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Continuation of a Deep Borehole Stress Measurement Profile Near the San Andreas Fault

1. Hydraulic Fracturing Stress Measurements at Hi Vista, Mojave Desert, California

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Hydraulic fracturing stress measurements were made in a 592-m-deep well at Hi Vista, California, 32 km from the San Andreas fault in the western Mojave Desert. The relative magnitudes of the horizontal principal stresses and the calculated overburden stress indicate that the stress regime at this site is transitional between thrust faulting and strike-slip faulting. The azimuths of the induced hydraulic fractures at Hi Vista exhibit considerable scatter, and the indicated direction of the maximum horizontal principal stress ranges from north-northeast to northwest. The measured magnitudes of the horizontal principal stresses and the horizontal deviatoric stress in this well are less than or equal to those measured in a nearby well of comparable depth 4 km from the San Andreas fault. This result contrasts with the increase in these stress components with distance from the San Andreas fault that was observed in a shallower borehole profile in the same area. Marked fluctuations in both stress magnitudes and orientations with depth in the Hi Vista well, however, may result from a localized perturbation to the regional stress regime. No correlation was found to exist in this well between stress magnitudes and either *P* wave velocities or natural fracture densities, although the low stresses measured at a depth of about 540 m may reflect proximity to an intensely fractured and permeable zone at the bottom of the well.

INTRODUCTION

Resolution of the debate concerning the magnitude of shear stress acting on tectonically active faults such as the San Andreas [see *Hanks and Raleigh*, 1980] is essential to an understanding of plate tectonic driving forces and the mechanics of faulting. The most convincing evidence for low shear stress (≤ 20 MPa) averaged over the upper 14 km of the San Andreas fault is the absence of an associated surface heat flow anomaly [*Brune et al.*, 1969; *Lachenbruch and Sass*, 1973, 1980]. A low-stress fault is also suggested by in situ stress indicators showing that the direction of maximum horizontal compression in central California is nearly perpendicular to the San Andreas fault [*Mount and Suppe*, 1987; *Zoback et al.*, 1987]. High average shear stress (≈ 100 MPa) on the San Andreas fault over this same depth interval is suggested, however, by laboratory observations of the frictional strength of fractured rock [e.g., *Stesky and Brace*, 1973; *Hanks*, 1977; *Sibson*, 1983].

Elastic models of the San Andreas fault system [*Lachenbruch and Sass*, 1973, 1980; *Zoback and Roller*, 1979; *McGarr*, 1980; *McGarr et al.*, 1982] have shown that variations in shear stress with distance from the San Andreas fault, and with depth in an individual well, have the potential for revealing the state of stress on the fault at seismogenic depths. Hydraulic fracturing stress measurements made in a profile of four shallow (≈ 230 m) wells near the San Andreas fault in the western Mojave Desert (wells Moj 1, 2, 4, and 5 in Figure 1)

show the following characteristics [*Zoback and Roller*, 1979; *Zoback et al.*, 1980]. First, in all wells the magnitudes of the horizontal principal stresses and the maximum horizontal shear stress increase with depth. Second, the horizontal principal stresses and the shear stress at comparable depths are greatest in the wells farthest from the fault. Third, the vertical gradients in these stresses are largest in the wells farthest from the fault.

The shallow-profile measurements can be explained by models incorporating either high or low ambient shear stress on the San Andreas fault, depending upon the choice of boundary conditions and the presumed effect of high near-surface natural fracture densities on the observed vertical and horizontal gradients in the horizontal principal stresses and shear stress [*Zoback and Roller*, 1979; *Zoback et al.*, 1980; *McGarr*, 1980; *Stierman and Zappe*, 1981]. In order to better constrain the vertical and horizontal gradients in stress near the San Andreas fault, the U.S. Geological Survey drilled three 0.6- to 0.9-km-deep holes along a profile roughly perpendicular to the San Andreas fault in the western Mojave Desert (Figure 1). Stress measurements from the first of these wells, the Crystalline well (XTLR), are discussed by *Zoback et al.* [1980]. Stress measurements were made in the second deep well, the Hi Vista well, in the summer of 1981 and *Hickman et al.*'s [1981] preliminary analysis of these data was discussed by *McGarr et al.* [1982]. Using a simple elastic model, *McGarr et al.* [1982] (see also *Leary* [1985, 1987] and *McGarr* [1987]) extrapolated the XTLR, Hi Vista, and shallow-profile stress data to seismogenic depths and concluded that the average shear stress acting on the upper 14 km of the San Andreas fault is about 56 MPa, a result that significantly exceeds the heat flow constraint [*Lachenbruch and Sass*, 1980] but is compatible with laboratory measurements of the frictional strength of fault gouge [*Morrow et al.*, 1982]. Only two impressions were made of the hydraulic fractures at Hi Vista in 1981 because of funding limitations; this well was reoccu-

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Fig. 1. Map of the western Mojave Desert showing the location of the Hi Vista, Crystalline (XTLR), Black Butte, and Cajon Pass deep holes and the shallow stress measurement holes Moj 1, 2, 4, and 5; wells XTLR and Moj 2 are located within 20 m of each other. Well-located faults exhibiting Quaternary displacements are shown as solid lines; approximately located or concealed Quaternary faults are shown as dashed or dotted lines, respectively [after Jennings, 1975].

ried in the summer of 1987 with longer impression packers for the purpose of obtaining additional hydraulic fracture orientations. Here we present the final analysis of all hydraulic fracturing data from the Hi Vista well and examine the implications of these data for the stress regime near the San Andreas fault. Stress measurements from the most recent of the deep profile wells, the Black Butte well, are presented and discussed by Stock and Healy [this issue].

