Directional Hydrofracturing: Fact or Fiction

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ABSTRACT

Because it has proven to be both economical and efficient, solution mining has become a major method of extracting subsurface evaporite minerals. As chemical technology improves other economic minerals, especially low-grade ore deposits, should become amenable to solution mining. Hydrofracturing to develop permeability, surface area and connection conduits between wells is a prime factor to the success of the method.

The hydrofracturing of rocks has progressed from an art with unknown and unpredictable results to the present state in which techniques, based upon various hypotheses and model studies, are applied with a reasonable degree of predictable results. Some of the prevailing thoughts on the principles of hydraulic fracture initiation, propagation and connection are discussed.

Two borehole conditions, smooth-wall and notched control how hydraulic fractures will initiate from a well. Fractures emanating from smooth-wall boreholes are controlled predominantly by the state of stress in the surrounding rocks. For notched wellbores, fractures will develop out from the notch especially if the notch is deep and knife-edge. Data is presented to illustrate horizontal fractures can be initiated from a wellbore under controlled conditions.

Hydraulic fractures have been shown to propagate along preferred paths in anisotropic materials. This phenomenon is called "channelization" and results from discontinuities within materials imparting a directional control to fracture propagation. Earth materials are anisotropic and data is presented to prove the existence of channelized hydraulic fractures under natural and artificial situations.

Target wells tend to act as barriers to approaching fractures, with the result a fracture may deflect and bypass a well. Several possible remedial measures are presented to overcome this adverse condition.

INTRODUCTION

Conventional underground mining practices are becoming less feasible every year because of increasing economic and physical limitations. This is especially true for the development of low grade or marginal ores. Near surface ore bodies can be economically mined by open pit methods. Below the practical depth of open pit mining, new mining methods must be sought and developed to make deep ore bodies amenable to economic extraction.

Solution mining has proven to be both an economical and efficient method of mining buried evaporite minerals. This technique of mineral extraction potentially is a completely feasible method of mining non-evaporite deposits. Its application is limited at present by the lack of suitable solvents for all the different ores that occur. A concentrated research effort by chemical engineers could alleviate this problem.

Solution mining has many desirable aspects that enhance its use. It overcomes problems of labor and safety associated with men working underground. The method involves the use of little equipment and is subject to minor maintenance. In addition, solution mining leaves the gangue material in place which eliminates problems of milling and tailings disposal. As a secondary benefit, the cavities created by the solution extractions are potential sites for waste disposal and the storage of liquids and gases.

In order for solution mining to be successful, the solvent must be brought into contact with the ore body and the resulting solute must be recovered. For evaporite deposits, this is accomplished by cross-connecting two or more wells with a horizontally induced hydraulic fracture near the base of the deposit to form a gallery system. By introducing fresh water into the injection well, saturated brine can be pumped from the discharge well. Due to gravity differences in fresh water and brine, the salt bed will thus be dissolved upwards. Non-evaporite deposits may have to be fractured in other ways to obtain maximum ore recovery.

Regardless of how hydrofracturing is used in solution mining, the process accomplishes three things; it creates the necessary permeability to move the solvent, it produces surface area to facilitate solutioning, and it provides conduits to transmit both the solvent and solute to and from the ore body.

Hydraulic fracturing is a process whereby a wellbore is filled with a fluid that is subsequently pressurized by pumps at the surface until a state of stress is achieved at which the rocks surrounding the wellbore fail by an extension (tension) fracture. The horizon selected for fracturing is isolated by casing, packers, or other means.

Hydraulic fracturing is not new. Prior to formal application, its occurrence had been detected during water flooding and squeeze cementing operations in the recovery of petroleum. Rocks have been accidentally fractured during grouting treatments and when high specific gravity muds have been used in drilling deep wells. The phenomenon also applies to the natural processes of dike and sill emplacement of igneous rocks.

Clark (1949) is credited with first suggesting artificially hydrofracturing the rocks around a wellbore as a treatment to stimulate oil wells. The technique was widely accepted and now is a major part of secondary oil recovery. Most hydrofracture literature to date has been written by oil field investigators.

Hydraulic fracturing is relatively new in solution mining. A patent was issued to M.W. Pullen, Jr., in 1958 for cross-connecting salt wells by means of extending a hydrofracture from one well to the other. The process is a boon to the salt industry since one gallery can replace from 10 to 30 single wells.

Hydrofracturing has progressed from a happening by accident to an art, with unpredictable results, to the present state in which techniques, based upon various hypotheses and laboratory experiments, are applied with a reasonable degree of predictable results. In order to increase its scope of application, hydrofracturing should be directionally controlled. Although many workers in this field feel controlled directional hydrofracturing is not possible, much evidence can be presented to show it has been accomplished with moderate success at the present. There is reason to believe techniques will continue to improve as more and more information becomes available. This paper is an attempt by the authors to establish the criteria and to present some of the problems that must be solved to successfully execute controlled directional hydrofracturing.

Any consideration of controlled hydrofracturing must include:

1. the direction or azimuth of the individual fractures,
2. the attitude of the fractures, and
3. the number or density of the fractures.

