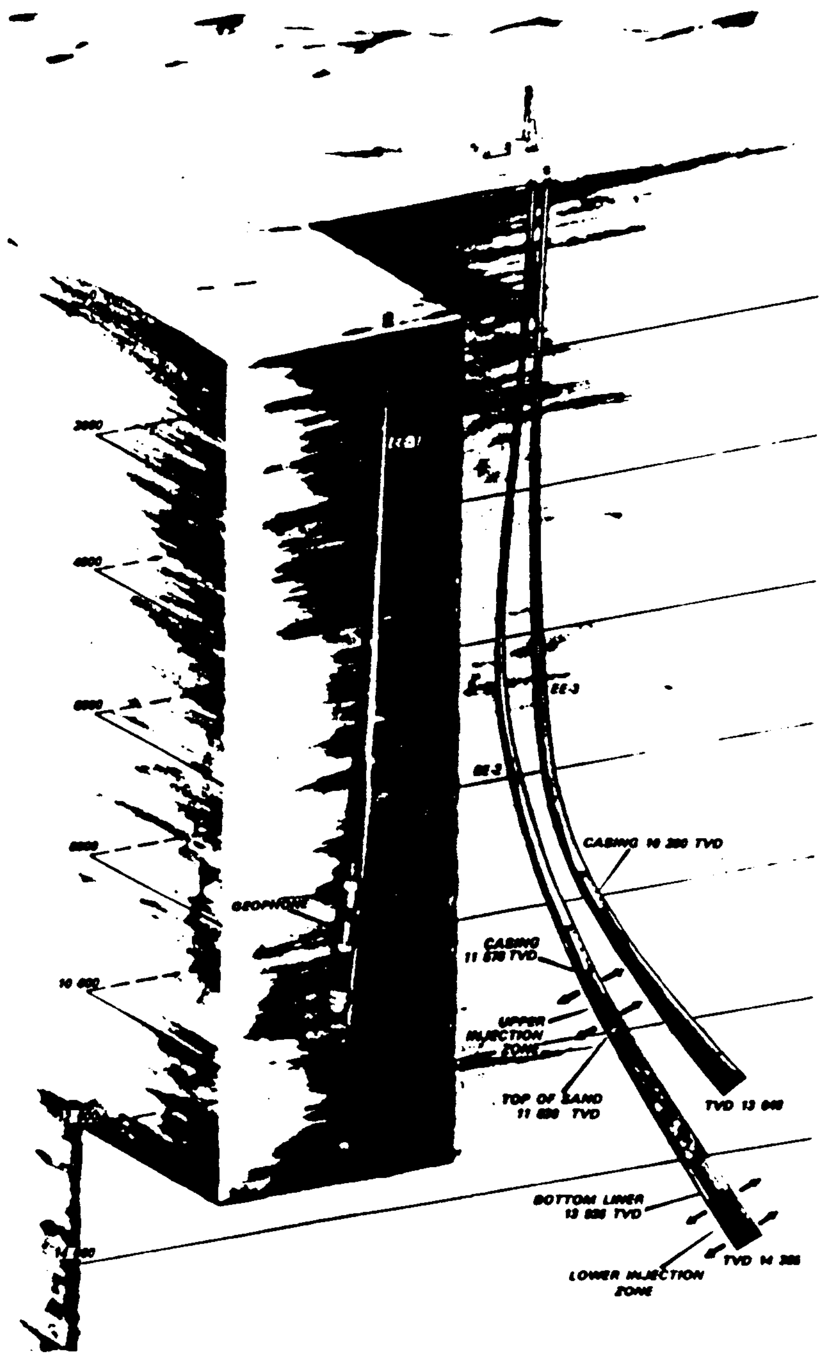
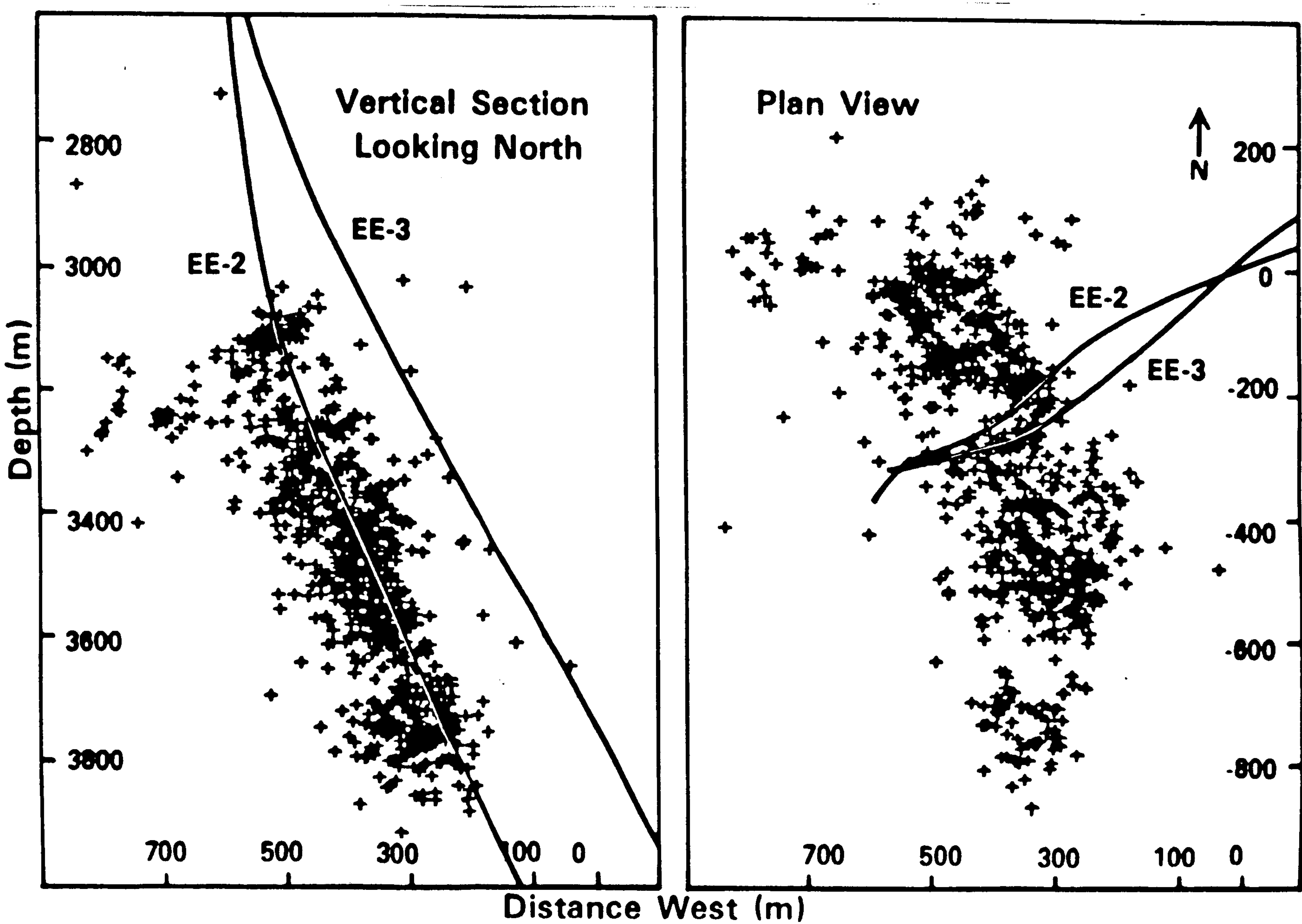