MEASUREMENT SITE

The Hi Vista well is located 32 km northeast of the San Andreas fault in the western Mojave Desert (Figure 1). This well was drilled using the air hammer technique [see Healy and Urban, 1985] and penetrated about 2–4 m of alluvium before entering the regionally extensive late Mesozoic intrusive basement. Drill cuttings indicate that the rock at Hi Vista is granite of uniform mineralogy [Stierman and Healy, 1985]. The diameter of the Hi Vista well decreases with depth in a steplike manner from 18 cm between 90 m and 274 m, to 17.2 cm between 274 m and 427 m, to 16.5 cm between 427 m and the bottom of the hole at 592 m. During drilling, an intensely fractured zone at 469 m produced a large influx of water and rock debris and was cemented off to stabilize the hole. An

intensely fractured, rubbly, and highly permeable zone was also encountered at about 570 m and extends to an unknown depth below the bottom of the well [see Healy and Urban, 1985]. Because topographic relief at the Hi Vista site is negligible (the nearest butte lies 7 km to the southwest) and the hole is everywhere within 3° of vertical, no topographic or drift corrections were applied to the stress data.

METHOD

The hydraulic fracturing technique and the interpretation methods and equipment used at Hi Vista are described in detail elsewhere [Zoback et al., 1980; Hickman and Zoback, 1983; Hickman et al., 1985] and will only be summarized here. Before conducting a hydraulic fracturing test, borehole televiewer [see Zemanek et al., 1970] and caliper logs are used to select an approximately 4.5-m-long interval of the borehole that is free from discernable natural fractures, borehole elongation, and other borehole irregularities. Rubber straddle packers are then inflated in this interval and the pressure between the packers is raised until a fracture is induced. Repeated pressurization cycles are employed to extend this fracture away from the borehole (see pressure and flow records in the appendix). Following the hydraulic fracturing test, impression

Fig. 2. Downhole instantaneous shut-in pressure (ISIP) as a function of total pumped volume for hydraulic fracturing tests at Hi Vista. The first ISIP shown for each test is from the second cycle because of rapid pressure decays after breakdown on the first cycle. Flow rates during the initial cycles of these tests were held constant at about 34 L/min and, with the exception of the 178-m test, were decreased in a stepwise manner during the final one to two cycles (see Figure A1 in the appendix). ISIPs determined after low-flow rate pumping are circled and the corresponding flow rate is indicated. Also shown is the calculated overburden stress S_v at each depth.

packers [Anderson and Stahl, 1967] or a borehole televiewer are used to determine the orientation of the induced fracture.

When the hydraulic fracturing stress measurement technique is used in vertical boreholes, one principal stress is assumed to be vertical and equal in magnitude to the overburden pressure S_v . A vertical hydraulic fracture should then form at the borehole in a direction perpendicular to the minimum horizontal principal stress S_h and, if the least principal stress is horizontal, continue to propagate in its original plane [e.g., Hubbert and Willis, 1957; Haimson and Fairhurst, 1970]. When the least principal stress is vertical, however, the hydraulic fracture should rotate into the horizontal plane as it propagates away from the borehole [see Warren and Smith, 1985]. The latter phenomenon is indicated by tests in which the long-term shut-in pressure approaches S_v [Zoback et al., 1977, 1980] or, if the horizontal segment of the hydraulic fracture propagates back into the borehole, both the pumping and instantaneous shut-in pressures dramatically decrease [Haimson and Fairhurst, 1970; Haimson, 1982]. Alternatively, although the use of inflatable packers is thought to favor the formation of axial fractures [e.g., Haimson and Fairhurst, 1970], horizontal hydrofracs have been observed to initiate at the borehole when $S_v < S_h$, apparently due to the pressurization of preexisting horizontal flaws [Evans et al., 1988a] or bedding planes [Haimson, 1982].

The magnitude of S_h is determined from the stable instantaneous shut-in pressure (ISIP) attained in later pressurization cycles (Figure 2). In the manner of Gronseth and Kry [1983], the ISIP is defined as the pressure at which the pressure-time curve departs from an initial linear pressure drop immediately after the cessation of pumping (see Figure A1 in the appendix). We customarily reduce the flow rate at the end of a test in order to minimize viscous pressure losses in the hydraulic fracture and verify that a stable ISIP has been reached (Figure 2) [see Hickman and Zoback, 1983]. Furthermore, as discussed by Hickman et al. [1985], downhole pumping pressures measured during a stepwise reduction in flow rate can be used to

detect changes in the apparent permeability of the test interval resulting, presumably, from closure of the segment of the hydraulic fracture immediately adjacent to the borehole. At Hi Vista this type of pumping test helped to constrain the magnitude of S_h in cases where the ISIP obtained at the end of a test may have been contaminated by the near-field rotation of an initially vertical fracture in response to a vertical least principal stress (see the appendix). Since the final ISIP in such a case would underestimate the magnitude of S_h , the true magnitude of S_h should lie between the final downhole pumping pressure and the final ISIP provided that the relationship between downhole pumping pressure and flow rate determined in this pumping test is linear.

The magnitude of the maximum horizontal principal stress S_H is determined from the concentration of stresses around a circular borehole using the equation (Bredehoeft et al. [1976]; after Haimson and Fairhurst [1967] and Hubbert and Willis [1957])

$$P_{fo} = 3S_h - S_H - P_p \quad (1)$$

where P_p is the formation pore pressure and P_{fo} is the fracture opening pressure, or the pressure at which the already formed hydraulic fracture reopens at the borehole wall to accept fluid. In deriving (1) the rock in the vicinity of the borehole is assumed to be impermeable, linearly elastic, and isotropic. In determining fracture opening pressures for use in (1) we pump at the same flow rate in all cycles of a given test and pick as P_{fo} the pressure at which the pressurization curve in the third cycle deviates from that established in the first cycle prior to breakdown (Figure 3; see Hickman and Zoback [1983]).

The overburden stress (lithostat) was calculated for a density of 2.68 ± 0.02 g/cm³. We computed this density using X ray modal analyses of 14 whole rock samples collected at regular intervals during drilling of the Hi Vista well (D. Stierman, written communication, 1983) (see also Stierman and Healy [1985]), assuming a saturated porosity of 0.1%. This value is the same as that measured by Ross [1972] (2.68 ± 0.03 g/cm³) on nine hand samples collected from surface outcrops near Hi Vista.