Hydraulic fractures, especially horizontal ones, generally are visualized and treated as symmetrical-shaped features radiating out from a borehole. However, fractures can commonly develop as asymmetrical tongue and fan-like sheets as we will illustrate. Thus a fracture tends to develop in a specific direction. Hydraulic fractures also can originate and propagate in many orientations ranging from the horizontal to the vertical. Common practice, however, treats them as only vertical or horizontal. "Vertical" fractures apply to all high angle ruptures, whereas, "horizontal" fractures include those that are nearly flat lying. Although not given much attention in the literature up to now, the number of fractures induced from a borehole is an important aspect. Depending on the undertaking, there will be times when only one fracture is needed while in other cases multiple fractures may be required.

Directional hydrofracturing will be treated in three parts; fracture initiation, fracture propagation, and fracture connection.

FRACTURE INITIATION

The problem of controlling hydraulic fractures begins at the borehole. How fractures initiate will strongly influence their subsequent extension and development out from the well. Therefore any plan to control the attitudes, directions and numbers of hydrofractures must begin with their initiation. If hydrofractures are not initiated in the desired orientation and direction, they most certainly cannot be modified and controlled after propagation begins.

Fracture initiation must be considered in two distinct categories: the "smooth-wall" or unaltered borehole, and the notched borehole. Results of field and laboratory studies have not been translatable between the two categories. Unfortunately this division of borehole conditions has not always been recognized and many misleading statements have been made covering all aspects of fracture initiation at a borehole based solely upon the findings of one of the above categories. Much data have been collected on fracture initiation in smooth walled boreholes by the petroleum industry. Information relating to notched holes has come from investigators working in both the salt industry and petroleum industry.

Wells are discontinuities in the earth's crust and cause redistribution of stresses in nearby earth materials. In effect, wells unload adjoining material resulting in strain as the wellbore dilates inward. The amount of strain that occurs is dependent in part upon the amount of elastic strain the material has stored.[1] For homogeneous and isotropic media the resulting stress distributions can be calculated for simple and symmetric loadings (Hubbert & Willis, 1957). Earth materials rarely approach homogeneous and isotropic conditions. Sediments, in which most hydrofracturing is done, are strongly anisotropic.

Regardless of the relative isotropy of a material, stress alterations due to the wellbore die out rapidly away from the borehole. Highest stress concentrations occur in the borehole wall and drop off exponentially away from it so that after a distance of approximately only one hole diameter, the stress field is not much different from the undisturbed state.

Stress concentrations around the borehole due to the hole itself will have the most influence on fracture initiations from smooth-wall boreholes. Most notches will penetrate through the high stress region allowing the fracture to initiate in conditions nearer the undisturbed stress state. In addition, notches create new stress fields around them which further aid in defining the fracture initiation orientation.

Smooth-wall borehold.

Hydraulic fractures initiating from smooth-wall boreholes have orientations that are controlled predominantly by the state of stress in the surrounding rocks. Features and properties of the rocks themselves may play a subordinate role. Thus a fracture will initiate along a bedding plane only if the stress conditions warrant it.

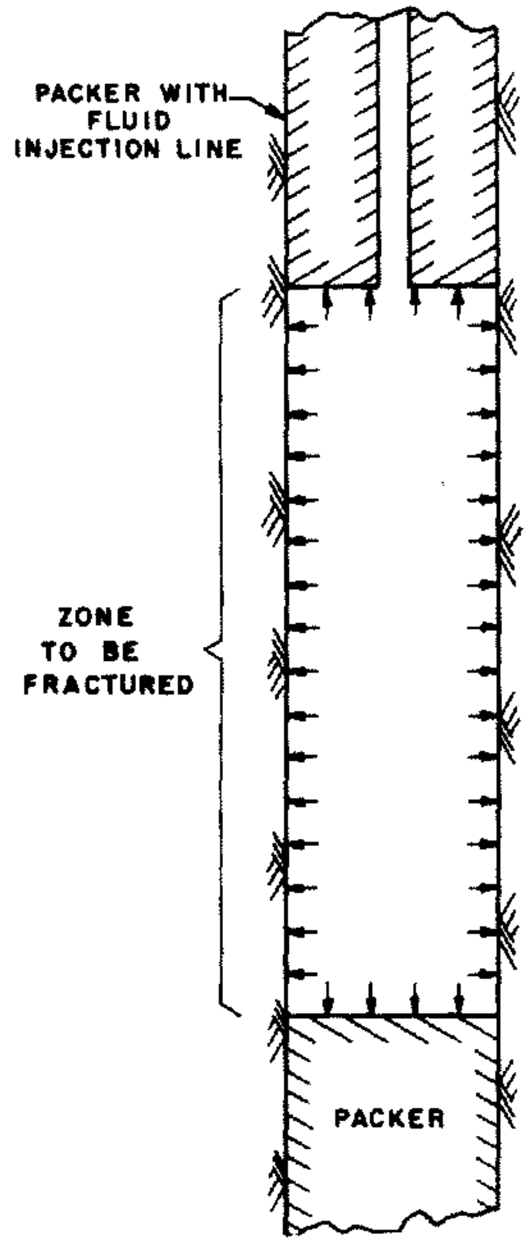

Figure 1. Sketch of a smooth-walled borehole illustrating the stresses in the pressurized zone to be fractured.

