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A Study of Stress in Devonian Shale: Part I—3D Stress Mapping Using a Wireline Microfrac System

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ABSTRACT

We describe an experiment to characterize in detail variations in the state of stress within a horizontally-bedded sandstone/shale limestone sequence in western New York. The measurements were made using a new wireline-based "microfrac" system which, by its nature, permits frequent sampling of stress. Three wells, 1 km or so apart featured in the study. In one well, 43 intervals were tested to 1 km depth. The measured stress-profiles in all three wells show an identical pattern of stress variations. Two stratigraphic regimes of markedly different stress ratio are recognized which are separated by a transition zone. Within this zone variations in stress are clearly correlated with lithology.

INTRODUCTION

The accurate estimation of in-situ stress is becoming an increasingly important factor for optimizing hydrocarbon recovery as our understanding and modeling of reservoir mechanical processes advances. For example it is now well established that variations in least horizontal stress exert the dominant influence on hydraulic fracture geometry (Warpinski et al., 1982). A common approach to stress prediction has been to utilize simple poro-elastic earth models incorporating gravity and perhaps a constant (stress or strain) tectonic loading term; these models are then calibrated to the case in hand using site-specific or regional fracture-gradient data (Anderson et al., 1973; Whitehead, et al., 1986). It is possible that in some geological situations the approach may be valid (Voegel et al., 1981). However, poro-elastic models are clearly limited by their failure to include "residual" stresses arising from processes acting in the rocks' past, such as creep, faulting and thermoelastic effects to name but a few (Price, 1974; Voight and St. Pierre, 1974). The question of "how limited" is inextricably linked to the fundamental issue of stress memory duration in sedimentary rocks. Our laboratory derived understanding of long-term stress-relaxation processes is far too poor to be of help in this regard. In the absence of relevant guidelines, it remains important to characterize site specific stress-lithology relationships through direct measurement, rather than by inference from some model or other. For only then can a basis be established for the local or perhaps regional validity of the models themselves and hence the stress-predictive techniques founded upon them (e.g., Frisinger and Cooper, 1985). There is also a long-term benefit from such measurements. The development of a database of detailed stress-characterization studies covering areas of widely different lithologic character and tectonic history could, in principle, provide an empirical basis for estimating a-priori the likely importance of inelastic stresses and relaxation time constants.

Unfortunately, owing to the expense of reliably characterizing in-situ stresses, published case studies of sufficient detail to resolve lithology-related variations in stress are few. Warpinski (1986) has recently reviewed theoretical aspects of this work and presented perhaps the most complete study of data-constrained stress-modeling to date. In this and a later companion paper we describe a further such case study in the Devonian shale section of the Appalachian basin of western New York. Detailed profiles of both maximum and minimum principal stress were obtained to 1 km depth in three uncased boreholes, a few kilometers apart, penetrating a horizontally bedded sequence of silt/mudstones, sandstones, and limestones.

References and illustrations at end of paper.

Stresses were measured using a new wireline based 'micro-frac' stress measurement system acquired and modified for use in 200mm diameter boreholes by Lamont-Doherty Geological Observatory (L-DGO). We report here only results and experiences derived from the stress-measurement program. Conclusions which draw upon the outcome of physical property testing of core and regional scale stress characterization will be presented at a later date.

The paper is organized as follows. Firstly, we describe the location, stratigraphy and regional geological structure of the study area. Secondly, we briefly describe the wireline stress-measurement system. Thirdly, we describe the design and execution of the experimental program, and fourthly, we present the results of the stress measurements and discuss some tentative implications and conclusions.

LOCATION, REGIONAL GEOLOGY AND STRUCTURE

Location: The three boreholes in which the measurements were made straddle the side of a 230m high hill to the west of the village of South Canisteo in Steuben County, New York (Figures 1 and 2). The easternmost well (Wilkins #1; API #31-101-17502) lies on the floor of a prominent NNW striking valley proximate to the village. The neighboring wellhead (Appleton #1; API #31-101-17443) lies some 100m up the hill a distance of 1.4 km to the WSW, and the westernmost (O'Dell; API #31-101-17364) lies a further 100m higher, some 1 km due west of the Appleton. The study area is located some 20 km to the southeast of Eastern Gas Shales Project well NY#1 (Figure 1) and penetrates an almost identical stratigraphic section to this well. This was by design as oriented core is available for the study section from NY#1. No core was taken during the rotary percussion drilling of the three S. Canisteo wells.

Stratigraphy: The stratigraphic section pertinent to this study is shown in the cross section A-A' of Figure 2 which we present as Figure 3. There is no vertical exaggeration. Bedding is essentially horizontal: specifically, the regional dip is 0.5° toward the south. For a detailed description of regional stratigraphy the reader is referred to the work of Van Tyne (1980, 1983). The base of the section considered consists of Silurian age evaporite beds of the Salina group which extend over much of the Appalachian plateau (Figure 1). Several of these beds contain substantial salt deposits, the composite thickness of which reaches up to several hundred meters to the east of the study area (Kreidler, 1957). This spatially extensive salt horizon has exerted a profound influence in the development of structures on the plateau region through its mechanical behavior as a decollement surface (Frey, 1973; Davis and Engelder, 1985) and as a source of diapirism (Beardsley and Cable, 1983). Overlying the Salina are the carbonates and evaporites of the Bertie group the top of which is truncated by an unconformity zone. Within this zone lies the locally intermittent yet regionally extensive Oriskany sandstone above which lies the Devonian shale section.