DETERMINED STRESSES

The hydraulic fracturing tests at Hi Vista are discussed at length in the appendix, and the results summarized in Table 1. The magnitudes of S_h , S_H , and the maximum horizontally directed shear stress acting on vertical planes (henceforth denoted "shear stress") are shown in Figure 4. The number of stress measurements at Hi Vista was limited by the scarcity of fracture-free intervals of sufficient length for the straddle packers, especially in the lower half of the well.

The hydraulic fracturing measurements at Hi Vista indicate an overall increase in magnitude of the horizontal principal stresses with depth, but with considerable local variability; the shear stress magnitude follows a similar pattern, although the amplitude of these oscillations is smaller (Figure 4). Except for the near-hydrostatic stress state observed at depths of 225 and 271 m, the relative magnitudes of the two horizontal principal stresses and the calculated overburden stress indicate a stress regime at Hi Vista that is transitional between thrust faulting and strike-slip faulting.

The measured magnitudes of S_h and S_H at Hi Vista can be analyzed in terms of the potential for slip on favorably oriented preexisting fault planes [e.g., Brace and Kohlstedt, 1980]. In

Fig. 3. Initial pressurizations on all cycles for the Hi Vista tests. Fracture opening pressures (solid triangles) were not picked on later cycles at 271, 491, and 537 m because of nonlinearity in the initial pressurizations (see general comments in the appendix). Fracture opening pressures on the third cycles were used in the determination of S_H , with uncertainties shown by open triangles. The surface pressure records presented here are affected by a viscous pressure drop in a high-pressure hose between the pressure transducer and the wellhead during pumping; the magnitude of this pressure drop ranges between 0.4–1.0 MPa at breakdown on the first cycle and 0.9–1.2 MPa during fracture opening on later cycles. After subtracting this pressure drop from the pressures shown, the approximate downhole pressure may be obtained by adding the hydrostatic pressure in the drill pipe (at a gradient of 9.81×10^{-3} MPa/m). No appreciable pressure drop due to flow occurred in the drill pipe at the flow rates used.

accordance with the Coulomb failure criterion, frictional sliding will occur on optimally oriented planes at a critical ratio of the maximum and minimum effective principal stresses. If these planes have zero cohesion, sliding would occur at the critical magnitude of the greatest principal stress S_1 [Jaeger and Cook, 1976, pp. 97, 223]:

$$S_1^* = [(\mu^2 + 1)^{1/2} + \mu]^2 (S_3 - P_p) + P_p \quad (2)$$

where S_3 is the least principal stress, P_p is the pore pressure, and μ is the coefficient of friction of preexisting fractures. We assume here that μ ranges from 0.6 to 1.0 [after Byerlee, 1978] and that P_p is in hydrostatic equilibrium with the water table at 117 m. Using (2), we have calculated the range of S_H magnitudes at which thrust faulting would be expected given the calculated overburden stresses (Figure 4). With the possible exception of the measurement at 178 m, comparison of the measured S_H magnitudes with this failure envelope indicates that the potential for frictional failure of the rock mass near the Hi Vista well is small. Similar conclusions are reached

through analysis of this data in terms of the potential for strike-slip failure. Given the measured magnitude of S_h at 544 m, for example, the critical magnitudes of S_H for which strike-slip faulting would be expected at this depth are 23.5 and 40.3 MPa for $\mu = 0.6$ and 1.0, respectively.

As the resolution of the borehole televiewer proved insufficient for this purpose, impression packers were used to determine the orientations of five out of the seven hydraulic fractures at Hi Vista. Four of these impressions are shown in Figure 5; a fifth impression was obtained of the hydraulic fracture at 323 m using a 1.3-m-long impression packer and revealed short segments of near-vertical hairline fractures extending for about 0.5 m on opposite sides of the borehole. As discussed in the appendix, S_H azimuths were determined from all but one of these impressions (Figure 4 and Table 1): no S_H azimuth was determined at 225 m because the impression from this depth (Figure 5b) showed two equally prominent vertical fracture traces which differed in azimuth by 110° . Unfortunately, the large scatter in azimuths and the relatively

Fig. 4. (a) Natural fracture density in the Hi Vista well as determined from the borehole televiwer. Two zones of unusually intense fracturing are indicated, one at a depth of 469 m and the other starting at about 570 m and extending to an unknown depth below the bottom of the well. (b) P wave velocity in the Hi Vista well determined with a downhole sonic logging tool at dominant frequencies of 10–20 kHz [Moos and Zoback, 1983]. (c) Magnitudes of the minimum horizontal principal stress S_h , the maximum horizontal principal stress S_H , and the overburden stress (lithostat) at Hi Vista. The thrust faulting lines indicate the domain of S_H magnitudes for which frictional failure might be expected on favorably oriented fault planes for coefficients of friction ranging from 0.6 to 1.0 (see text). The lithostat was calculated using a density of 2.68 g/cm³ (see text). (d) The maximum horizontally directed shear stress acting on vertical planes, equal to $(S_H - S_h)/2$. (e) The azimuth of S_H (quality: G, good; F, fair; P, poor).

small sample size preclude any meaningful statistical representation of the stress orientation at this site.

DISCUSSION

In Situ Stress Variations in the Hi Vista Well

Hydraulic fracturing stress measurements made in other wells near the San Andreas fault have shown that the magnitudes of both horizontal principal stresses and the shear stress at any given site tend to increase with depth, although often in a steplike manner [Zoback et al., 1980; McGarr et al., 1982; Stock and Healy, this issue]. In contrast, the Hi Vista data indicate marked decreases in the magnitude of S_H , and to a lesser extent S_h and shear stress, with depth over two discrete depth intervals (Figure 4). We will briefly examine possible causes for these fluctuations before discussing the implications of the Hi Vista data for the stress regime near the San Andreas fault.