1. A material when stressed will undergo two types of strain; plastic (permanent) and elastic (recoverable). Upon removal of the stress, the material will exhibit some rebound as a result of the recovery of the stored elastic strain. The amount of elastic strain a material has developed will depend on the atomic properties of the material and the stress history.

Analogies are made that conditions in the wellbore and surrounding rocks are similar to those of a cylinder in an infinite body (Kehle, 1964) or of a thick-wall cylinder under high pressure from within, (van Poolen, 1957). These simplifying assumptions are amenable to mathematical interpretation from which it can be shown that fractures will initiate with orientations perpendicular to the axis of least stress. Stress concentrations created by the wellbore are assumed to cause only slight deviations from local stress field in most cases. Data from field tests tend to substantiate the theoretical analyses.

For smooth-wall wellbores, the following generalizations can be made about the initiation of hydraulic fractures:

1. Vertical fractures overwhelmingly predominate.
2. If the breakdown pressure is less than the overburden (1 psi per foot of depth is a good approximation), a vertical fracture will form.
3. The greater the depth the less likely a horizontal fracture will form. Some investigators place a maximum depth for possible horizontal fractures (Harrison et al., 1953).

Notched boreholes.

The above generalities of hydraulic fracture initiation from smooth-wall boreholes are *not* applicable to notched wellbores. Notching disrupts the cylindrical shape of the pressurized region by extending a void out from the hole into the rock. Although notches can have an infinite number of sizes and shapes, they all modify a wellbore in several ways.

Smooth-walled holes transmit essentially only horizontal radial (hoop) stresses when pressured-up. The only significant vertical stresses that develop occur at the packing contact or casing seat. Vertical stresses due to borehole irregularities can be considered negligible unless during the drilling program an undue amount of calving and sloughing of the hole occurred. Notching creates surfaces with orientations different from that of the wellbore, with the result, stresses other than the hoop stresses are generated. Thus notches serve to develop stress fields at the wellbore different from those of a smooth-walled cylinder when the fluid is pressured-up.

Also, as noted previously, notching penetrates the high stress region surrounding the borehole and, in addition, redistributes the stress in its immediate vicinity. Being a discontinuity, a notch creates a directional weakness out from the well. Therefore, the fracture will initiate from the notch in most cases.

The most important feature of a notch is its shape. Bulbous, cylindrical or irregular notches will exhibit poor control on the type (horizontal versus vertical) of fracture that originates. They often influence the fracture direction but not necessarily the orientation. Sharp-edged notches will define both the direction and orientation of the nucleating fracture. The importance of knife-edged discontinuities in fracture nucleation is well known in material science (Averbach et al., 1959). Sharp leading edges create strong stress concentrations around and in front of the crack. Elastic deformation of the crack, such as would result from the pressurizing a fluid in a notch, will stretch the bonds of material components until a state of stress is achieved at which the bond strengths and surcharged stresses are overcomed, (The breakdown pressure threshold) and a fracture will nucleate and begin propagating outward. Figure 2 schematically illustrates the process.

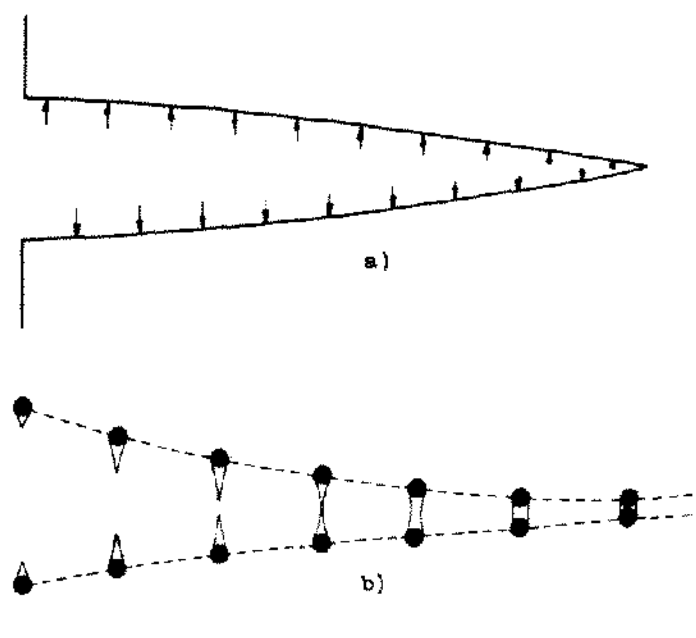

Figure 2. (a) A sharp-edged notch with fluid pressure distribution. (b) The leading edge of an extension fracture showing stretching and rupture of particle bonds as the fracture advances due to the "wedging" action of the fluid.

No real argument exists among investigators that vertical fractures can be initiated in both smooth-wall and notched boreholes. The controversy centers around the ability to induce horizontal fractures regardless of the conditions of the borehole. The fact that horizontal fractures have been produced has been established from field practice. Their existence has been proven time and again in the salt industry. The greatest success of the gallery method in the solution mining of salt depends upon developing a horizontal fracture connection between two wells near the base of the salt bed. A vertical fracture drastically reduces the amount of salt that can be recovered since solutioning takes place at the top of the fluid channel due to density differences in fresh water and brine. In addition, the chances of connecting with the target well are much reduced if a vertical fracture is extended from a borehole as compared to a horizontal fracture.

