INFLUENCE OF NATURAL FRACTURES AND IN SITU STRESSES ON PROPPANT-FREE HYDRAULIC STIMULATION OF HOT DRY ROCK RESERVOIRS

S.P. NARAYAN[1], Z. JING[2], Z. YANG[1] & S. S. RAHMAN[1]

[1]School of Petroleum Engineering, University of New South Wales, Sydney 2052, Australia
[2]Research Institute of Fracture Technology, Tohoku University, Japan

SUMMARY - The geometry and size of reservoirs stimulated by proppant-free hydraulic fracturing are controlled by presence of natural fractures and in situ stresses. This is due to the two fundamental requirements of proppant-free hydraulic stimulation: presence of natural fiactures and sufficiently large shear stress required to extend natural fractures. Results from numerical modeling study show that proppant-free stimulation is not simply controlled by either natural fractures or in situ stresses, but rather it is the interaction of both factors. In a normal or strike-slip stress regime, vertical to sub-vertical fractures can be stimulated with less effort when the maximum horizontal in situ stress is parallel to the average direction of natural fractures, with the resulting reservoir being strongly elongated in the common direction. In a reverse fault stress regime, on the other hand, sub-horizontal fractures can be stimulated with low stimulation pressure which result in a horizontally dominant reservoir. When multiple sets of natural fractures exist, it is likely that stimulated reservoirs will preferentially develop in the direction of maximum horizontal stress. It is also found that a high deviatoric stress helps develop a large volume of stimulated reservoir.

1. INTRODUCTION

Hydraulic fracturing has been the principal technology utilised for creating Hot Dry Rock (HDR) geothermal reservoirs in crystalline granites. Unlike conventional hydraulic fracturing of gas wells, no or low proppant is required to keep the fracture faces open during hydraulic stimulation of HDR reservoir. As such, it is called proppant-free hydraulic fracturing. Recently, hydraulic fracture treatments with low or no proppant have also been carried out in the petroleum industry (Mayerhofer et al., 1997; Meehan, 1992).

The mechanism for permeability enhancement of proppant-free stimulation is generally believed to be shear dilation of existing natural fractures (Jupe et al., 1993; Willis-Richards et al., 1995). Complex reservoir geometry and volume created by interaction between natural fractures and in situ stresses have been studied by microseismic observations at all HDR sites. For example, at the Hijiori site, Japan, seismic clouds observed at shallow and deep reservoirs have been found to have elliptical geometry trending approximately along the EW direction, similar to that of the maximum horizontal stress (Tezuka, 1997). However, at the Ogachi site, Japan, two reservoirs created at different depths produced contrary results. The shallow reservoir at this site observed by Acoustic Emission (AE) monitoring extended toward the NNE direction. However, the deeper reservoir, stimulated in the same way as the shallow one, was found to develop in the E-W direction. This behaviour is not well understood, (Nakatsuka, 1997). At Fenton Hill, USA, the horizontal elongation of the reservoir is approximately 45^0 with respect to the direction of the minimum horizontal stress, as opposed to the expected 90^0. As such, it appears that the direction of HDR reservoir development is more influenced by the fracture network present in the basement than the orientation of maximum principal stress (Brown, 1997). Furthermore, at the Soultz HDR site, France, hydraulic stimulation resulted in a complicated and irregularly shaped reservoir (Gerard, 1997).

Researchers in the petroleum industry, based on a number of similar proppant-free treatments in sandstones, have also recognised the complexity of fracture geometry associated with proppant-free stimulation. It was reported that there may indeed be a “zone of fractures” instead of one major fracture as depicted in most conventional hydraulic fracture design models (Walker et al., 1998; Mayerhofer et al., 1997). Likewise, Warpinski and Teufel (1987) concluded that geologic discontinuities, such as joints, faults and bedding planes, significantly affect the overall geometry of hydraulic fractures.

Although it is now generally believed that the geometry of a stimulated reservoir through proppant-free hydraulic fracturing is governed by natural fractures and in situ stresses (Willis-Richards, et al., 1995), it is very difficult, if not impossible, to predict the geometry of a reservoir stimulated through proppant-free hydraulic stimulation, due to the lack of quantitative studies. For the same reason, the design methodology of proppant-free hydraulic fracturing has not been available to both HDR research and the petroleum industry. Field scale experimental studies of the behaviour of proppant-free hydraulic fracturing are expensive and out of the question at present.