Stress contrasts are frequently observed within sedimentary or volcanic rock sequences [e.g., Barton, 1983; Haimson and Rummel, 1982; Evans et al., 1988b] or across major stratigraphic discontinuities [Haimson and Lee, 1980] and active faults [Anderson et al., 1983], apparently in response to changing mechanical properties or local geological structures. Other investigators using the hydraulic fracturing technique in apparently homogeneous granitic rocks have documented fluctuations in both stress magnitudes and orientations within a single well that are comparable to those seen at Hi Vista [Doe et al., 1981; Rummel et al., 1983; Haimson and Doe, 1983], although the reasons for these fluctuations are not well understood. Changes in S_H azimuth of 74° over a depth interval of 365 m have also recently been documented using bore-

hole breakouts in the granitic and gneissic rocks of the Cajon Pass borehole, about 40 km to the southeast of the XTLR well (Figure 1) [Shamir et al., 1988].

One possible explanation for these departures from the expected trend of increasing stress magnitudes with depth at Hi Vista is variation in the bulk elastic properties of the surrounding rock mass. As natural fractures have been shown to increase the compliance of granitic rocks [Pratt et al., 1977], the low stresses observed between 220 and 280 m and below 530 m might, for example, correspond to zones of anomalously high natural fracture density or low P wave velocity. This is especially likely if the majority of the natural fractures dip steeply ($> 50^\circ$), as is the case in the Hi Vista well [Springer and Ader, 1987], or if these fractures were sites for enhanced geochemical alteration or microcrack production [see Moos and Zoback, 1983]. A comparison between the in situ stresses, the natural fracture density, and the sonic P wave velocity (Figure 4), however, shows no discernable increase in fracture density, or decrease in sonic P wave velocity, coincident with the low stresses measured at 225, 271, 537, or 544 m. The pronounced decrease in stresses between 491 and 537 m, however, might reflect proximity of the lowermost measurements to the intensely fractured and permeable zone at the bottom of the well.

Slip on a nearby fault might also be responsible for the fluctuations in stress magnitudes or orientation observed in the Hi Vista well [e.g., Zoback and Wesson, 1983], although the short vertical distances over which these stress fluctuations occur (Figure 4) require that such a fault must be within several hundred meters of the borehole. A number of fault scarps have been mapped in the pediment surrounding the Hi Vista well (Figure 6). Although insufficient information exists to

TABLE 1. Hi Vista Hydraulic Fracturing Results

Depth, m	Hydrofracturing Data					In Situ Stresses				
	Breakdown Pressure, MPa	Fracture Opening Pressure, MPa	In Situ Tensile Strength,* MPa	Instantaneous Shut-In Pressure, MPa	Pore Pressure,† MPa	Minimum Horizontal Principal Stress, MPa	Maximum Horizontal Principal Stress, MPa	Vertical Stress,‡ MPa	Azimuth of Maximum Horizontal Stress (Quality)	Maximum Horizontal Shear Stress,§ MPa
178	25.5±0.2	8.6±0.6	16.9±0.8	7.4±0.2	0.6	7.4±0.2	13.0±1.2	4.7	N7°E±15° (good)	2.8±0.7
225	26.5±0.2	11.6±0.8	14.9±1.0	7.1±0.2	1.1	7.1±0.2	8.6±1.4	5.9	¶	0.8±0.8
271	25.4±0.2	7.8±0.8	17.6±1.0	5.8±0.3	1.5	5.8±0.3	8.1±1.7	7.1	N39°W±15° (good)	1.2±1.0
323	24.6±0.4	12.0±0.8	12.6±1.2	9.3±0.4	2.0	9.3±0.4	13.9±2.0	8.5	N40°W±20° (poor)	2.3±1.2
491	21.5±0.2	9.8±1.0	11.7±1.2	12.2±0.2	3.7	12.2±0.2	23.1±1.6	12.9	N23°E±20° (fair)	5.5±0.9
537	22.5±0.2	14.2±1.2	8.3±1.4	11.7±0.2	4.1	11.7±0.2	16.8±1.8	14.1	...	2.6±1.0
544	22.6±0.4	10.4±0.8	12.2±1.2	10.4±0.2	4.2	10.4±0.2	16.6±1.4	14.3	...	3.1±0.8

*Equal to the difference between the breakdown and fracture opening pressures.

†Calculated assuming hydrostatic equilibrium with the water table at 117 m depth.

‡Calculated for a density of 2.68 g/cm³.

§Equal to one-half the difference between the maximum and minimum horizontal principal stresses.

¶High-quality impression obtained but displays two vertical fracture segments differing in azimuth by only 110°.

assign a reliable date to the northeast striking fault scarp closest to the Hi Vista well (Figure 6), offset of later Pleistocene to Holocene alluvial deposits by the north-northeast striking fault approximately 2.3 km southeast of the Hi Vista site indicates that it has been active sometime in the last 14,000–4000 years [Ponti and Burke, 1980; D. Ponti, personal communication, 1988].

Random measurement errors may also contribute to the observed stress fluctuations. Heterogeneities in tensile strength (e.g., healed fractures or mineral veins) or tensile strength anisotropy are suggested, for example, by the complex fracture trace observed in the test at 491 m (Figure 5d) and should lead to errors in both stress magnitude and orientation [e.g., Abou-Sayed *et al.*, 1978; Cornet and Valette, 1984]. Although it is difficult to estimate the potential size of these errors, the high and relatively uniform in situ tensile strengths exhibited by the tests at Hi Vista (Table 1; see also Figure 3) suggest that variations in rock strength are insufficient to account for the observed fluctuations. The decrease in stress magnitudes and the change in S_H azimuth observed between 178 and 271 m, for example, are documented by tests exhibiting nearly ideal hydrofrac geometries at the borehole wall (Figures 5a and 5c).