Proponents who argue that horizontal fractures are rare or even non-existent in deep wells cite the overriding influence of the overburden on the stress conditions. By this reasoning, which appears logical and convincing, a horizontal fracture would have to lift the entire overburden above it in order to originate and propagate. It is further assumed that the vertical stress due to the overburden is usually the maximum principal stress making a vertical fracture the most probable fracture to develop since the stresses, in lateral directions would be less and more easy to overcome.

The principal stresses and their orientation can have a strong effect on the initiation and subsequent extension of hydraulic fractures. It is axiomatic that, a fracture, whether hydraulically or otherwise induced, will tend to orient itself perpendicular to the direction of the minimum principal stress. However, the actual influence of the principal stresses depends upon the stress difference between the maximum and minimum stresses. For small stress differences, the stress conditions approach a "hydrostatic" state (generally referred to as geostatic conditions) in which there is no preferred stress relief direction. In this case, the attitude of the hydraulic fracture is not influenced by the geologic stress conditions but rather by the stress field generated by the fluid at the wellbore. The greater the stress differential, the more the principal stresses bear upon the position of the induced fracture. Laboratory experiments involving hydrostone (a homogeneous and isotropic material) have substantiated this principle (Kabieseman, 1966). With the lack of quantitative field data, no real numbers can be attached to the limiting stress differentials for earth materials. The authors are of the opinion that the general state of stress in areas where most hydrofracturing operations are employed is one in which the stress difference between the maximum and minimum principal stresses is relatively low and in the range where it has little influence especially when considering the effects of notching and anisotropy.

The role of the overburden is a perplexing one. Although the overburden is intimately associated with the principal stresses discussed above, its actual transmission as a vertical stress and the resulting stress distribution at the wellbore has been much disputed. Two arguments can be presented to counter the belief that a horizontal fracture would have to lift the entire overburden.

The first relates to strain itself. Referring once again to material science, stressed bodies can be treated two ways: as deformable solids, or as rigid bodies. Deformable materials well undergo volume and shape change in readjustment to stress whereas rigid bodies will strain by a change of position and/or orientation. In reality all materials will exhibit various combinations of the above strains depending upon the existing conditions. It also has been proven that when a force is applied to a body, the greatest strain takes place at the point or area of contact and decreases rapidly with increasing distance. To claim a thin fracture will have to lift the entire overburden is to infer the constituent earth materials that make up the overburden form an "ideal" rigid body—which is a false assumption. The strain resulting from a hydrofracture thickness especially when nucleated for most fluids[2] is small (several inches or smaller). This magnitude of strain can be absorbed by earth materials within a 10 to 20 foot distance depending upon the material types. Above this level the remaining overburden is unaware of the fracture existence.

As noted earlier, sediments are the rocks in which most hydrofracturing takes place. Sediments are sheet-like deposits of various competency stacked one upon another. Layered sequences of unlike materials transfer stress much differently than homogeneous and isotropic materials. Therefore to state that the vertical stress at a point is equal to the weight of the overburden above it is not correct.

The phenomenon of redistributing stresses with depth in layered sequences of unlike rocks we will

2. The more viscous fluid the thicker the resulting fracture. Cement and other similar slurries may open fractures in excess of a foot.

call *arching*. The concept of arching in rocks is not new (Howard and Fast, 1950), however, its function as proposed in this paper does differ from previous concepts.

Arching has been visualized as massive competent beds acting as beams to carry the load from the overlying materials thereby reducing the stress on the underlying beds. Massive competent beds such as limestones and sandstones can act as beams over finite distances of a few hundred feet. This principle is important to the design of any subsurface opening. Without arching no opening could remain intact without artifical support such as propping agents.

As proposed in this paper, arching also involves the reaction with time between beds of different competency. The result is the disruption of the uniform stress distribution with depth, which is assumed under homogeneous and isotropic conditions, and the creation of regions of both high and low stress concentrations. The mechanics involves the uneven contact among beds such that the competent beds will carry and concentrate loads to areas of high "bearing" with underlying weaker formations. A similar phenomenon, also called arching, is known to occur in soils (Terzaghi and Peck, 1968). The high stress transfer to the weak bed at a localized area will cause this bed to begin readjusting mostly by creep processes to reduce the concentration. The readjustment causes a transfer of load to other areas and the process is repeated. Slickensides and flow structures in non-metamorphosed shales testify to this action. The phenomenon is time dependent with the result the stress distribution is constantly changing. Model experiments with photoelastic materials have visually demonstrated this action (personal communication, Scott, 1969). The interaction of a concrete pavement with its base course is an analogous action.

The greatest importance of arching is its influence on the breakdown pressure. Much emphasis has been placed upon whether fracture nucleation occurs above or below the "overburden" pressure which can be approximated at 1 psi per foot of depth. Although this pressure gradient has value in estimating the approximate pressure to expect at fracture initiation, it cannot be used as the absolute criteria for the true state of stress because first it is just an approximation of the average unit weights and, secondly, arching can significantly alter the stress distribution. In the same well field, at the same horizon, breakdown pressures can vary significantly. On occasions, breakdown pressures have varied above and below the 1 psi per foot of depth in the same well field.