The objective of this paper is to investigate the influence of natural fractures and in situ stresses on reservoir creation processes using numerical modelling. It is hoped that studies like this will provide a theoretical basis for practical design of proppant-free hydraulic fracture treatments for both HDR reservoir creation and petroleum reservoir stimulation.

2. NUMERICAL MODELING OF PROPPANT-FREE HYDRAULIC STIMULATION

As mentioned earlier, proppant-free hydraulic fracturing relies on shear displacement and associated dilation of natural fractures for permeability enhancement. Commercially available hydraulic fracture models in the petroleum industry are clearly inadequate to analyse proppant-free stimulation, since these models are based on the assumption that fractures propagate by opening mode (mode I) of fracture mechanics, and the effect of existing fractures is neglected. In this paper a 3D hydraulic fracturing model, FRACSIM3D (Jing, 1998; Willis-Richards et al., 1996) was used, which takes account of random nature of natural fracture distribution. The random nature of natural fractures is modeled by using a stochastic approach where fracture centres are randomly distributed and fracture radii follow fractal distribution. Similarly, other attributes of fractures such as attitude (azimuth and dipping angle) and density, are also described by probability functions.

Stimulation of individual fi-actures is approximated with linear elastic mechanics. Shear displacement is proportional to excess shear stress (it is the stress in excess of the minimum required shear stress to cause shear slippage) according to the Mob-Coulomb criterion. Dilation of a stimulated fracture is the product of shear displacement and tangent of shear dilation angle which represents fracture roughness. It should be noted that the model does not solve for global elasticity equations. Instead it approximates local fracture shear and opening compliance (Willis-Richards et al., 1996).

3. MODELLING RESULTS

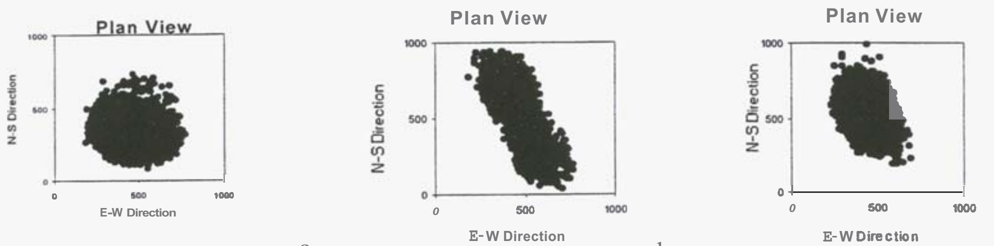
The geometrical model used in this study is a cube of 1000m x 1000m x 1000m. A stimulation well is located at the centre of the model. Rock mechanical properties input in the model are listed in Table 1. The modelling methodology is to investigate variation in geometry (size and shape) of a stimulated reservoir caused by changes in characters of fractures, in situ stresses and stimulation pressure. The modelling results are presented below.

Table 1. Input data used for simulation

Rock Properties		
Young's modulus (GPa)	32	
Poisson's ratio	0.20	
Density (kg/m^3)	2700	
Basic friction angle (deg)	40	
Permeability (m^2)	6x10^{-17}	
Fracture Sets	Dip	Azimuth
Set No. 1	50^0	200^0
Set No. 2	80^0	250'
Fracture density (m^2/m^3)	0.5	
Fractal dimension	2.1	

3.1 Direction of Natural Fractures Relative to In situ Stresses

In as much as proppant-free stimulation relies on shear displacement of existing natural fractures, the direction of natural fractures relative to principal in situ stresses is expected to play a key role in determining reservoir shape and volume. Figure 1 shows plan view of a stimulated reservoir in a normal stress regime where vertical stress *(S,)* is 39MPa, maximum horizontal stress (S_H) 32MPa and minimum horizontal stress (S_h) 21MPa respectively. Two sets of fractures of equal proportion were used: 1. strike N110^{0}E, dip 50^0 SW (50%); and 2. strike N160^{0}E, dip 80 **SW** (50%). The stimulation pressure used in this study was 8MPa, with the original static fluid pressure being 13MPa.



a b c

Fig. **1:** Plan view of stimulated reservoir with two sets of natural fractures in a normal faulting stress regime (Sv=39MPa, SH=32MPa, Sh=21MPa), Stimulation pressure=8MPa: a. SH azimuth = N90^{0}E; b. SH azimuth = N135^{0}E; c. SH azimuth = **N180^{0}E**.