Comparison With Other Hydraulic Fracturing Tests in the Mojave Desert

The thrust faulting stress regime indicated at shallow depths in the Hi Vista well was also observed in all of the shallow-profile Mojave wells (to depths of 230 m) and in the upper 300 m of the XTLR well [Zoback *et al.*, 1980]. Furthermore, in situ stress measurements in the Black Butte well (Figure 6) indicate thrust faulting conditions to depths of at least 650 m [Stock and Healy, this issue]. These results are fairly typical of stress measurements made in crystalline rock [e.g., Brace and Kohlstedt, 1980; McGarr and Gay, 1978; Zoback and Healy,

1984] in that both horizontal principal stresses exceed the lithostat and the greatest principal stress is near the critical value for reverse faulting to a few hundred meters depth.

At depths of 178, 323, and 491 m the magnitudes of S_H , S_h , and shear stress in the Hi Vista well are similar to those measured at comparable depths in the XTLR well, while at all other depths the stress magnitudes in the Hi Vista well are lower than those in the XTLR well (Figure 7). Because of the low-stress zones in the Hi Vista well the vertical gradient in shear stress at Hi Vista, for example, is lower than that at XTLR (5.7 and 10.6 MPa/km, respectively) and also lower than is typical for rocks such as granite and quartzite in compressional stress regimes (8.7 MPa/km) [McGarr, 1980]. When compared with the XTLR results, the stress measurements made in the Hi Vista well conflict with the hydraulic fracturing results from the shallow profile wells and imply that the magnitudes of the horizontal principal stresses and the shear stress, as well as the vertical gradients in these stresses, remain constant or even decrease with distance from the San Andreas Fault [see McGarr *et al.*, 1982]. Although causes for the discrepancy in stress magnitudes between the nearby shallow wells Moj 4 and 5 and the Hi Vista well (Figure 7) are unknown, active faults (as discussed above; see Figure 6) or differences in bulk elastic properties between wells might lead to lateral variations in the regional stress field. There is not, however, a simple correlation between overall stress level and either lithology or mean natural fracture density in these wells. The Moj 4, Moj 5, XTLR, and Hi Vista wells penetrate granitic rock of similar mineralogy [e.g., Ross, 1972] and the average density of natural fractures in these wells differs by less than 10% over comparable depth intervals [see Seeburger and Zoback, 1982].

The S_H azimuths from Hi Vista can be compared with other hydraulic fracturing results in the Mojave Desert (Figure 6). In making this comparison, we have omitted poor-quality azimuths from Zoback *et al.* [1980] and from the Hi Vista data,

Fig. 5. Traces of the hydraulic fractures at (a) 178 m, (b) 225 m, (c) 271 m, and (d) 491 m depth in the Hi Vista well, obtained using impression packers. Hydraulic fractures are shown as solid lines (lines dashed where interpretation uncertain); the shaded regions indicate portions of each impression that were abraded away. Straight vertical lines denote the S_H azimuth determined from each test (see discussion of individual tests in the appendix). The length and position of the original hydraulic fracture interval (i.e., the distance between the bottom of the upper packer seal and the top of the lower packer seal) are shown for each test; the seal length of the straddle packers used is 1.3 m. Impressions were taken of the hydraulic fracture at 491 m in both 1981 and 1987, and this tracing is oriented using the average of compass surveys taken in both years (see the appendix); the impression taken of this fracture in 1981 was used to fill in detail across the east-southeast abrasion on the 1987 impression. No vertical exaggeration.

as these may not always represent hydrofracs. For the XTLR and Moj 2 wells, which are located within 20 m of each other, the azimuths shown are from tests at 230 m (N14°W, excellent), 338 m (N43°W, fair), and 787 m (N24°W, excellent). The azimuths given for Moj 1 are from tests at 80 m (N20°W, fair) and 218 m (N4°W, fair). One orientation was obtained from the Black Butte well at a depth of 309 m (N41°E, good [Stock and Healy, this issue]). Also shown are S_H directions from an analysis of borehole elongation (breakouts) in the Cajon Pass borehole. Although these data cover a range of 74° in azimuth, they indicate a mean S_H direction of N73°E at depths of 1750–2115 m [Shamir et al., 1988].

Despite the large scatter in hydraulic fracture azimuths at Hi Vista, the direction of S_H at this site agrees roughly with

that determined at the XTLR and Moj 1 sites and indicates right-lateral shear stress on planes parallel to the San Andreas fault (Figure 6). The north-northeast to northwest range of S_H azimuths at Hi Vista does not, however, agree favorably with the N41°E direction of maximum horizontal compression observed in the Black Butte well, which is between the Hi Vista and XTLR sites (Figure 6). Furthermore, the approximately N73°E direction of maximum horizontal compression at Cajon Pass is about 90° clockwise of that observed at XTLR, Moj 1, and Hi Vista and would indicate left-lateral shear stress on planes parallel to the San Andreas fault (Figure 6). Unfortunately, the large scatter in S_H azimuths at Hi Vista and Cajon Pass, together with the disparity between the mean S_H directions at the Hi Vista, XTLR, and Moj 1 sites and

Fig. 6. Map of the western Mojave Desert in the immediate vicinity of the hydraulic fracturing test wells. Faults showing evidence of Quaternary displacement are shown as heavy black lines; faults lacking evidence of Quaternary displacement are shown as thin black lines. Faults are solid where well located, dashed where approximately located, and dotted where concealed; barbs indicate thrust faults [from *Bortugno, 1986; Ponti and Burke, 1980; D. Ponti, personal communication, 1988*]. S_H azimuths determined from hydraulic fracturing tests are shown as solid black bars; the length of each bar is proportional to the quality of the impression or postfrac televue picture obtained (fair, good, or excellent; see text). Data from Moj 1, Moj 2, and XTLR are from *Zoback et al. [1980]* and data from Black Butte are from *Stock and Healy [this issue]*. Also shown are the mean (solid bar) and scatter (shading) of S_H azimuths determined in the Cajon Pass well from borehole breakouts at depths of 1750–2115 m [*Shamir et al., 1988*].

those at Black Butte and Cajon Pass, prohibits a good understanding of the stress trajectories in the western Mojave Desert at this time.