FRACTURE PROPAGATION

After a hydraulic fracture has been initiated and begins to propagate out from a wellbore, less and less control can be exercised on its pattern of development. However, if the factors that influence the mode of fracture extension are known, wells developed by hydrofracting can be designed to take advantage of any directional features. Therefore the value of a preliminary geologic and rock mechanic study cannot be overemphasized. Unfortunately too many laboratory investigators fail to appreciate the role of the in-situ geologic environment. It is a credit to the authors in the two previous Salt Symposia, that geology was one of the prime factors considered. (Jacoby, 1963, 1966; Pegler, 1966; Henderson, 1963).

In discussing fracture propagation, horizontal fractures will be used as the model. However, the factors and concepts discussed apply equally to vertical fractures.

Concept of channelization.

Fractures emanating from a borehole often are visualized as extending radially equally in all directions in a symmetric fashion so that the fracture front traces a circle at any time period, Figure 3.

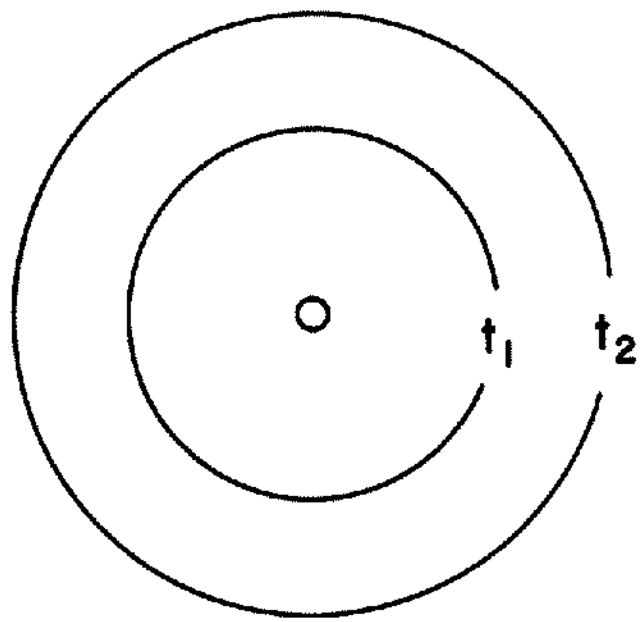

Figure 3. Assumed propagation out from a borehole of a hydraulic fracture in a homogeneous and isotropic material. t_1 and t_2 are traces of the leading edge of the crack at different time intervals.

This assumed shape of hydraulic fracture extension has its foundation on ideal theoretical analyses of homogeneous and isotropic material. However, laboratory experiments with homogeneous and isotropic materials do not completely conform to the theoretic models. Figure 4 illustrates a typical hydraulic fracture pattern from a controlled laboratory test.

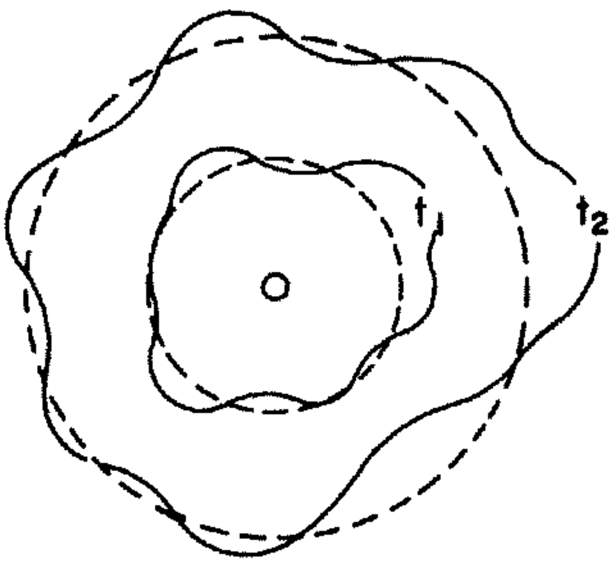

Figure 4. A typical hydraulic fracture pattern out from a borehole in a homogeneous and isotropic material. The dashed line indicates the ideal fracture growth.

A circular-type of fracture growth from a well is rare. The reason is simple: energy in any form (which includes hydraulic fracturing) will follow paths of least resistance. Because earth materials are anisotropic, energies propagating through them will be *channelized* as their movements are impeded in some directions and are relatively unhindered in other directions.

Since channelization is the most efficient way of transferring energy through anisotropic materials, we can find many examples of its use in nature and by man. One of the most obvious is the movement of water on the land surface after a rain. When the water droplets first reach the ground, they begin to move downslope in parallel paths. However, small surface irregularities and unequal slope changes (anisotropy) will deflect the droplets and cause them to converge to form small rills of water which will intersect with other rills to form larger and larger streams. Therefore streams are the channelization of surface water flow.

Extension fractures, which include hydraulic fractures, do not occur simultaneously over an entire surface. Instead failure begins at one or more nuclei. Features of the rupture surface give evidence of the failure mechanism. Natural and artificial extension fractures exhibit *plumose* or *feather* structures on their surfaces, (Gramberg, 1965; Hodgson, 1961). These structures testify to the fact that extension fractures develop along channels (Fig. 5).