It is clear from the figure that the geometries **of** the stimulated reservoir change significantly with orientations of S_H (90^0, 135' and 180'). When S_H orients at N90^0E, the reservoir is roughly equally stimulated in all directions (Fig. la). In the case of S_H bearing of **NS** direction (N180^0E), the reservoir is slightly elongated in **NNW-SSE** direction (Fig. lb). When S_H orients at 135^0, which is the average direction of the natural fractures, the reservoir develops strongly in the **NW-SE** direction (Fig. 1c).

The maximum reservoir volume can be obtained for the two sets of fiactures studied above under strike-slip stress regime (S_H=57MPa, S_v=39MPa, S_h=32MPa), when the average fracture strike **(NW-SE)** and maximum horizontal stress coincide. This is indicated by a much larger seismic cloud in Figs. **2d-f** (S_H in **NW-SE** direction) than those presented in Figs. 2a-c (S_H in E-W direction).

The dependence of stimulation on relative direction of natural fractures and maximum horizontal stress is not so clear in case of reverse fault stress regime (Fig. 3). This observation is discussed further in the following sections.

3.2 Dip Angle of Fractures

Upon comparison between Figs. 1 and 3, one notices a much smaller volume of the stimulated reservoir for the reverse fault stress regime than that for the normal stress regime. One reason is that the dipping angles of the two sets of natural fractures used in this study are sub-vertical (50' and 80') which according to the Mohr-Coloumb criterion, are unfavourable for a reverse fault stress regime as far as shear displacement is concerned. To investigate the effect of dipping angle of fractures on stimulation pressure, the dipping angles are changed to 20' and 40' respectively. Comparing Figs. 4a-c and 4d-f it **is** evident that the stimulated reservoir is much larger for sub-horizontal fractures (Figs. 4d-f) than that for sub-vertical fkactures. It is also apparent that the created reservoir **is** sub-horizontal instead of sub-vertical (Figs. 4e-f).

A corollary of the above results is that for normal or strike-slip stress regimes, sub-vertical fractures are preferable over sub-horizontal fractures, which requires **low** injection pressure to create shear slippage.