The Devonian section consists of an alternating sequence of black and grey pro-deltaic turbidite piles (mudstones and siltstones) the color of which reflects differences in organic content (Van Tyne, 1983). The sequence has been interpreted by Ettensohn (1985) as denoting cycles of basin subsidence and quiescence in response to proposed collisional phases of the Acadian orogeny. Within this framework, the two principal extensive limestones of the section, the Onondaga and Tully, represent periods of tectonic quiescence between the two major tectonic cycles present in the local section, and the alternating black and grey "shales" represent sub-cycles reflective of episodic variations in water depth (Figure 3). Below the Sonyea formation the lithology is dominantly calcareous with the typical recurrence of calcareous siltstones grading upward into limestones (Cliffs Minerals, 1980). Thereafter, quartzitic clastics begin to dominate with sandstone beds becoming increasingly common above the base of the Rhinestreet black shale. These thin sandstone beds, although widespread, are rarely individually extensive on a scale greater than county-wide (A. Van Tyne, pers. comm.). An exception perhaps is the lowermost bed above the Rhinestreet base (the Grimes sandstone) which has been mapped by Bradley and Pepper (1938) in adjacent counties to the north and west and is also present in the core from EGSP well NY1. Sandstone beds which are continuous on at least the scale of well separation were of special interest to this study and those which were individually recognizable in all three γ-logs are indicated in Figure 3 and distinguished by the prefixes 'B' through 'K'.

Structure: A cross section through profile A-A of Figure 2 is shown in Figure 3. The principal local structure affecting the area is the family of northeast striking faults which are defined at the level of the Oriskany but nowhere break the surface (A. Van Tyne, unpublished data). We have shown these as listric faults ramping up from the Salina salts through association with the (locally northeast trending) fault population which Gwinn (1964) and Frey (1973) have described as underlying plateau anticlinal structures. The larger of the faults break the Tully limestone but probably not the Grimes sandstones. The faults are largely thought to have formed in response to compression during the Alleghanian orogeny (Engelder and Engelder, 1977). However, Bradley and and Pepper (1938) from an examination of upper Devonian (Canadaway) surface exposures of northeast trending faults some 15 km east of South Canisteo, report evidence of syndepositional movement. In perhaps a similar vein, Beardsley and Cable (1983) have reported seismic reflection evidence of active diapirism in south Steuben County during upper Devonian time. Thus some doubt remains about the genesis and history of slippage on these faults although there is no reason to believe that they have been active post-Alleghanian (Permian).

INSTRUMENTATION

The technology at the core of our stress measurement program is the wireline microfrac system shown in Figure 4. The system consists of a trailermounted hydraulic winch supporting 1 km of standard 7-conductor armored cable, a hydraulic high-pressure pump capable of delivering 10 liters/min of water at a surface pressure of 50 MPa and a compressor. Fluid to both inflate the downhole straddle packer and fracture the interval is delivered downhole via a single high-pressure hose clamped to the wireline every 30m to prevent entanglement. A downhole valve operated by wire tension determines whether fluid is ported to the fracturing interval or the packers. Fluid pressure is monitored downhole with a Sensotec TJE Series 69 MPa transducer (1 part in 10^3 precision) and recorded at the surface together with flow-rate on strip-chart and analog tape recorders. The basic system was supplied by MESY systems of Bochum, West Germany, and has been described by Rummel et al. (1983). The straddle packer used is a standard high-pressure wash tool manufactured by TAM International of Houston, Texas. A 1.45m straddle interval length was used in all stress-tests. Packer seal length was 1.04 m.

The advantages of a wireline mini-frac system are primarily the elimination of drill-rig or work-over rig costs and the ability to proceed quickly from one measurement horizon to the next without fuss. The L-DGO rig can be operated by three personnel and, in favorable circumstances, can execute an average of nine stress measurements per 12-hour day.

PROJECT DESIGN

Prior to stress testing, a borehole televiewer survey was conducted in each well using a tool loaned to the project by a division of the Ocean Drilling Project (ODP) based at L-DGO. The purpose was to identify intervals free of natural fractures for stress testing and also to calibrate the absolute depth standard of the L-DGO wireline against the Gearhart gamma and density logs which were used to identify stratigraphic horizons of specific interest for stress measurement. Figure 5 shows the sonic reflectivity imaging of a stratigraphically equivalent 30 m section of each well which spans the K-sand (Grimes sandstone). The sand can clearly be distinguished from the mudstones bounding above and below by the shadow that meanders across the record. Using this technique, a program of stress testing was drawn up which would reveal any lithology-related stress contrasts that might exist.

Due to ease of access, the Wilkins well was selected for detailed study and a complete suite of logs was run in cooperation with Dr. R. Plumb of Schlumberger-Doll Research of Ridgefield, Conn. The suite consisted of spectral gamma ray, sidewall neutron, litho-density, full-waveform sonic, digital televiewer, four-arm dipmeter and micro scanner (MST). The results of the logging program will be discussed elsewhere.