Figure 3. Perspective view of wells and geophone tool placed for microearthquake monitoring during hydraulic stimulation.

Figure 4. Hypocentral locations of microearthquakes induced by massive hydraulic injection in well EE-2. Left hand side is elevation view, looking north, while right hand side is plan view, looking down.



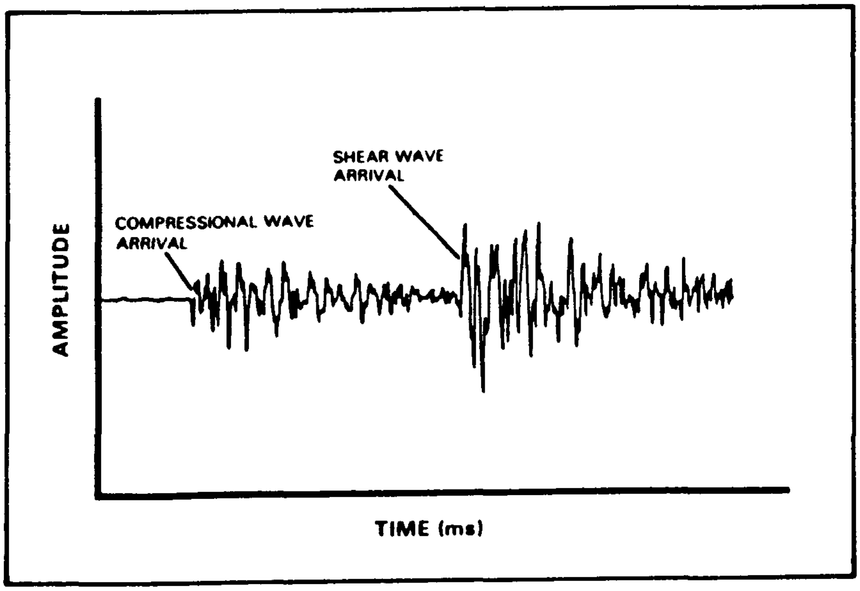


Figure 5. Seismogram of typical microearthquake.

