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Natural and Induced Fracture Orientation[1]

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Washington, D.C.

Abstract Natural fractures in rocks comprise (1) joints, which are commonly closely spaced, are of limited linear extent, and have negligible tangential displacements, and (2) faults across which opposite blocks have tangential displacements ranging from millimeters to tens of kilometers. Induced fractures are principally those produced in surrounding rocks by fluid pressures applied within well bores.

The orientation of fractures with respect to applied stresses may vary widely, depending upon the amount of finite strain the rock has undergone after the fractures were formed. This discussion will be limited to fractures in rocks that have undergone only minor strain subsequent to the fracturing.

Because rocks are elastic solids, there exists in three-dimensional space beneath the surface of the ground a field of stress definable at each point by three mutually perpendicular, principal compressive stresses and by the space orientation of these stress axes. On the three planes perpendicular to the principal stresses, shear stresses are zero; on all other planes, if the principal stresses are unequal, nonzero shear stresses exist.

Parallel with the ground surface, the shear stresses must be zero. Hence, at each point of this surface, one of the three principal stress trajectories must terminate perpendicularly. Therefore, in regions of gentle topography and simple structure, the underground stress field is usually characterized by a system of principal stress trajectories, one of which is nearly vertical and the other two nearly horizontal.

When rocks are subjected to compression under unequal triaxial stresses, failure by fracture and tangential slippage occurs for certain stress combinations. Usually, conjugate sets of slip surfaces are formed whose lines of intersection are parallel with the intermediate axis of stress and whose acute angle (commonly about 60°) is bisected by the greatest principal stress. This phenomenon forms the basis for relating the orientation of common faults—normal, reverse, and transcurrent—to the associated stress fields.

Hydraulically induced fractures, whether by fluid pressure in wells or by the intrusion of igneous dikes, tend to follow surfaces parallel with the greatest and intermediate principal compressive stresses and perpendicular to the least stress. Therefore, the orientations of hydraulic fractures, or of igneous dikes and sills, are greatly influenced by the prevailing stress state in the ambient rocks. In particular, in tectonically relaxed regions characterized by normal faulting, the greatest principal stress is nearly vertical and the intermediate and least principal stresses are nearly horizontal, the intermediate stress being in the strike direction of the local normal faults. In such a region, the preferred orientation of hydraulic fractures is vertical and perpendicular to the least principal stress and parallel with the strike of the local normal faults.

Hydraulic-fracture orientation may also be influenced by anisotropy or planar inhomogeneities in the rock such as bedding, schistose cleavage, or a system of parallel joints. If such a planar system does not depart too far from perpendicularity to the axis of least stress, hydraulic fractures may follow such a zone of weakness, across which the shear stress will not be zero. In this case, provided the rocks are also stressed tectonically, slippage along the fracture and possible resultant earthquakes are expectable consequences of increasing the fluid pore pressure in the rock.

My assigned topic for this conference, "Natural and Induced Fracture Orientation," to a large extent duplicates a study entitled "Mechanics of Hydraulic Fracturing," made for Shell Oil Company by David G. Willis and me in 1955 and presented before the Society of Petroleum Engineers of AIME during its Annual Meeting in Los Angeles in October 1956 (Hubbert and Willis, 1957). Because this topic has been treated in detail, both theoretically and experimentally, in the cited paper, and because the conclusions drawn in that paper have been amply verified by subsequent developments, this brief introduction will serve to update the Hubbert and Willis paper of 1957, which is reproduced in full on succeeding pages.

My own interest in the hydraulic fracturing of oil wells was first aroused when, about 1947, I participated in a Shell engineering conference on the then serious problem of lost circulation in wells being drilled into the Tertiary strata of the Texas-Louisiana Gulf Coast. In this region, I was told, down to depths of about 5,000 to 7,000 ft (1,525–2,135 m) the pressure of the fluids in the sedimentary units is about the same at any given depth as that of a hydrostatic column of water extending to the surface of the ground. Below this interval of normal pressure, abnormal fluid pressures that may be as much as 1.5 times the normal hydrostatic pressure are encountered rather abruptly.

In the normal-pressure zone, drilling muds having a density of only about 1.1 g/cm^3 were

[1] Manuscript received, July 4, 1972. This paper serves only to introduce and update the paper, "Mechanics of Hydraulic Fracturing," by M. King Hubbert and David G. Willis, which follows.

[2] U.S. Geological Survey.

used; for the high-pressure zone, drilling muds of higher densities had to be used to prevent a disastrous blowout and loss of the well. As the high-pressure zone is approached, the drilling-mud density is increased to possibly as much as 1.5 g/cm^3. However, if the density is too great, lost circulation occurs and the drilling mud pumped down the drill pipe fails to return. If the mud density is reduced to perhaps 1.3 g/cm^3, circulation is regained.