Stress Measurement Technique: The same procedure was used in testing all intervals. To summarize, upon selection of an interval for stress-testing the packers are lowered so as to straddle the interval. Precise depth control is attained through reference to color-coded marks emplaced on the wireline every 10m and originally calibrated using a laser-ranging distance measuring device having a standard error of 5cm over a kilometer. A correction was applied to account for cable-stretch under the weight of the tool. The packers are then inflated so as to apply a "squeeze" pressure of between 5 and 7 MPa against the borehole wall. The downhole valve is then actuated, thereby affecting a hydraulic path from the high-pressure hose to the straddled interval and isolating the packers. The interval is now prepared for testing. A typical sequence of tests administered can be appreciated from Figure 6 which shows pressure-time and pumped flow-time (input only) records obtained during the testing of two intervals within and below the K-sand bed. A permeability test is first conducted by raising the pressure in the interval by 2 MPa, and monitoring the stability of the pressure after shut-in. A stable pressure is taken as confirmation that no permeable natural fractures intersected the straddled interval. Pressure is then released at the surface and the interval pressure allowed to drop to hydrostatic in preparation for breakdown. The pumps are then turned full-on until the attendant steady increase in downhole pressure either ceases or changes slope, thereby indicating fluid loss into a presumed induced fracture. Pumping is then abruptly stopped and the interval shut-in until the pressure has stabilized after which time it is flowed-back at the surface. Care is taken to monitor the volume of fluid injected and returned during all pump cycles. Flow-back is interrupted periodically to monitor interval repressurization as the fracture drains its contained pressurized fluid back into the interval. The effect of this can be seen in Figure 5 as occasional jags in the pressure record during flow back periods. These jags serve to confirm the inducement of a fracture. The rate of pressure increase during these flow-back interruptions is directly proportional to the flow rate of fluid entering the interval from the draining fracture and hence provides a measure of drainage state. Once the shut-in repressurization rate has become negligible (i.e. the fracture had adequately drained), the first re-open pump is conducted. During this cycle, ten liters of fluid is injected, again at full pump rate, and the interval then shut-in and flowed back, observing the same procedure as in the breakdown pump. Once fracture drainage has again diminished to low levels, further pumping cycles are conducted involving the injection of progressively larger volumes of fluid.

During the suite of re-opening pumps, initial shut-in-pressure (ISIP), taken as the pressure at which the downhole pressure curve departs from the initial linear drop defined immediately following shut-in, was observed to decline from one cycle to the next. Successively larger volume pumping cycles were conducted until both the injection pressure and the subsequent ISIP stabilized. The largest fluid volume injected during a single pump test was 100 liters.

The fluid flow rates and volumes administered during a test are modest in comparison to those typically used by the industry in similar tests.

Elastic models of the induced fracture constrained by realistic values of fracture toughness and elastic modulus suggest that fracture dimensions of the order of 10-20m can be anticipated using our procedures (Evans and Engelder, 1986). Drainage of the fracture between pump cycles is important in limiting fracture dimensions. In those cases where downhole injection pressure appeared to be limited by our modest injection rate, slow pump tests were performed to demonstrate the independence of initial shut-in pressure to flow rate.

Induced fracture geometry at the wellbore was determined by conducting post-fracture televiewer surveys of the tested intervals. Fracture definition was enhanced by setting an impression packer against each fracture at a pressure slightly less than the breakdown pressure (to ensure that no fresh fractures were induced). This technique, which proved satisfactory in 70% of cases, has the advantages of both speed and of revealing (in principle) the full extent of the induced fracture even though it may run out of the interval. This proved to be common and will be discussed later. Conventional impression packers surveys would normally reveal only the fracture trace in the interval.

RESULTS

Least Principal Horizontal Stress: In all a total of 22 intervals were stress tested in the Appleton well, 43 in the Wilkins and 10 in the O'Dell. The resulting stable ISIP values are plotted in Figure 7 as function of depth for each well. The depth axes have been displaced to a common elevation datum, such that common stratigraphic horizons are aligned. The diagonal line represents the overburden load as estimated from the Schlumberger density log mean value of 2.71 gm/cc. We believe this may be an overestimate as direct density measurements on core from NY#1 suggest an average value of 2.65 gm/cc (Kalyoncu, 1979). Measurement error of each ISIP datapoint is less than ±0.15 MPa. As induced fracture geometry was determined to be vertical in all but one case (Appleton: 311.85 m depth), we equate ISIP with the least principal horizontal total stress, S_{HMIN}.

There are several features of the data, shown in Figure 7, which are noteworthy.

Firstly, with the exception of the section between the H and K sands, it can be seen that the datapoints define remarkably consistent linear trends with very little scatter. Wherever closely spaced tests were performed, essentially the same ISIP values were observed. We take this as a measure of data quality.

Secondly, two distinct stress regimes can be recognized, separated by a transition zone between the H and K sands. The uppermost regime is characterized in all three wells by near-lithostatic ISIP values although the Wilkins and, to a lesser extent, the Appleton profiles do lie significantly above the lithostat. The stress ratio (defined as S_{HMIN}/S_V) for the O'Dell, Appleton and Wilkins wells in this region is 1.0, 1.07 and 1.17 respectively, which is consistent with the regional stress characterization proposed by previous workers (Haimson, 1977, Komar and Bolyard, 1981). In contrast to the upper regime, minimum horizontal stress levels in the lower regime extending below the K-sand do not reflect the differences in overburden load acting at each of the well sites. In fact, measured minimum stress magnitudes at a given stratigraphic horizon are the same, thus suggesting a sub-surface stress regime which is laterally uniform on at least a kilometer scale. Stress ratio values, however, reflect the difference in overburden and were determined to be 0.64, 0.72 and 0.79 for the O'Dell, Appleton and Wilkins wells respectively immediately below the K-sand horizon.