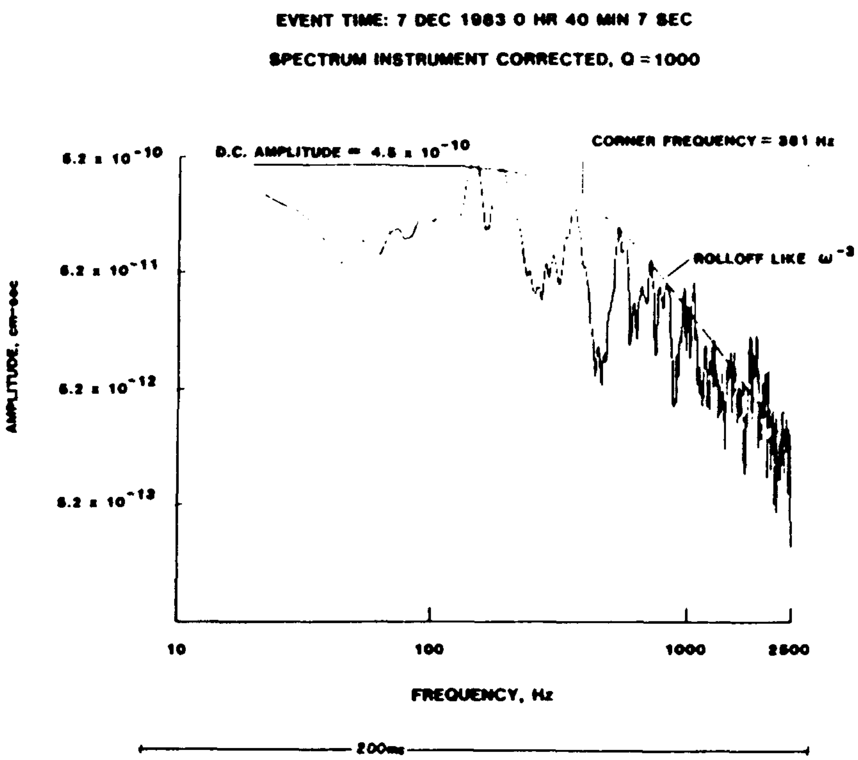


Figure 6. Spectrum of compressional wave of seismogram in Figure 5.