Because the sedimentary beds involved consist solely of loosely cemented sandstones and claystones which contain no cavernous openings and are also incapable of being penetrated by drilling mud, the only explanation for the behavior observed is that a fracture must have been opened by the excess mud pressure and closed as the pressure was reduced. The question asked me was: How is it possible mechanically for a mud pressure of only about two thirds of the sediment pressure due to the weight of the overburden to open a fracture in the sedimentary units?

Once the conditions were understood, the answer became obvious. The engineers were assuming implicitly that the state of stress in the rocks was hydrostatic—*i.e.*, that the three principal compressive stresses were equal. Actually, the stress state in these rocks must be triaxial, as indicated by the fact that they have been broken repeatedly throughout Tertiary time by a system of normal faults striking parallel with the coast and with the strike of the sediments. By means of the sand-box experiment illustrated in Figures 2, 3, and 4 of the Hubbert and Willis paper, I showed that the stress state producing normal faulting is one in which the axis of greatest compressive stress is vertical, that of intermediate stress is horizontal and parallel with the strike of the faults, and that of least stress is horizontal and perpendicular to the strike. Furthermore, at the time of faulting, the least stress might be as small as one half the pressure of the overburden.

From the geologic evidence of faulting, it was concluded that the indigenous regional stress state for these Gulf Coast rocks is triaxial. When a well is drilled into such rocks, a stress distortion in the immediate vicinity of the drillhole is produced. The plane along which a fracture could be induced by the least pressure in the drillhole would be one that bisects the drillhole vertically and is perpendicular to the axis of least principal undisturbed stress. Hence, the fracture causing lost circulation could readily be induced by a mud pressure much less than that of the overburden. Furthermore, such a fracture should be vertical and parallel with the strike of the local normal faults.

The problem with which we were concerned was an essentially negative one: How can hydraulic fracturing be prevented? About 2 years later, a postive use for hydraulic fracturing was introduced by J. B. Clark (1949), an engineer with Stanolind Oil and Gas Company. In his paper, Clark described a method whereby oil wells were intentionally fractured by means of a sand-laden fluid or gel. Upon reduction of the pressure, the fracture was propped open by the sand, allowing the fracture to serve as a conduit for draining oil into the well.

In this paper and in a sequence of subsequent papers by Stanolind engineers, it was argued that these hydraulic fractures in deep oil wells were horizontal and parallel with the bedding planes of the rocks, notwithstanding the fact that, in the same papers, the downhole pressures required to induce fractures were shown to have an average value of only about 0.8 of that of the overburden.

Hydraulic fracturing proved to be one of the more important developments in reservoir engineering, and by 1955 more than 100,000 oil and gas wells had been hydraulically fractured. The notion that the fractures were mostly horizontal came to be an accepted dogma among petroleum engineers, with rarely a dissenting voice.

At this stage, Willis and I were given the assignment by Shell Oil Company of trying to determine whether these fractures were in fact horizontal or whether they might be vertical. The results of that analysis are given in the following paper. We concluded that the fractures should form perpendicular to the prevailing least principal tectonic stress. In relaxed areas such as the Gulf Coast and the Mid-Continent area of the United States, such fractures should be vertical and should be induced by pressures less than the overburden. In tectonically compressed areas, they should be horizontal and should require pressures equal to or greater than that of the overburden.

At the time of the 1957 paper, very little evidence, other than downhole pressure, was available on the fracture orientation. Shortly thereafter, however, unequivocal evidence was revealed; it included the following:

1. Downhole photographs of gas wells, taken over the same interval before and after fracturing, showing vertical fracture traces on

diametrically opposite sides of the hole (Dempsey and Hickey, 1958);

2. Vertical fracture imprints on hydraulically inflated, soft-rubber packers (Fraser and Pettitt, 1962; Anderson and Stahl, 1967);

3. Gamma-ray logs run before and after fracturing of wells in which a radioactive tracer was added to the fracturing fluid, showing fracture intervals extending vertically for tens of feet;

4. Vertical fracturing shown by an acoustical scanning device which is capable of revealing fractures or other details of the wall rock behind the mud-cake lining of oil wells (Zemanek *et al.*, 1969).

The net result of such cumulative evidence is that it now is generally conceded that, in tectonically relaxed regions and at well depths greater than 1,000 ft (300 m), nearly all hydraulic fractures are vertical and stress-oriented. An exception occurs at shallow depths—commonly less than 1,000 ft—where horizontal fractures have been observed in several localities. The reason for this exception is not entirely clear, but it is possible that even small horizontal tectonic stresses at such depths are larger than the also-small pressure of the overburden.