Thirdly, we recognize a transition zone between the upper and lower stress regimes which extends from the H to the K sands. Within this zone, least horizontal stresses measured in the "shale" generally decrease with depth and contrast strongly with stresses measured in the quartz-rich siltstone beds which largely follow the ISIP trend defined in the uppermost stress regime. These stress contrasts attain a value of 5 MPa in the O'Dell well between both K and J sands and the intervening shales. The Tully limestone was also found to exhibit much higher least horizontal stresses than the surrounding shale.

It may be suggested that the two regimes merely reflect a change from vertical fracture propagation in the lowermost regime to horizontal fracture propagation remote from the wellbore in the uppermost. We reject this hypothesis, primarily because the observed fracture gradient of 1.17 for the Wilkins well is well-defined and consistently much higher than one would expect for a fracture sampling the true vertical stress. Although topographic loading can locally increase the "vertical" principal stress to values in excess of the estimated overburden, we would expect the difference to decline with depth whereas we observe a sustained linear gradient in the sands to a depth of 700 m. We note that using the mean density of 2.65 gm/cc as given by Kalyoncu et al. (1979) further increases the inferred fracture gradient in the Wilkins well to 1.20. Even ignoring this objection we find that the horizontal fracturing hypothesis leads to the same conclusion regarding the existence of stress contrasts. For it is clear than on grounds of vertical stress continuity, the lithology correlated ISIP variations observed in the transition zone cannot be explained by horizontal fracture propagation in both sands and shales. Indeed, the decline in shale ISIP with depth suggests that the shale at least fractured vertically in this regime. Furthermore, we observe that small yet significant lithologic contrasts in ISIP are evident at the level of the H-sand in the Wilkins well. If it is maintained that fractures in the sand propagate horizontally and hence the ISIP reflect vertical stress, then we would have the result that the least horizontal stress in the shale near the H-sand is almost the same as the vertical stress. Thus bedding plane weakness could not be a significant factor in determining fracture attitude in the shale. As the sands are likely to show lesser strength anisotropy, we must conclude that if the induced fractures turned horizontal in the sands during propagation, they did so because of high horizontal stresses, substantially in excess of the surrounding shales. The form of the horizontal stress profiles shown in Figure 7 is thus maintained with the exception that values in the sands would then be lower bounds to the true stress: that is, inferred stress contrasts would be even greater than that shown. As we have discussed, this interpretation is not consistent with the observed super-lithostatic fracture gradient. On the whole, the evidence favors equating the observed ISIP's with least principal horizontal stress levels, even where the local fracture gradient exceeds unity.

Maximum Principal Horizontal Stress: Two methods are commonly used to estimate S_{HMAX} from open-hole pressurization data. Both are essentially based upon Hubbert and Willis's (1957) discussion of the mechanics of vertical borehole rupture in the presence of arbitrary far-field horizontal stresses. The first considers the wellbore fluid pressure required to induce an axial fracture in a previously unfractured borehole. This method suffers from the drawback of requiring knowledge of the "appropriate" tensile strength of the rock in question, a requirement which at best can only be fulfilled in a statistical sense (Ratigan, 1981). Neglecting poro-elastic effects due to fluid infiltration of the borehole during pressurization (which is justified in view of the extremely low permeability of Devonian shales), maximum principal total stress, S_{HMAX}, is given by (Haimson and Fairhurst, 1967),

$$S_{HMAX} = 3\ S_{HMIN} - P_b + T - \alpha P_c \quad ..... \quad (1)$$

where P_b is the wellbore pressure at breakdown, T is the tensile strength (T>0), Pc is the pore-pressure and α is a poro-elastic parameter to be discussed later. Compression is taken as positive.

The second method was suggested by Bredehoeft et al. (1976) as a means of avoiding the need to estimate tensile strength and considers the wellbore pressure required to re-open the fracture induced during the breakdown pump. If it is assumed that the fluid pressure within the fracture near the wellbore remains at the level of the formation pore pressure during the pumping period that leads to re-opening, the mechanical formulation follows that underlying equation 1 with the exception that the tensile strength term is now zero. That is,

$$S_{HMAX} = 3\ S_{HMIN} - P_{RO} - \alpha P_c \quad ..... \quad (2)$$

where P_{RO} is the wellbore pressure at which the fracture begins to take fluid.

Unfortunately, method 2 is practically applicable only provided $S_{HMAX} < 2\ S_{HMIN}$. Where this condition is not met, the elastic hoop stress across the fracture in the immediate vicinity of the wellbore is less than S_{HMIN}. Hence, although the fracture may begin to open at the wellbore when the true re-opening pressure (required by equation 2) is reached, the "opening" will not propagate until the wellbore reaches the value of S_{HMIN} which is the stress normal to the crack face beyond the immediate vicinity of the wellbore. The associated fluid loss will thus become significant and detectable only when the pressure has reached the value of S_{HMIN}. In such circumstances, a re-opening pressure equal to the ISIP will be recorded and equation 2 will yield only a lower bound to the value of S_{HMAX}. This was found to be the case in all but the shallower of the tests here reported. In view of this, we have analyzed the data using both methods.