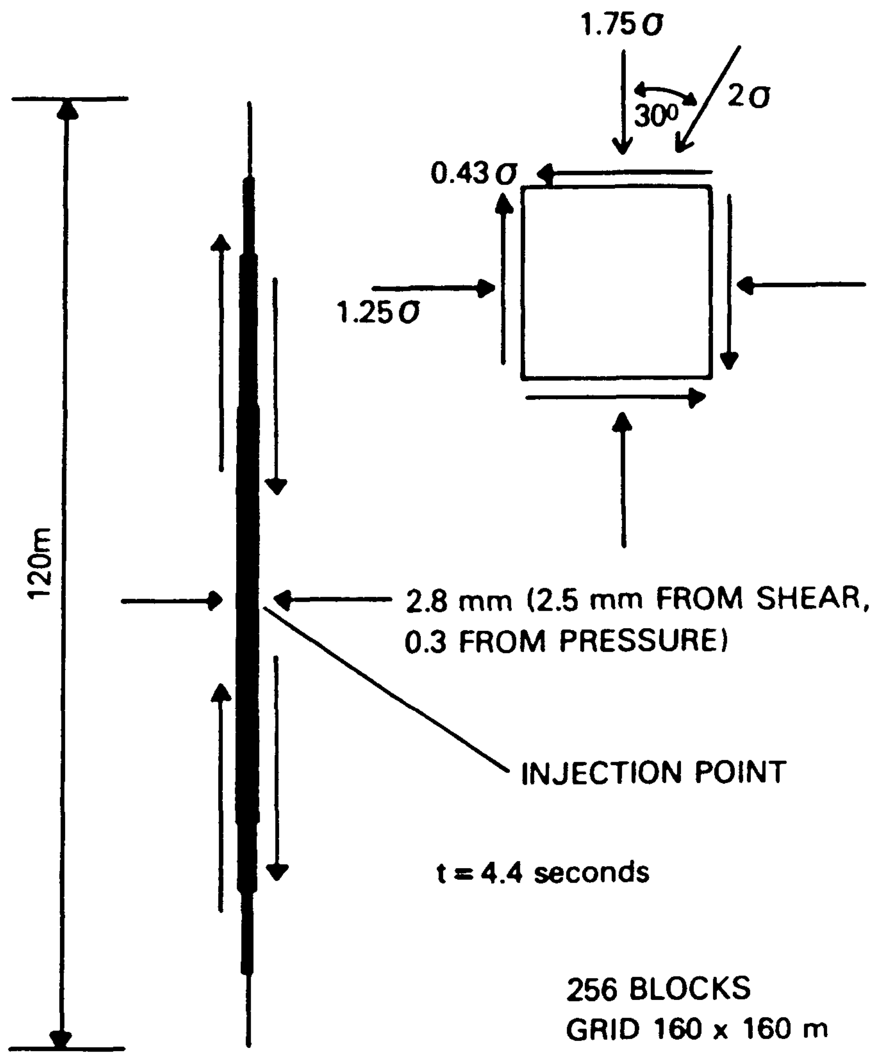


Figure 7. Single joint stimulation induced by shear slippage when frictional resistance to shear slippage is low or the ability to open the joint in shear is high.

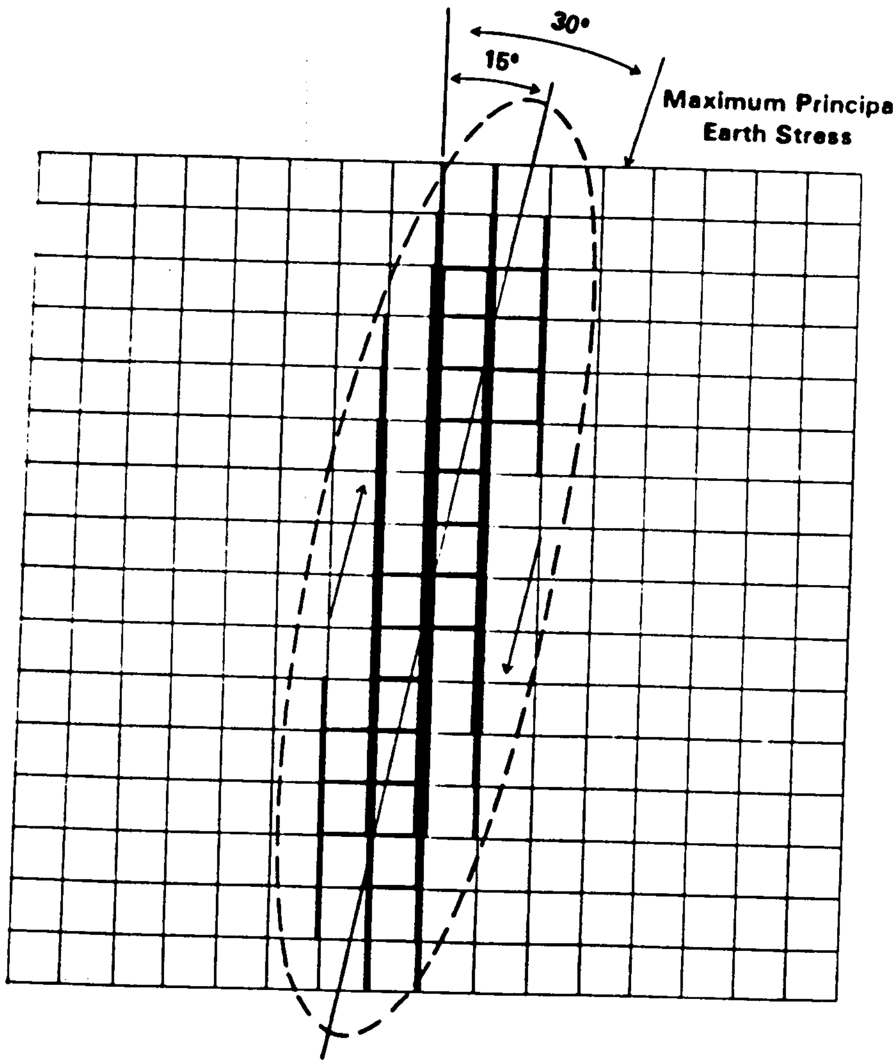


Figure 8. Multiple joint shear stimulation which occurs when shear resistance is high or shear dilatancy is low.