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Discussion

P. Hughes, U.S. Corps of Engineers, Davis, California

You mentioned some of the geopressured zones in the Gulf Coast. What is your feeling about the possibility of subtracting fluid and reinjecting waste liquid in these geopressured zones? They are holding fluids at a very high pressure at the present time.

M. King Hubbert

It can be done, but what are you going to do with the brines that you withdraw? Right now, we're injecting brines—oil-field brines—back into the ground because, what else can we do with them? So if you take the brines out of the ground and put something else in their place, what are you going to do with the brines?

R.-J. Sun, U.S. Geological Survey, Silver Spring, Maryland

I have devoted 6 or 7 years to a study of hydraulic fracturing and have benefited from discussions with Dr. Hubbert. In both New York State and Oak Ridge, Tennessee, hydraulic-fracturing tests have been made, and in each instance we found that some fractures formed parallel with the bedding. Some followed vertical joints, but not very far—about 20 to 30 ft up and down. The rocks into which fluids were injected are marine shales.

The question that I would like to ask of the speaker is this: In his model experiments we see that the fractures formed perpendicular to the least principal compressive stress; but in these experiments the model material was uniform, homogeneous, and isotropic. For inhomogeneous and anisotropic materials, however, such as sedimentary rocks—and especially at shallow depths—should we not consider the tensile stress in the material added to the external stress?

M. King Hubbert

What you say is essentially correct. Donald T. Secor, Jr., a graduate student at Stanford about 10 years ago and now professor of geology at the University of South Carolina, has been doing some unusually important work on the effects of fluid pressures on the stress states in rocks underground. Employing Mohr diagrams, as I have done, in which compressive stresses are taken to be positive, Secor has shown that, in many cases, the increase in the groundwater pressure can cause the Mohr circle representing the effective stress state to migrate to the left on the diagram until the minimum principal stress can actually become negative or tensile.

You are also correct in noting that the behavior of rocks with respect to triaxial stress will be somewhat different if the rock is inhomogeneous and anisotropic—as in the case of sedimentary rock or of schistose rock—from what it would be if the rock were homogeneous and isotropic. This behavior was noted explicitly in the last paragraph of my abstract. If a zone of planar weakness—it may be bedding, jointing, or schistosity—is not too far from perpendicular to the axis of least principal stress, a hydraulic fracture may follow this zone rather than form precisely perpendicular to the least principal compressive stress.

In our oil-field fracturing experience in the Mid-Continent and the Gulf Coast, I know of no report of an earthquake occurring as a result of a fracturing operation. In fact, on one occasion Shell Oil Company planted a ring of highly sensitive seismometers around a well being fractured. No detectable jolt was recorded, which indicates that the shear stress along the fracture must have been zero and that the fracture was perpendicular to the axis of least principal stress. On the other hand, in the basement-rock fracturing in the Rocky Mountain Arsenal well near Denver, the fracturing apparently followed a preexisting NW-SE-striking system of regional joints which were oblique to the axes of principal stress. In this case, the shear stress parallel with the fracture plane was not zero, and the resulting shear displacements along the fractures produced the series of Denver earthquakes.

With regard to homogeneity in the models, in two separate experiments, inhomogeneity was achieved by forming the models with alternating horizontal layers of gelatin with contrasting degrees of stiffness, so as to simulate sedimentary rock. For this material also, the fractures formed perpendicular to the least principal stress, being either vertical or horizontal when the least principal stress was made horizontal or vertical, respectively.

R.-J. Sun

Yes, this behavior occurs because the oil-field fractures are commonly produced at great depths where the induced tensile stress is very small compared with the tectonic stresses. However, in waste disposal, the injections may be at shallow depths of a couple of thousand feet or less, as at Oak Ridge. Then the induced tensile stress compared to the tectonic stress becomes significant.

M. King Hubbert

All of the cases of horizontal fracturing with which I am acquainted have occurred at comparatively shallow depths. The deepest one that I can recall was that reported in the Sacatosa field in southwest Texas, where a horizontal fracture was produced at a depth of 1,438 ft. The fracture was initiated by radial shots in a single horizontal plane.

At Oak Ridge, Tennessee, the Atomic Energy Commission has produced horizontal fractures in highly indurated Paleozoic shale at depths of 700–800 ft. In the Athabasca "oil sands," horizontal fractures at a depth of 100 ft have been reported. It appears that horizontal fracturing at shallow depths may be due to more rapid decrease of the vertical stress than of the horizontal compressive stresses as the depth is decreased.

With regard to induced tensile stress, hydraulic fracturing at any depth becomes possible only when the induced circumferential tensile stress about the well bore becomes equal to, or greater than, the natural compressive stress.