The tensile strength values used in implementing method 1 were derived from the tabulated results of oriented Brazilian tests conducted on core samples from the neighboring EGSP well NY#1 (Cliffs Minerals, 1981). Enormous variability was found in the reported data-values ranging from 3 to 23 MPa. To reflect this uncertainty we calculated the statistical mean value and RMS standard deviation of the ensemble of values reported for each stratigraphic group. For each value we used the smallest of the three tensile strengths measured across planes striking between N30E and N90E. This was because the vast majority of the induced fractures were determined to strike ENE. The West Falls Group was particularly well sampled with 81 data suites, the others involved typically 15 test suites. The resultant mean values range between 6.5 to 9 MPa and are similar to those reported by Blanton, et al. (1981) from direct-pull tests conducted on Devonian shales from more central parts of the basin. No measurements were reported for the Tully and Lodi limestones. Hence for these two formations we have taken as a reasonable value the Brazilian test tensile strength of Indiana limestone of 5.2 MPa as given by Hardy and Jayaraman (1970) and have somewhat arbitrarily assigned an uncertainty of 3 MPa.

The value of the poro-elastic weighting factor 'α' in equations 1 and 2 (Haimson and Fairhurst, 1967) is perhaps the principal uncertainty involved in microfrac stress measurements conducted in compacted lithified shales of high bound water content: for it is not clear whether the linear poro-elastic theory is valid for such materials. The two extreme values of the parameter (one or other of which is almost invariably used in published measurements) are unity for high-porosity rocks of low clay content and zero for low porosity crystalline rocks. However, mercury porosimetry measurements of the NY#1 core suggest a mean porosity of 4% (Kalyoncu et al., 1979). As this is not large, we have used a value $\alpha = 0$ in deriving all estimates of S_{HMAX}. The estimates are thus strictly upper bounds although we do not believe the overestimation can be large. A more detailed discussion of this issue will be presented in Evans and Engelder (1986).

The resulting estimates for S_{HMAX} derived using both methods are shown for the Wilkins and Appleton wells in Figures 8 and 9. We have not presented estimates for the O'Dell well as an intermittent blockage in the downhole system prevented the reliable measurement of the breakdown and re-opening pressures (we are confident shut-in pressures are reliable). It is evident that estimates derived using Method 2 (re-opening pressures) are generally were sufficient to constitute a potential breach of seal. That no direct evidence was observed in these cases can be partially ascribed to the uncertainty in interval location on the televiewer images (which we suggest is less than 40 cm at 1 km depth).

The section below the K-sand interval was particularly prone to fracture transection of the packer seal. In fact in all but two Wilkins well tests in this section was either direct (unequivocal) or equivocal (televiewer) evidence of seal breach found. As this section corresponds to the lowermost stress regime it is important to determine whether the low ISIP values which characterize this zone are merely a consequence of seal breach. The following summarized observations testify that the observed ISIP values are indeed valid indications of S_{HMIN}. For a more detailed account see Evans and Engelder, (1986).

1) The three lowermost tests in the Appleton well showed no evidence whatsoever of by-pass and are thus immediately valid. These serve to define the existence of the stress transition in the vicinity of the Appleton well at least. We note that the ISIPs for these three tests correspond closely with those measured at equivalent stratigraphic horizons in the Wilkins and O'Dell wells where by-pass is suspected. This would be expected for a laterally-uniform stress regime.

2) By-pass was clearly established to have occurred in a few shallower tests in the Wilkins and Appleton wells. If the shut-in values measured in the deeper Wilkins tests were substantially reduced below S_{HMIN} levels due to the availability of a high-conductivity (fracture) drainage path to the low-pressure wellbore, we would expect to see a similar ISIP reduction in these shallower tests. Two such tests are at 342 m and 420 m in the Wilkins well. From Figure 7 we see that the shut-in pressures fall on the same super-lithostatic trend defined by neighboring tests for which fracturing was contained within the interval. Thus we infer that the ISIP for these two tests is unaffected by the breach of seal and is a valid indicator of S_{HMIN}.

3) The shut-in values measured in the lower stress regime define a clear quasi-linear trend which does not correlate with variations in packer setting pressure.

4) Tests conducted in the transition zone were largely free of fracture seal breach. The only exception, the J1-sand test in the Wilkins well, showed an ISIP which is consistent with the pattern of stress variations in this zone.

Fracturing around packers is a common occurrence during open-hole treatments in Devonian shale. The section below the Grimes sandstone was found to be particularly prone to this phenomenon in the Wilkins well but not the Appleton well. We do not understand the reason for this, although we do note that the packers were set an average 2 MPa higher in the Appleton well. As far as stress-measurements are concerned, we have established, albeit empirically, that shut-in pressures are not largely affected by fracture propagation around the packer seal, at least in shales. This would seem to suggest that in small volume tests, as we have conducted, the observed shut-in pressure is largely determined by the fracture pressure distribution existing within essentially 1 m vertically of the fracture interval.

DISCUSSION AND CONCLUSIONS

We have presented three stress profiles which serve to describe in detail the state of stress in a seemingly simple in-situ volume of sedimentary rock. As far as we know, to first order, this rock has not been disturbed since Permian time. The results show that the stress distribution is far from simple. We have taken great pains to argue that the variations we infer are real. The consistency of the pattern the measurements define was crucial in convincing us of this and was a direct consequence of the dense sample-point density made possible through the use of a wireline-based system.