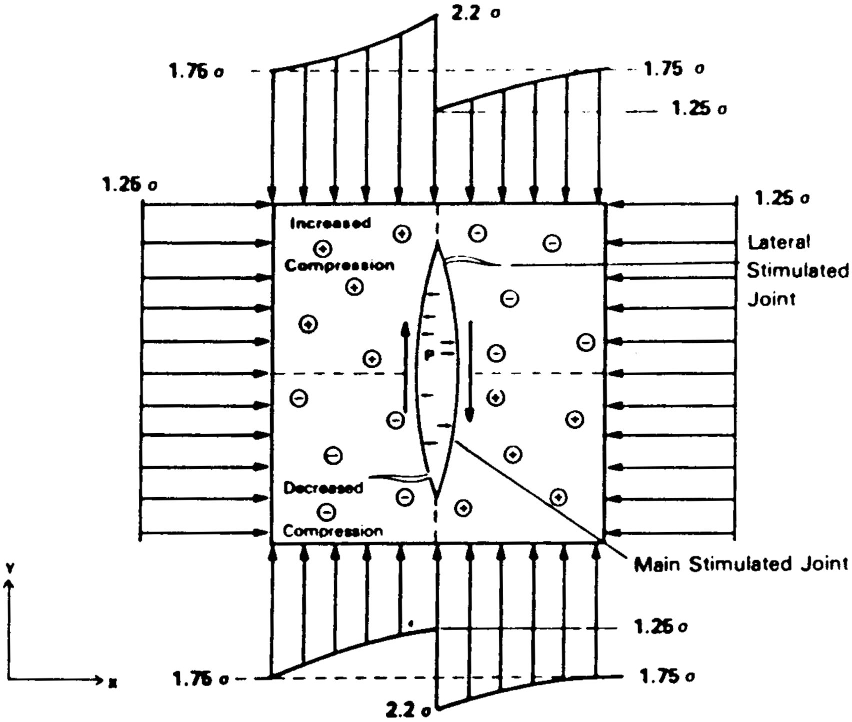


Figure 9. Stimulation of lateral joints.

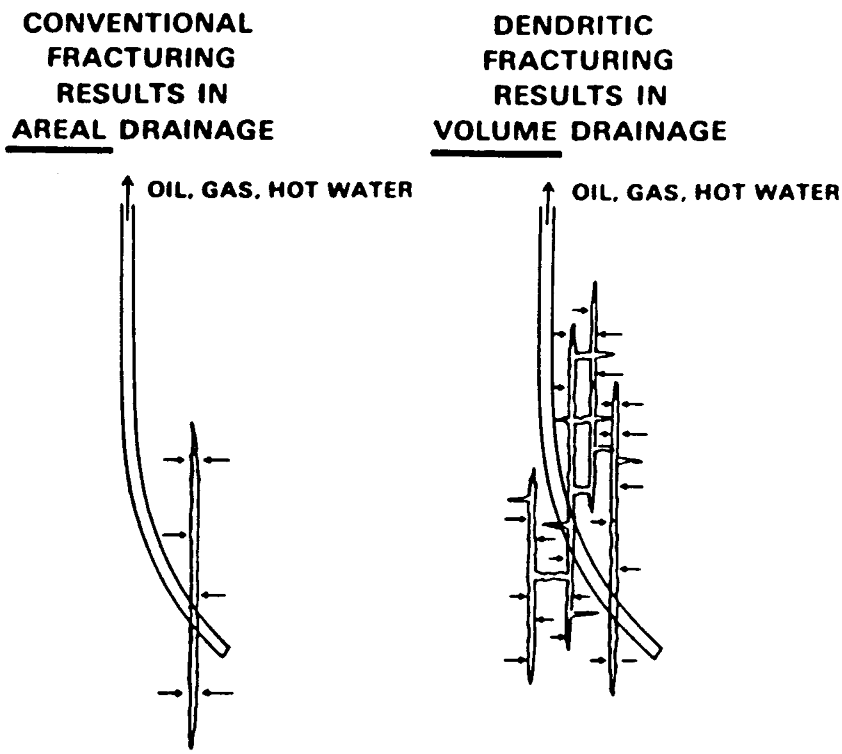


Figure 10. Volume drainage of fluids is more effective than areal drainage.