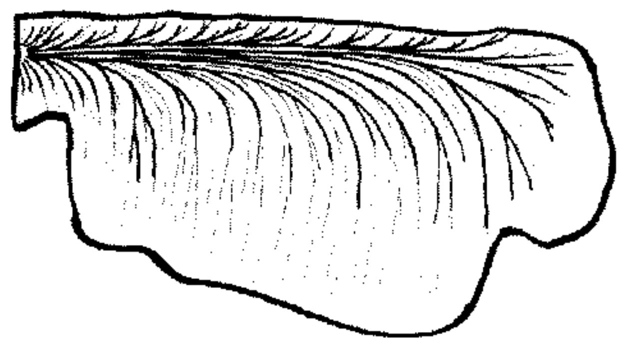

Figure 5. Plumose structures on the surface of a rock fractured in tension. The extension fracture initiated on the left and channelized to the right. (Sketched from an actual specimen).

A number of case histories can be cited to prove the existence of channelization of hydrofractures. However, much of the data is privileged information and is not available for publication. In several instances, fractures have missed target wells 300 feet away and connected with wells in excess of 1000 feet distance. In other instances two wells have not been frac connected in one direction while similar spaced wells in the same well field were rapidly connected in another direction.

A simple channelized propagation path of a hydrofracture at two different time intervals might be similar to that in Figure 6, which could explain

Figure 6. Propagation pattern of a simple channelized hydraulic fracture.

the situation shown in Figure 7. A more complex channel path due to changes in anisotropy is illustrated in Figure 8. Since no two hydrofracture extensions seem to be the same, an infinite number of channel patterns can form.

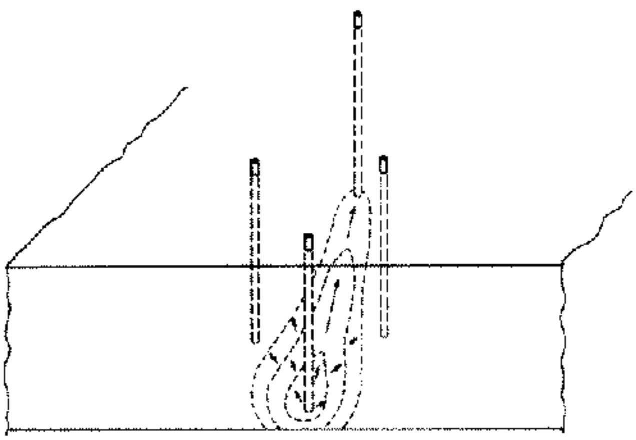

Figure 7. Example of how a channelized hydraulic fracture could miss two nearby target wells and connect with a distant well.

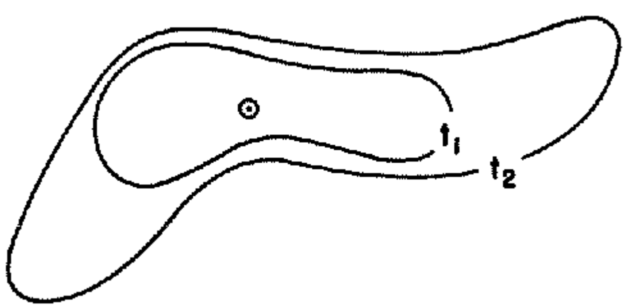

Figure 8. Possible fracture propagation pattern in a variable anisotropic material.

Channelization of fluid fractures *in nature* can be documented. as Ode (1956), and Hubbert and Willis (1957), have pointed out, dikes are emplaced by hydraulic fracturing processes and in the example they cite, at Spanish Peaks, Colorado, the dikes are strongly channelized to the east. What they failed to note, sills and laccoliths also are produced by hydraulic fracturing. A classic example of channelized sills and laccoliths is the Henry Mountain complex in Utah. Figure 9 illustrates the strong channelization of the laccoliths in the northeast-southwest direction and the lesser control in the east-west direction.

The state of stress and discontinuities are the two factors that control the channelizing of fractures. We have discussed the role of the stress field earlier under fracture initiation and will elaborate

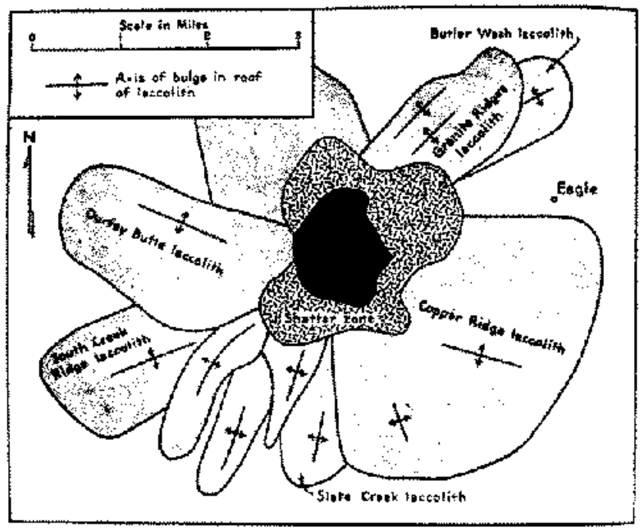

Figure 9. An example of channelized sills and laccoliths feeding off of a control stock, Henry Mountains, Utah. Note strong trend to the NE and SW. (After Hunt, et al., 1952)

later more on its influence to fracture propagation. Before this, we must gain some appreciation of the causes of anisotropy.

Discontinuities.