The quartz-rich beds in which we measured stress contrasts are of the order of only 10-15 m in thickness (Figure 7). In resolving stress in such thin beds we feel it is crucial that the fracture does not become overpressurized, thereby giving rise to closure stress curves of the form discussed by Smith (1985). It seems reasonable that the larger the fluid volume injected, the greater is the fracture area that participates in determining the pressure decline at the wellbore immediately following shut-in. Small volume injections with drainage between pump cycles would thus seem to have advantage in this regard. The initial shut-in pressures we observed were in almost all cases well defined and established within a couple of seconds after flow check.

It is worth commenting on the applicability of wireline microfrac systems to commercial oil- and gasfield application. Firstly, in openhole measurements, an ever-present anxiety arises from the prospect of the straddle packer becoming stuck due to wellbore spalling. However, the vast majority of commercial completions are cased, and hence this potential pitfall does not arise. Secondly, the L-DGO system is not suited to operation below 1.5 km. Below that depth, management of the high-pressure hose clamped to the wireline becomes, in our opinion, too cumbersome. A reliable solution would be to employ a downhole pump which utilizes wellbore fluid. Admittedly, this requires careful consideration of hydraulic power requirements, particularly during formation breakdown when power demand might exceed that which can be supplied via commercial wirelines, but the problems are not intractable.

An explanation of the nature of the stress variations is beyond the scope of this paper. Our intention here is merely to establish the validity of the stress characterization. However, several important implications may be deduced without lengthy argument or supplementary data.

twice the corresponding S_{HMIN} values and hence constitute only lower bounds, as has been discussed. The estimates derived using Method 1 are largely consistent with this, inasmuch as they are higher. A few exceptions are evident (physically unacceptable estimates which were less than S_{HMIN} are omitted from the figures) which we ascribe to exceptionally high tensile strength of the rock in the straddled interval. Where such anomalies occur, the lower bound given by Method 2 remains valid. The majority of the high strength intervals were encountered in the shallow sections of the well and breakdown pressures as much as 30 MPa in excess of re-opening pressures were observed. We note that Haimson and Stahl (1970) also report similarly high breakdown pressure excesses for tests conducted in a neighboring county at a stratigraphic level equivalent to our B-sand, and ascribe it to mud lining the borehole wall. This was not the case here as mud had never been loaded into any of the holes. Rather, we believe the inferred high tensile strengths are real and reflective of locally intact rock of unusually small microcrack size. That the material is capable of such strength is borne out by the results of the Brazilian tests (Cliffs Minerals, Inc., 1981).

The profiles show that maximum horizontal stress generally follows the same pattern as the minimum, the ratio of the two being approximately 2.5 to 1. The implied shear stress, although high, falls within the compressive failure envelope for Devonian shales as determined by Blanton, et al. (1981). We note that the inferred principal stresses in the upper section of the Tully limestone both lie on the super-lithostatic trends defined in the Rhinestreet sand beds, in stark contrast to the surrounding shales. The S_{HMAX} profile also suggests the existence of a further stress discontinuity at the level of Genundewa limestone.

Fracture Trace Geometry: Owing to time constraints, post-fracturing televiewer surveys were conducted in only the Appleton and Wilkins wells. In 70% of cases it was possible to identify a new trace of sufficient extent and clarity to sensibly determine the strike and vertical extent of the induced fracture(s). The vast majority of the fractures were determined to be within ten degrees of vertical. The only clear exception was the fracture induced at the H-sand horizon (311.85 m) in the Appleton well which was determined to be horizontal. Several other intervals showed fractures which were tentatively interpreted as horizontal. However, the confidence level of the identification was low. The inferred mean strikes of the vertical fracture limbs from the Wilkins and Appleton well surveys are shown in Figures 11 and 12 respectively. The data are segregated into successive 200 m depth groupings. Fractures induced in the quartz-rich beds are indicated by dashed lines. In summary of the trace data, we note the following:

In several cases only one fracture limb could be identified. This should not be taken to imply uniaxial fracturing as it may be a consequence of limited televiewer resolution. In only two examples was both the image background favorable for fracture identification and a solitary trace clearly defined.

Bilateral fractures were rarely straight and 180° opposed. Rather, there was a strong tendency for bifurcation, the splays occasionally spanning 40° of wellbore. Where splaying was observed, the orientation of the limbs shown in Figures 11 and 12 was taken as the mean value.

A large degree of scatter in limb orientation is evident. Some of this can be ascribed to instrumental error. Our experience in running three different televiewer tools during the surveys, often with multiple passes of the same interval, led us to conclude that image orientation varied in a seemingly non-systematic manner at the level of about ± 7° from magnetic north. This was found, even for the same tool imaging the same interval on different days. However, even allowing for this, the scatter in orientation is surprisingly large, given the smooth variation in ISIP's. Using the circular statistical methods of Mardia (1972) we find a mean orientation of N68.5°E (true) for the Wilkins and N80°E for the Appleton, the standard deviations being 24° and 23° respectively. In Figures 8 and 9 we have plotted mean strike alongside the corresponding stress estimates. For bilateral fractures it was assumed that the two traces represent the expression of a single planar fracture that intersects the wellbore, not necessarily diametrically. Unlike the stress magnitudes, no systematic first-order correlation with lithology is evident in the stress transition zone. Furthermore, outside of this zone, the scatter in orientation is not reflected in the inferred stress magnitudes which define smooth consistent trends. From this we conclude that the scatter largely reflects the distribution of flaws which serve as fracture initiation points, and that the fractures tend to align themselves with the maximum stress direction after propagating some short distance from the wellbore. Similar scatter in wellbore fracture orientation has been reported by Overbey and Rough (1968) for induced fractures in sandstones equivalent to our B-sand in a neighboring county.