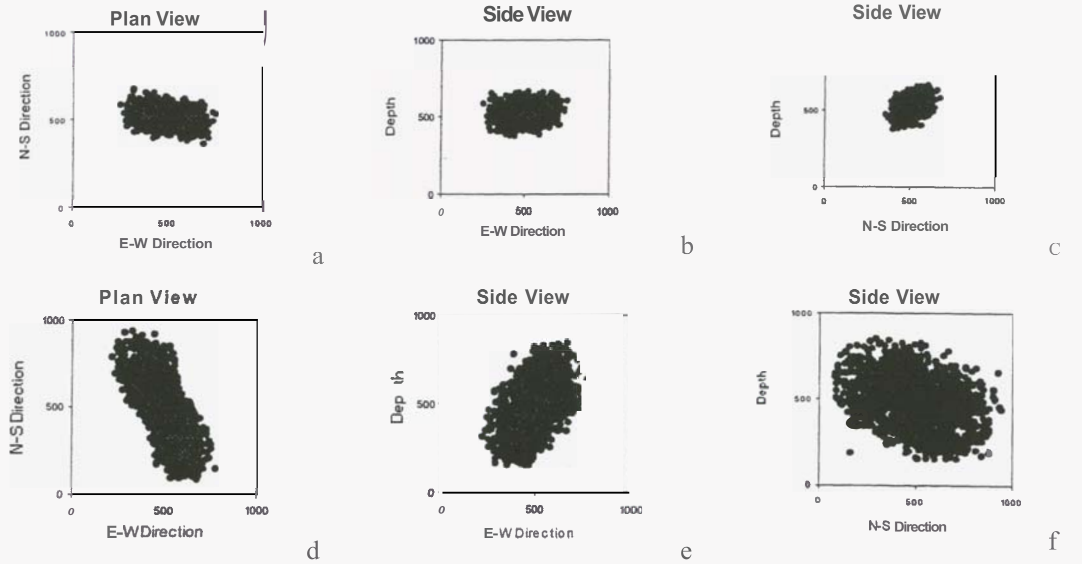


Fig. 2: Stimulated reservoirs with **two sets of natural fractures in strike-slip faulting stress regime** (Sv=39MPa, SH=57MPa, Sh=32MPa), **Stimulation** pressure=18MPa: **a, b and c: SH azimuth** = N90^0E; **d, e and f: SH azimuth** = N135^0E.

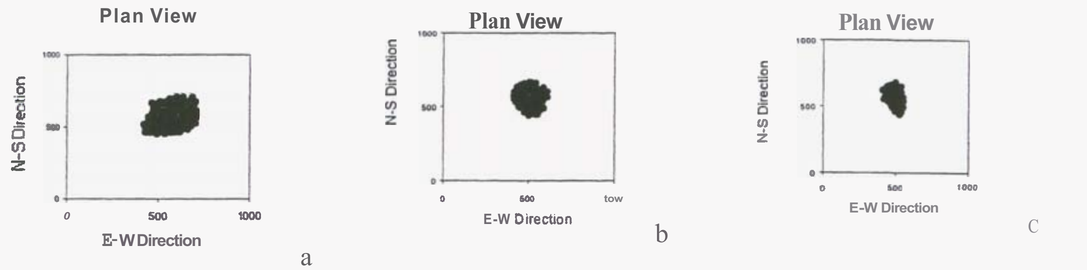


Fig. 3: Plan view of stimulated reservoir in a reverse faulting stress regime (Sv=39MPa, SH=37MPa, Sh=46MPa) and two sets of natural fractures, Stimulation pressure=26MPa: **a** SH azimuth = N90^0E; **b. SH azimuth** = N135^0E; **c. SH azimuth** = N180^0E.

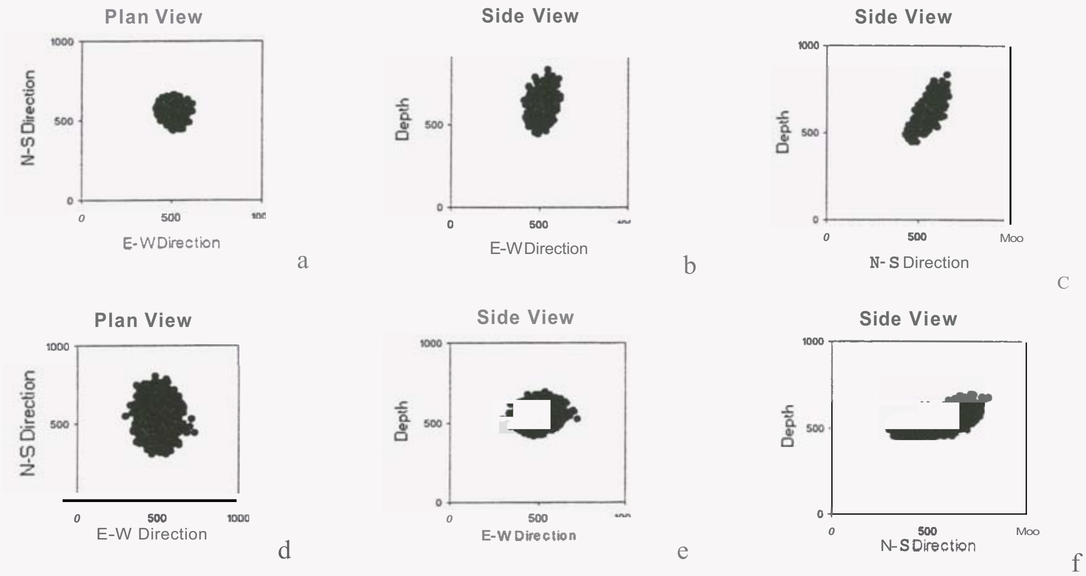


Fig. 4: Stimulated reservoirs in a reverse faulting stress regime with **two sets of natural fractures, Stimulation pressure=26MPa: a, b and c: fracturing dipping angles 50 and 80'; d, e and f: fracture dipping angles 20 and 40^0.**