All properties and features that give a directional control to materials can be considered as *discontinuities.* Scale is important since discontinuities occur in many forms and will have varying degrees of influence on energy transmission. Thus microscopic discontinuities individually may have little effect but when considered in mass as an infinite number, they exhibit significant directional control. The most ideal homogeneous and isotropic material man can fabricate will have flaws and defects (discontinuities) and will exhibit some modification from the theoretical model Figure 4. Large discontinuities can act as barriers which will deflect the propagating energy in new directions (Fig. 10).

What constitutes natural discontinuities for hydraulic fracturing? Bedding planes, joints, seams, voids, faults, folds, and unconformities, are ready examples. Any mineralogic or textural changes, whether abrupt of transitional, also must be treated as discontinuities. Changes in the character of sediments in the lateral direction (facies changes) can have a marked effect on a propagating fracture.

The stronger the discontinuity, the more work a hydraulic fracture must perform to penetrate it. Thus if another direction affords an easier path, the fracture may deflect (Fig. 11). The new propagation path can be either in the horizontal and/or

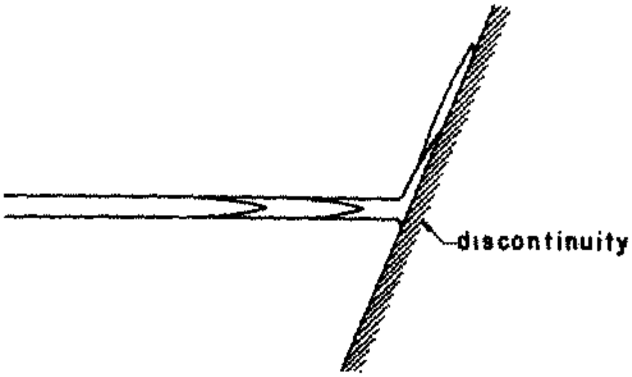

Figure 10. A schematic example of how a strong discontinuity can deflect a propagating fracture.

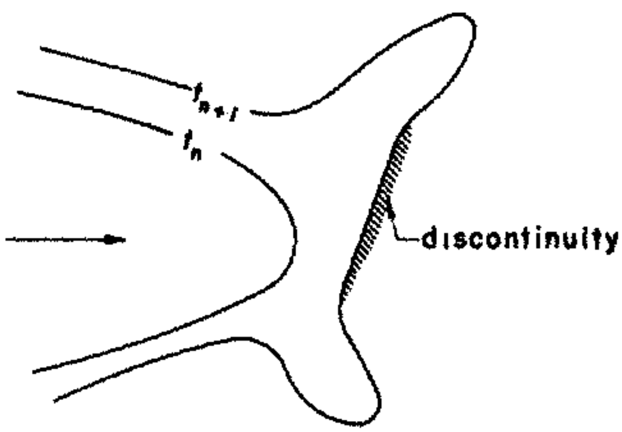

Figure 11. An example of how a localized discontinuity can deflect a propagating fracture.

vertical (Fig. 12). The new propagation path may also have a different orientation.

Discontinuities versus the stress field.

As stated earlier, how hydraulic fractures propagate will depend upon the combined effects of discontinuities and the magnitude and orientation of the stress field. Any evaluation that takes only one into account is incomplete. In some cases the stress field may dominate, in other cases the discontinuities may control, whereas, at other times the two may have almost equal influence. It is important to establish their relative importance in each case if any rational hydrofracture program is to be achieved.

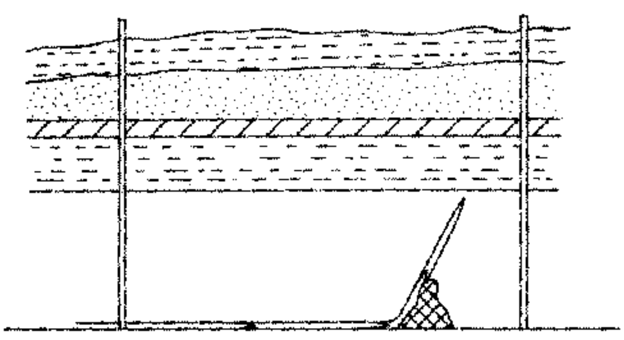

Figure 12. An example of how a bottom initiated hydraulic fracture can be deflected to different horizons.

The literature contains numerous articles relating to laboratory investigations of hydraulic fracturing. Several investigators have used their results to "prove" that discontinuities have no appreciable effect on the direction of fracture extension (Lamont and Jessen, 1963; Haimson and Stahl, 1969). Laboratory experiments are valuable tools for unraveling the mechanics of earth materials. However, they also seem to be used to prove almost anything one *wants* proved. Results of laboratory experiments are controlled by the boundary conditions imposed upon them. Any translation of laboratory data to the field must be done with the full assessment of the boundary conditions in each case. If a test specimen is confined between steel vices in one or more directions, an induced hydraulic fracture will form and propagate in only one plane regardless of the anisotropy of the material. The overriding confining conditions in this case will completely dominate the experiment. Care also must be taken not to overemphasize joints, bedding planes and other anisotropy. In other words, a cross joint may or may not deviate a propagating fracture depending upon the state of stress that exists. *A hydrofracture will propagate in directions of least work.* The amount of energy expended to overcome the formation resistance will dictate the preferred direction a fracture will take.