A more detailed analysis of the data is beyond the scope of this paper. Our immediate concern is to make the point that the variations in horizontal stress magnitude that we observe, notably in the transition zone, are real and not a consequence of systematic variations in fracture orientation.

Packer By-pass: Direct evidence of fluid by-pass of the packer seals was observed in 13 Wilkins, 3 Appleton and 2 O'Dell well tests. Lower packer by-pass was recognized by rushes of fluid up-hole during packer de-pressurization indicative of a pressurized wellbore below. Fluid effusion from the wellbore during pumping indicated upper packer by-pass. Inspection of televiewer images showed that in all but two cases, fracture extension in excess of .85 m along the 1.04 m packer seals had occurred. Furthermore, in the Wilkins well a further 8 intervals showed fracture extensions which

Firstly, it is clear that no single stress ratio can be assigned to the study area. Fracture gradient was observed to vary between 1.17 and 0.65, depending upon stratigraphic horizon.

Secondly, the stress variations are not consistent with simple poro-elastic models involving gravitational and uniaxial tectonic loading. We note that stresses in the quartz-rich and limestone beds are substantially higher than the surrounding mudstones, contrary to that frequently supposed or reported.

Thirdly, fracture orientation at the wellbore does not define the orientation of fracture propagation to better than 20°, at least in the materials encountered in this project, to depths of 1 km.

Fourthly, initial shut-in pressures appear to have remained unaffected by fracture extension along the length of the packer seals. This result may hold only for small volume tests as were conducted in this study.

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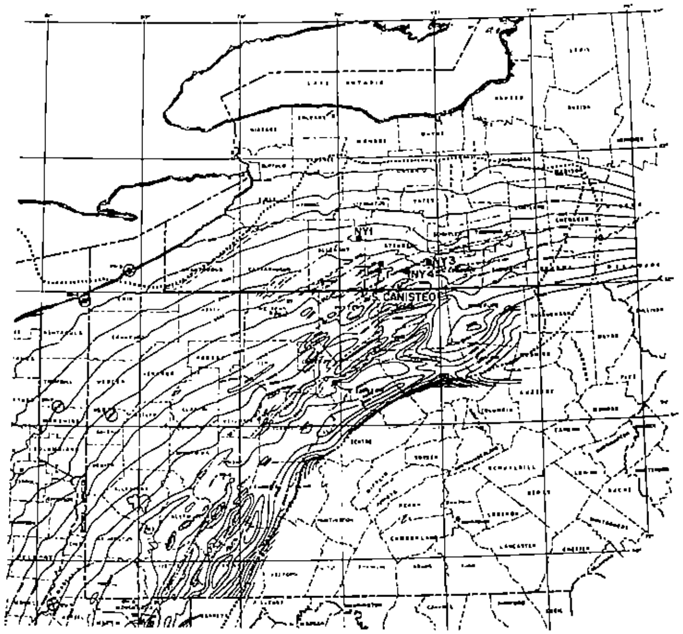

Fig. 1—Location of the study area with respect to neighboring EGSP wells in the north Appalachian basin. The dotted line represents the Silurian salt margin.

STUDY AREA

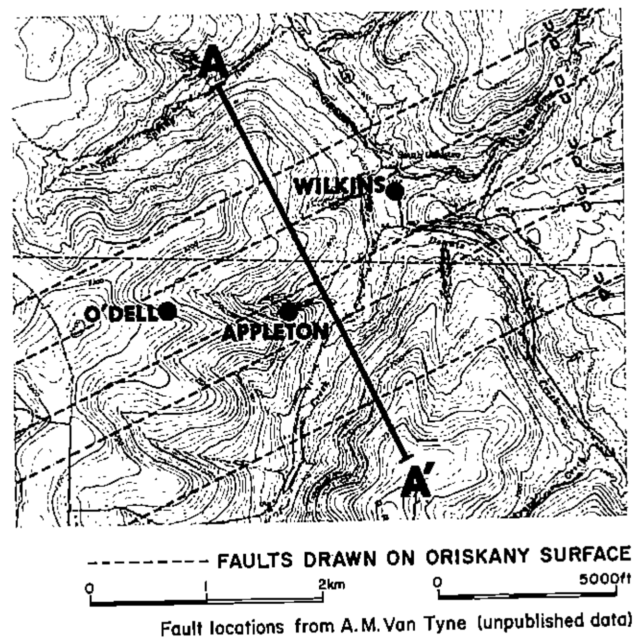

Fig. 2—Site map showing well locations and topography.

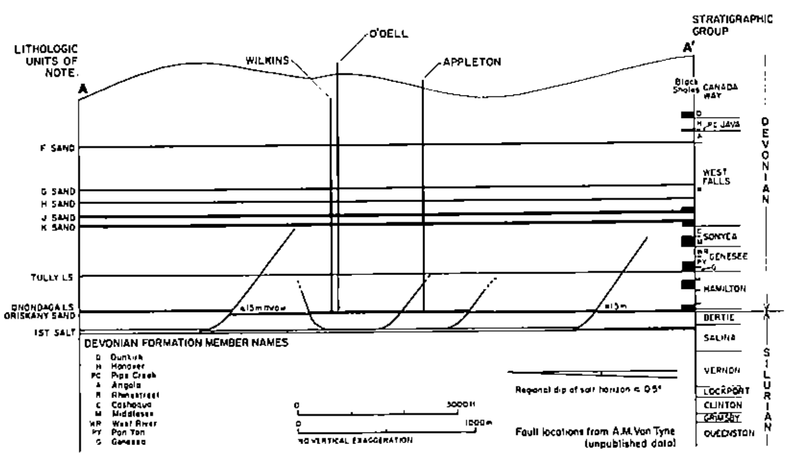

Fig. 3—Cross-section along A-A' of Fig. 2.