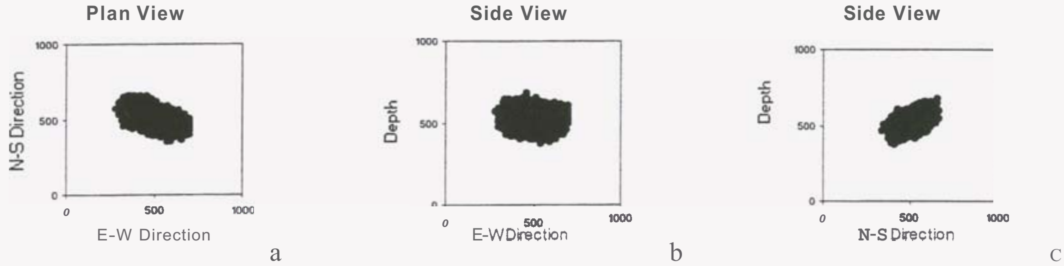


Fig. 5: Reservoir geometry in a strike-slip faulting stress regime (Sv=39MPa, SH=57MPa, Sh=32MPa, SH azimuth=N135^{0}E) with **one set of fractures (strike N110^{0}E, dip 50^0 SW), Stimulation pressure=18MPa.**

3.3 Number of Fracture Sets

For all cases presented earlier, two sets of fractures with different orientations were used. The reasons for selecting the above two fracture sets are that maximum horizontal stress will rarely have the same orientation as the dominant fracture set, and that multiple sets of fracture increases the chance of maximum horizontal stress being closely aligned with at least one set of fractures.

It has been found that high injection pressure is required to stimulate the reservoir with one set of fractures (strike N110^{0}E) in all stress regimes. For example, when the azimuth of maximum horizontal stress is N135^{0}E, the stimulated reservoir volume (Fig. 5) is much smaller than that of two sets of fractures (Figs. 2d-f). When the azimuth of maximum horizontal stress is N180^{0}E, the reservoir cannot be stimulated without a substantial increase in stimulation pressure. The implication of the modelling results is that multiple sets of fractures are beneficial to proppant-free fracturing.

3.4 Stress Regime

The stress regime affects proppant-free hydraulic fracture stimulation because different stress regimes lead to different spatial relations between fractures and maximum principal stress for a given set of fractures. As discussed earlier, a much larger stimulated reservoir volume is created for normal or strike-slip stress regime than for reverse fault stress regime (Figs. 1a-b, 2a, d versus Figs. 3a-b), despite similar effective stimulation pressures and deviatoric stresses. The main reason for smaller reservoir volume in a reverse fault stress regime is that the two fracture sets considered are sub-vertical which is difficult to shear.

The importance of the orientation between maximum horizontal principal stress and fractures in reverse fault stress regime is further demonstrated in Fig. 4, where the stimulated reservoir has been enlarged significantly, simply because of presence of horizontal fractures (Figs. 4d-f). This indicates that in reverse fault stress regime sub-horizontal fractures are preferentially stimulated, whereas steep fractures are more favourable for stimulation in normal or strike slip fault regimes.

3.5 Deviatoric Stress

Deviatoric stress is probably the most important factor in determining the reservoir size. Figure 6 compares the geometry of the stimulated reservoir in a normal stress regime with different deviatoric stresses: (S_v-S_h) 8MPa (Figs. 6a-c) and 18 MPa (Figs. 6d-f). It is obvious that the stronger a deviatoric stress, the larger the stimulated reservoir in size.

4. DISCUSSION

Modeling results from the limited number of case studies presented earlier show that attitude of fractures, stress regime and deviatoric stress have profound effects on proppant-free stimulation of a reservoir (size and geometry) to various degrees. However, horizontal elongation of the stimulated reservoir does not always follow the strike of natural fractures, nor does it necessarily follow the direction of maximum horizontal stress.