Comparison With Other Regional Stress Field Indicators

A comparison can be made between the range of S_H azimuths determined from hydraulic fracturing tests at Hi Vista and the S_H azimuths inferred from other stress field indicators in this region. Compression (P) and tension (T) axes derived from earthquake focal mechanisms are often equated with the maximum and minimum principal stress axes, respectively. Although this neglects, among other things, the potential for slip on preexisting fault planes and can result in large errors in stress direction [e.g., *McKenzie, 1969*], average P and T axes derived from a number of earthquakes on different faults within a given area appear to be valid indicators of the principal stress directions [see *Zoback and Zoback, 1980*].

Average P axes derived from first-motion studies of the main shock and aftershocks of the 1971 San Fernando earthquake sequence, approximately 35 km west-southwest of Palmdale (Figure 1) [*Whitcomb et al., 1973*], and of 22 small ($2.2 \leq M_L \leq 4.6$) earthquakes in the central Transverse Ranges (including the San Gabriel Mountains in Figure 6) [*Pechmann, 1988*], indicate an approximately north-south S_H direction [see *Zoback and Zoback, 1980*]. Although the determined P axes cover a wide range of azimuths, an approximately north-south S_H direction is also indicated by focal mechanisms for 26 small ($2.0 \leq M_L \leq 3.9$) earthquakes on and near the San Andreas fault in a region extending about 50 km to either side of Palmdale [*Sauber et al., 1983; McNally et al., 1978*]. Thus the north-northeast to northwest range of S_H azimuths determined from hydraulic fracturing tests at Hi Vista, and the north-northwest S_H azimuths determined at XTLR and Moj 1, agree fairly well with the direction of maximum horizontal compression inferred from earthquakes adja-

Fig. 7. A comparison of the horizontal principal stresses and the shear stress from the XTLR [Zoback *et al.*, 1980] and Hi Vista deep holes, which are at distances of 4 and 32 km, respectively, from the San Andreas fault. The total depth (TD) of each well is indicated. The measurements at depths of 149, 167, and 230 m were made in well Moj 2, which is 20 m from XTLR. Regression lines fit to data from the nearby shallow stress measurement wells Moj 4 and Moj 5 [Zoback *et al.*, 1980] are shown for comparison with the deep hole results.

cent to and immediately to the southwest of the San Andreas fault in this area. Although our stress measurements do not extend to seismogenic depths, the predominance of thrust faulting mechanisms, with some strike-slip events, for the central Transverse Range and Palmdale earthquakes [Pechmann, 1988; Sauber *et al.*, 1983] is compatible with the transitional thrust faulting to strike-slip faulting regime indicated by the stress measurements at Hi Vista (Figure 4). Focal mechanisms of nine earthquakes ($2.5 \leq M_L \leq 5.2$) in the central Mojave Desert about 100–200 km east of Palmdale, however, are predominantly strike-slip, with some normal faulting events, and indicate a north-northeast maximum horizontal compression direction [Sauber *et al.*, 1986].

Our measurements at Hi Vista can be compared with nearby shallow stress measurements made using other methods. Using the U.S. Bureau of Mines strain relaxation technique, Sbar *et al.* [1984] made stress measurements in two approximately 30-m-deep boreholes in this region. Although data were taken throughout each well, only measurements below 6 m were used in their analysis to minimize the effects of near-surface thermal stresses. The resultant directions of S_H were $N13^\circ W \pm 2^\circ$ (12 km southwest of Hi Vista, near Moj 4) and $N22^\circ W \pm 9^\circ$ (1.4 km northwest of Moj 1), in good agreement with the S_H azimuths determined from hydraulic fracturing tests at XTLR and Moj 1 and in reasonable accord with the range of values observed at Hi Vista (Figure 6). Shallow strain relaxation stress measurements were also made in

this region by Sbar *et al.* [1979] and Tullis [1981] using the “doorstopper” and U.S. Bureau of Mines techniques, respectively. Sbar *et al.* [1984], however, suggest that these measurements, which were all made within 3 m of the surface, are dominated by near-surface thermal stresses and therefore may not indicate the tectonic stress field. Nevertheless, their results at six sites 10–20 km away from Hi Vista (to the east, south, and southwest) yield an approximately northeast mean azimuth for S_H (with a scatter of $\pm 46^\circ$) and are closer to the $N41^\circ E$ S_H azimuth at Black Butte [see Stock and Healy, this issue] than they are to the S_H orientations from Hi Vista, XTLR, or Moj 1.

Finally, it is interesting to compare the maximum horizontal stress directions determined from hydraulic fracturing tests in the Mojave Desert with results from two geodetic networks in the Palmdale area [King and Savage, 1984] (see also Savage [1983]). Trilateration surveys conducted from 1973 to 1983 in the Palmdale network, an approximately 10 km by 20 km network spanning the San Andreas fault near Palmdale (Figure 1), and in the southeast Tehachapi subregion of the Tehachapi network, which spans the intersection of the Garlock and San Andreas faults and encompasses the Palmdale network, indicate maximum shortening directions of $N19^\circ W \pm 2^\circ$ and $N17^\circ W \pm 2^\circ$, respectively. These directions are consistent with the north-northwest direction of maximum horizontal compressive stress indicated at XTLR and Moj 1 and fall within the range of S_H azimuths determined at Hi Vista but are about 60° counterclockwise of the S_H azimuth obtained at Black Butte [Stock and Healy, this issue]. Note that equating the maximum shortening direction determined from a geodetic network with the direction of S_H requires an elastically isotropic crust, a uniform strain accumulation within the network, and a direction of maximum shortening that does not rotate with time (i.e., so that the principal axes of incremental strain and total strain are parallel) [see Sauber *et al.*, 1986; Zoback and Zoback, 1980].