FRACTURE CONNECTION

Less is known about this aspect of hydraulic fracturing than any other part. However, some generalities and inferences can be made based upon field information and pilot laboratory studies.

As was stated previously wells are discontinuities. Their introduction into the subsurface causes a redistribution of stresses around the borehole. The change of stress conditions creates high stress concentrations, with the net result, the target well acts as a source rather than a sink to the approaching fracture wave. Sources and sinks are mathematical entities used to describe the relative ease of energy flow to and from point sources. Energy will flow from a source and to a sink. The pressurized well from which the hydrofracture originates is a source. Ideally the target well should act like a sink so that the propagating fracture will want to intersect it. With the high stress concentrations around it, most target wells act like a minor source.

Several lines of evidence indicate the validity of the target well acting like a minor source, thereby, deflecting the propagating fracture around it. The approaching hydrofracture may cause a pressure increase (shut-in) or slight flow (open valve) at the target well. The dissipation of either indicates the fracture has bypassed the well. Some indication of how close the fracture came to the target well can be obtained from the amount of time it takes to back fracture connect from the original target well. Cases in which communication occurred in a matter of minutes are known. Such evidence indicates the original fracture must have advanced close to the target well and may have in some cases, wrapped around the borehole.

Pilot studies in the laboratory also indicate a wellbore may deflect a hydraulic fracture around it. Figures 13 and 14 give the impression the propagating fracture was inhibited from connecting with the second hole in the "isotropic" lucite matrix.

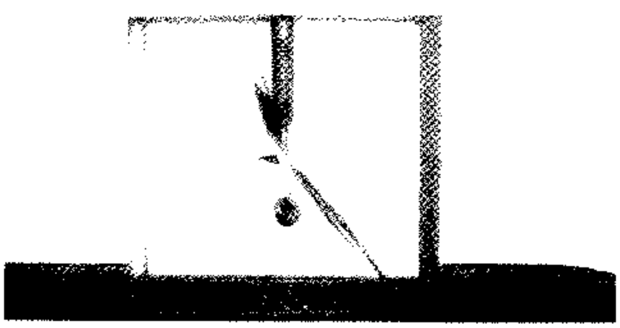

Figure 13. Model studies illustrating how a hydraulic fracture apparently is deflected around a borehole.

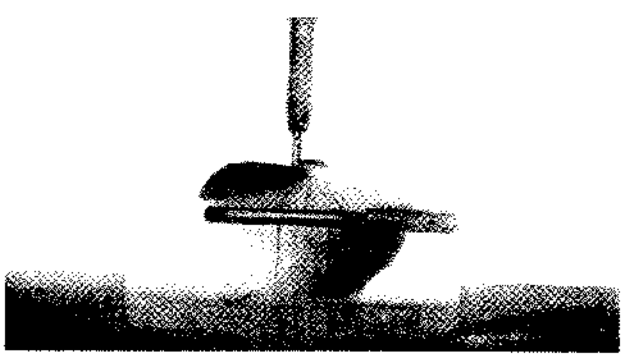

Figure 14. Model studies illustrating how a hydraulic fracture apparently is deflected around a borehole.

Assuming the stress concentrations around the target well act as a barrier to the approaching fracture, what remedies are available to overcome this effect? Several techniques have promise. It might be good practice to always prefracture the target well before attempting a hydrofracture connection. Back fracturing has proven to be successful in a high percentage of cases where a fracture connection was not successful in the original direction. Some investigators have successfully employed the technique of pressuring up and fracturing both wells at the same time until communication is obtained, (Bays et al., 1960). Much of the stress concentrations might be alleviated, if the target well is pressured up and held during the fracture operation at a pressure less than the breakdown pressure.

SUMMARY

Induced hydraulic fractures have a directional pattern. To produce controlled directional fracture patterns, one must understand and approach the problem from three aspects; the initiation, the propagation and the connection.

If hydraulic fractures with the desired azimuth and orientation cannot be initiated at the borehole, controlled directional hydraulic fracturing is unattainable. Directional hydrofractures cannot be nucleated from a smoothwalled borehole. A knife-edge, deep notch is needed to initiate and guide the fracture in the correct direction and orientation. Contrary to some opinions, horizontal fractures can be induced at great depths if the hole is properly notched. The entire overburden does *not* have to be lifted by the fracture since earth materials are capable of absorbing elastic strain in the vicinity of a fracture. The redistribution of stresses by arching of roof strata will dictate the pressure at which fracture will occur.

Hydraulic fractures tend to propagate in unsymmetrical, channel-like or fan-like patterns. Channelization is the result of the propagating fracture seeking a path of least resistance. A combination of the discontinuities and the state of stress within earth materials will dictate in what azimuth and in what form a fracture will channelize. Discontinuities are various properties and features, such as bedding, joints and textural changes, that give earth materials a direction control or anisotropy. The state of stress mostly relates to the stress difference between the maximum and minimum principal stresses and to their direction as produced by past geologic events.

A directional hydrofracture is successful only when it connects with a target well. Several lines of evidence point to the fact that a propagating fracture may deviate its path and bypass the target well due to the high stress concentrations existing around the borehole. This problem might possibly be overcome by back fracturing at the target well either before, during, or after the fracture attempt.

Although unsolved problems are many, controlled directional hydrofracturing may be possible with good geologic studies and appropriate fracturing techniques.

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