The complicated relationships between reservoir geometry, natural fractures and in situ stresses can be understood from two fundamental requirements of proppant-free stimulation (shear dilation): sufficient shear stresses and existence of natural fractures. The two requirements are met when the maximum horizontal stress aligns in the average direction of steep fractures in normal or strike slip stress regime or when the minimum horizontal stress is parallel to the strike of sub-horizontal fractures in a reverse fault stress regime. If multiple sets of natural fi-actures exist, it is more likely that two conditions will be satisfied. In this case, the stimulated reservoir will probably follow the direction of maximum horizontal principal stress. In all other cases, where the dominant fiacture sets and maximum horizontal principal stress differ significantly in direction, the stimulated reservoir aligns with neither the natural fractures nor maximum horizontal principal stress.

5. CONCLUSION

The following conclusions can be drawn based on the modelling results:

1. Both natural fractures and in situ stresses affect geometry and size of stimulated reservoirs due to shear nature of proppant-free stimulation which requires both sufficient shear stress and existence of pre-existing (natural) fractures.
2. In a normal or strike-slip fault stress regime, most effective stimulation is achieved and the stimulated reservoir strongly preferentially develops in a common direction when maximum horizontal stress lies in the average direction of natural fractures.
3. In a reverse faulting stress regime, effective stimulation can only be achieved when natural fractures have a gentle dip, which creates a horizontally dominant reservoir.
4. When multiple sets of natural fiacture exist in a normal or strike-slip fault stress regime, it is likely that those fractures which align closely with maximum horizontal stress will be stimulated and consequently the overall reservoir geometry will probably elongate along maximum horizontal stress.
5. When natural fractures and in situ stresses do not align in most favourable directions, the volume of a stimulated reservoir will be small, and in the case of normal or strike-slip stress regime, the reservoir will develop in a direction which is a compromise between the directions of fractures and maximum horizontal stress.
6. The size of stimulated reservoirs is strongly dependent on deviatoric stresses. A large deviatoric stress leads to strong stimulation and large reservoir volume.

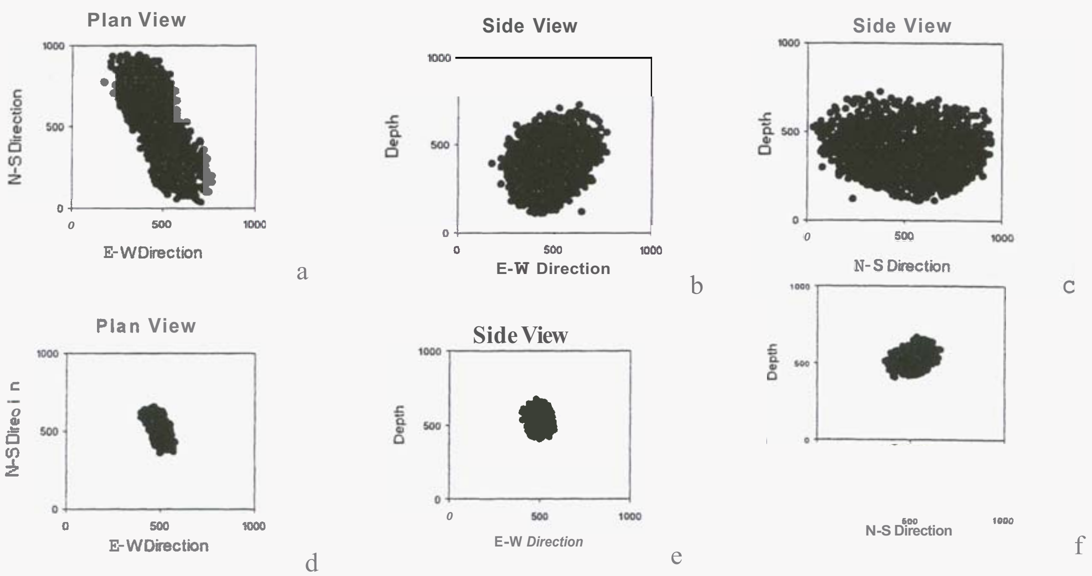


Fig. 6: Reservoir geometry in three orthogonal sections in a normal faulting stress regime (SH azimuth=N135E) and two sets of fractures: a, b and c: (Sv=39MPa, SH=32MPa, Sh=20Mpa), Stimulation pressure=8MPa; d, e and f: (Sv=39MPa, SH=32MPa, Sh=30MPa), Stimulation pressure=17MPa.

6. ACKNOWLEDGEMENT

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