CONCLUSIONS

Hydraulic fracturing stress measurements were conducted in a 0.6-km-deep well at Hi Vista, California, 32 km from the San Andreas fault in the western Mojave Desert. The relative magnitudes of the horizontal principal stresses and the calculated overburden stress indicate a stress regime that is transitional between thrust faulting and strike-slip faulting at this site. Although the azimuths of these hydraulic fractures span a 63° range, they indicate a northwest to north-northeast direction for the maximum horizontal compressive stress at Hi Vista.

Comparison of these results with stress measurements made in a 0.9-km-deep well at a distance of 4 km from the San Andreas fault in this region indicates that at similar depths in both wells the magnitudes of the minimum and maximum horizontal principal stresses and the horizontal deviatoric stress either remain constant or decrease with distance from the San Andreas fault. This is in marked contrast to the results from a nearby profile of shallower stress measurements, in which these stress components increase with distance from the San Andreas fault. Two zones exhibiting unusually low levels of deviatoric stress in the Hi Vista well, however, may indicate a perturbation to the regional stress field at this site. This perturbation may result from factors such as inelastic material behavior or heterogeneities in elastic compliance near the borehole.

Comparing stress data from all wells in the western Mojave Desert, we concur with McGarr *et al.* [1982] that the existing in situ stress data in this region show considerable local variability and do not demonstrate a systematic variation in stress magnitudes with distance from the San Andreas fault. Complexity in the stress field in the western Mojave Desert is also indicated by variations in the direction of the maximum horizontal principal stress among wells. Therefore inversion of stress measurements made along a profile of relatively shallow holes (depth ≤ 1 km) for the magnitude of shear stress at depth on the San Andreas fault is not feasible until the origins of the observed variations are understood.

APPENDIX

General Comments on Hi Vista

Hydraulic Fracturing Data

Fracture opening pressures. In the tests at 271, 491, and 537 m a pronounced curvature developed in the pressure-time curves during initial pressurization on later cycles and obscured the corresponding fracture opening pressures (Figure 3). This curvature may result either from packer bypass (see below) or propping open of the hydraulic fractures by asperities or rock debris and the infiltration of fluid into the fractures at pressures less than P_{fo} . Fracture infiltration prior to reopening, and the resulting reduction in the tangential stress concentration at the borehole wall [Cornet, 1983; Cornet and Valette, 1984], might also explain the suppression of the peak pumping pressure immediately after fracture opening that was observed in the tests at 271 and 491 m (Figure 3).

Impression packer results and packer bypass. Two hydraulic fracture impressions were taken in the Hi Vista well in 1981, using impression packers (manufactured by Lynes, Inc.) which were 14.3 cm in diameter and 1.3 m long; four additional impressions were taken in 1987 using impression packers (manufactured by TAM International) which were 2.7 m long and either 12.9 or 14.6 cm in diameter. Impression packer orientations were determined using a downhole compass both before and after impressions were taken. Impression and straddle packer depths were determined using a mechanical depth counter on the logging cable winch and are given relative to ground level. From comparison of features on borehole televiewer logs run in both years and the repeatability of wireline depth checks during a test, we estimate the relocation accuracy for the impressions at Hi Vista (i.e., the accuracy with which a depth occupied in 1981 could be reoccupied in 1987) to be about ± 0.2 m. Impressions of the 491-m test, obtained in both years, yielded nearly identical fracture traces in the range of overlap (see Figure 5d) and agree to within 6° in azimuth and 8 cm in depth.

Impression packers were inflated for about an hour; with the exception of the 178 m test the corresponding external packer pressures, estimated using a seal efficiency (ratio of external packer pressure to internal fluid pressure) of 0.88 and 0.85 for the 1981 and 1987 tests, respectively [Evans, 1987], were maintained to be greater than P_{fo} but less than or equal to P_b . At 178 m a leak in the drill pipe resulted in large fluctuations in fluid pressure and the external packer pressure ranged from about $0.26P_b$ to $1.19P_b$. Hydraulic fractures were identified through the presence of narrow ridges of extruded rubber, which were about 0.2–1.0 mm wide and extended up to 1–2 mm away from the surface of the impression packer.

Propagation of the hydraulic fracture beneath one of the straddle packers and out into the open hole during a test

(packer bypass) is suggested by the impressions obtained at 225 and 491 m (Figures 5b and 5d), although coverage of the straddle packer seals by the impression rubber is insufficient to demonstrate unequivocally that bypass has occurred. If bypass did occur, however, the slow pressure decays following shut-in and the similarity of these shut-in decay curves between cycles (Figure A1) suggest that the resulting leak rates are small. In this regard, Evans *et al.* [1988b] describe a number of hydraulic fracturing tests in shale for which packer bypass was indicated and note that this did not appear to have a significant effect upon the determined ISIPs.

Discussion of Individual Tests

The surface pressure and flow records are presented in Figure A1; expanded versions of these records (Figure 3) were used to determine the fracture reopening pressures for each test as a function of cycle. In addition, records from a downhole Amerada-type mechanical pressure recorder (manufactured by Kuster, Inc.) located in the test interval were used to determine downhole pumping pressures and ISIPs, but these records are not amenable to reproduction. Notable features of these tests are as follows (estimated overall test quality; F, fair; G, good; or E, excellent).

Test at 178 m (E). This test exhibited a stable ISIP (Figure 2), modest decreases in P_{fo} (Figure 3), and a clearly defined vertical fracture trace at the borehole wall (Figure 5a). Both the ISIP and the long term shut-in pressure were $\gg S_v$ (Figures 2 and A1) indicating that if this hydraulic fracture rotated into the horizontal plane, it did so at sufficient distance from the borehole that the vertical (high stress) segment of the fracture dominated the shut-in behavior. The downhole pumping pressure at the end of the test (at 34 L/min) was 0.16 MPa above the final ISIP. Only the southern hydrofrac trace on the impression packer from this test was used to determine the azimuth of S_H as most of the northern trace appears to have been abraded away (Figure 5a).

Test at 225 m (F). The ISIP was stable at the end of the test and P_{fo} was stable during cycles 2–4 but decreased rapidly after the fourth cycle (Figure 3). The cause of this decrease is unknown, but it may be due to packer bypass (as discussed above); fluid infiltration into the hydrofrac at pressures $< P_{fo}$ is not a likely explanation for the decrease in P_{fo} because the initial pressurization rates were similar in early and late cycles (Figure 3). Although the long-term shut-in pressure at the end of the test $\approx S_v$ (Figure A1), suggesting that the hydrofrac may have rotated into the horizontal plane away from the borehole, we do not think this seriously affected our estimate of S_H because (1) horizontal hydrofracs were not observed on the impression packer [cf. Evans *et al.*, 1988a], (2) the pressure decays following shut-in on all cycles are quite similar, even before the sudden decrease in P_{fo} (Figure A1), (3) the ISIP was stable at the end of the test and 20% in excess of S_v (Figures 2 and A1), and (4) there were no inflections in the variable flow rate pumping test and the downhole pumping pressure at the end of this test (at 13 L/min) was only 0.18 MPa above the final ISIP. No S_H azimuth was determined from this test because the impression packer showed two equally prominent vertical traces which were separated by only about 110° (Figure 5b).

Test at 271 m (E). This test exhibited a clearly defined vertical fracture trace at the borehole wall (Figure 5c), a stable P_{fo} in cycles 2–4 (Figure 3), and a nearly stabilized ISIP in later cycles that was $< S_v$ (Figures 2 and A1). The downhole pumping pressure at the end of this test (at 18 L/min) was 0.19

Fig. A1. Surface pressure and flow records from the hydraulic fracturing tests at Hi Vista. Positive flow corresponds to fluid injection, and negative flow corresponds to fluid withdrawal from the well. These pressure records are affected by a viscous pressure drop in a high-pressure hose between the pressure transducer and the wellhead during pumping. The magnitude of this pressure drop ranges from about 1.1 MPa at a flow rate of 34 L/min to about 0.2 MPa at 12 L/min; no pressure drop occurs once the well is shut in. After subtracting this pressure drop from the pressures shown, the approximate downhole pressure may be obtained by adding the hydrostatic pressure in the drill pipe (at a gradient of 9.81×10^{-3} MPa/m). The breakdown and fracture opening pressures from each test are shown, together with the magnitudes of S_h and S_v (surface pressure). The instantaneous shut-in pressure (ISIP) is illustrated for the 178-m test.

MPa above the final ISIP. The S_h azimuth at this depth was rated "good" rather than "excellent" because of the low horizontal stress difference ($S_h - S_h$) determined from this test.

Test at 323 m (G). Both P_{to} (Figure 3) and the ISIP (Figure 2) were stable. The rapid pressure decay during shut-in on cycles 1 and 2 (Figure A1) was due to a leak at the well-

head, which was repaired prior to cycle 3. The pressure step at the very beginning of cycle 1 (Figures 3 and A1) indicates air in the system and illustrates the viscous pressure losses in the hose between the surface pressure transducer and the wellhead. The pronounced curvature prior to breakdown on cycle 1 resulted from pump deceleration at high pressure (Figures 3

and A1). Although the final ISIP was only 8% greater than the calculated S_v at this depth (Figures 2 and A1), only high-angle fractures were seen on the impression packer obtained. Furthermore, the relative stability of the ISIP, the absence of inflections in the variable flow rate pumping test at the end of cycle 5 (over the range 11.4–9.5 MPa), and the small (0.13 MPa) pressure difference between the final pumping pressure and the ISIP in cycle 5 suggests that the measured ISIP does not reflect the normal stress on a hydrofrac that has rotated into the horizontal plane near the borehole. Although several subvertical hairline fractures were seen on the impression packer from this test, the S_H azimuth quoted for this depth is of relatively low quality (Table 1) because these presumed hydrofrac traces were intermingled with other high-angle features of unknown origin.

Test at 491 m (G). P_{fo} was stable in cycles 2–4 (Figure 3), and the ISIP was stable at the beginning and end of the test and $\ll S_v$ (Figures 2 and A1). Incomplete flowbacks prior to cycles 6 and 8 were an attempt to see the effect of high residual fluid pressures on P_{fo} (the results were indeterminate owing to high curvatures on these cycles). The final downhole pumping pressure (at 22 L/min) equals the ISIP on the last cycle. The hydrofrac trace on the impression packer from this depth was quite complex (Figure 5d) and the corresponding S_H azimuth was estimated as the average of (1) the N10°E strike of the steeply dipping (80°) nearly continuous fracture comprising the lowermost feature on the impression, and (2) two diametrically opposed vertical lines roughly bisecting all hydrofrac traces (N36°E).

Test at 537 m (F). P_{fo} decreased slowly from cycles 2–5 (Figure 3) and the ISIP was quite stable at the end of the test and $\ll S_v$ (Figures 2 and A1). The tensile strength implied by this test (8.3 ± 1.4 MPa) was somewhat lower than that for other tests in this well (about 12–18 MPa; Table 1) and both the ISIP and the long-term shut-in pressures showed an unusually large decrease in the first few cycles (Figures 2 and A1). The final downhole pumping pressure (at 18 L/min) was 0.13 MPa above the ISIP on the last cycle.

Test at 544 m (E). P_{fo} decreased slowly during this test (Figure 3) and the ISIP was stable and $\ll S_v$ (Figures 2 and A1). The relationship between flow rate and downhole pumping pressure (covering the range 10.4–11.2 MPa) determined in cycles 5 and 6 was linear; the final downhole pumping pressure (at 25 L/min) equals the ISIP on the last cycle.

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