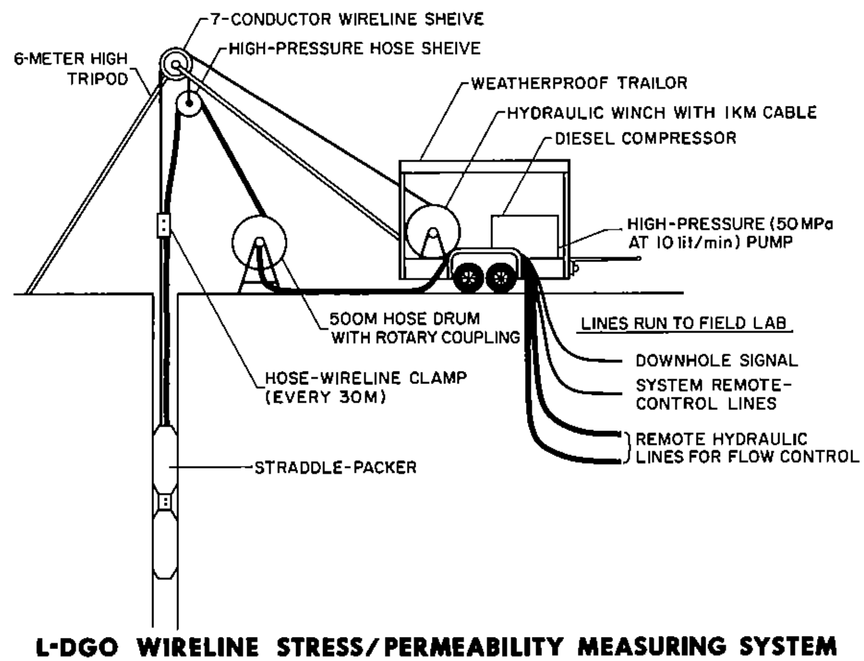

Fig. 4—Stress-testing microfrac system used in the project.

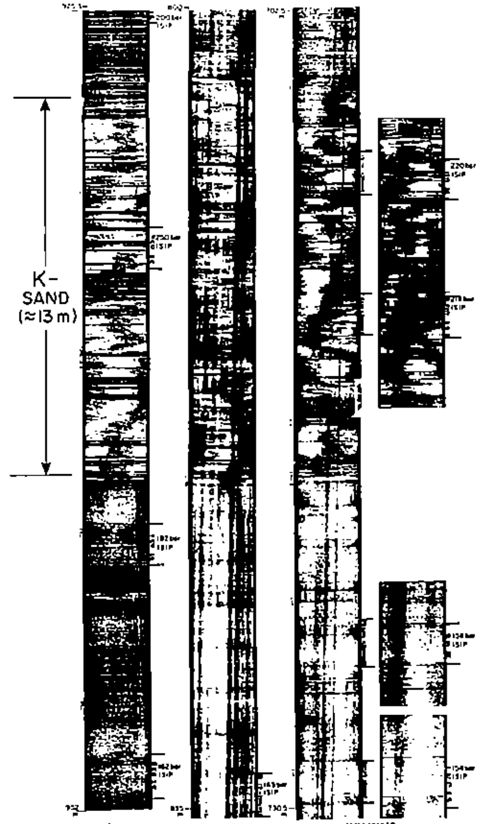

Fig. 5—Sections of acoustic reflectivity log from each well spanning the K-sand horizon. The location of stress-tested intervals is also shown.

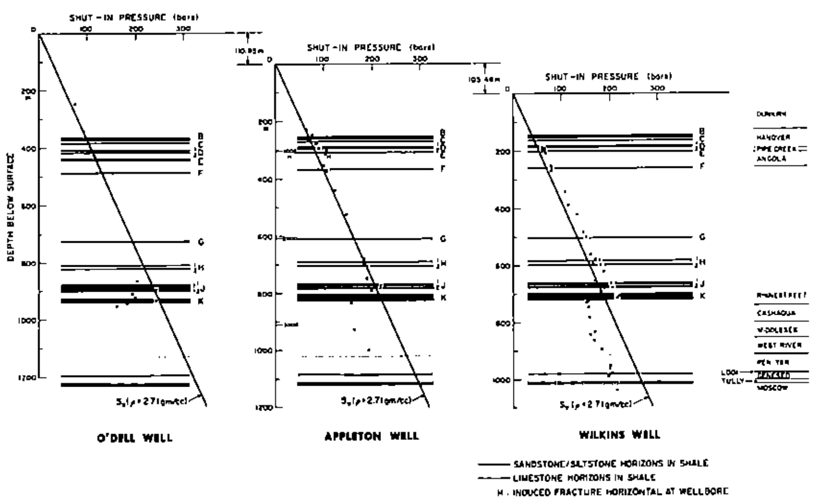

Fig. 7—ISIP as a function of depth for each well. The depth axes have been displaced such that common stratigraphic horizons are aligned.

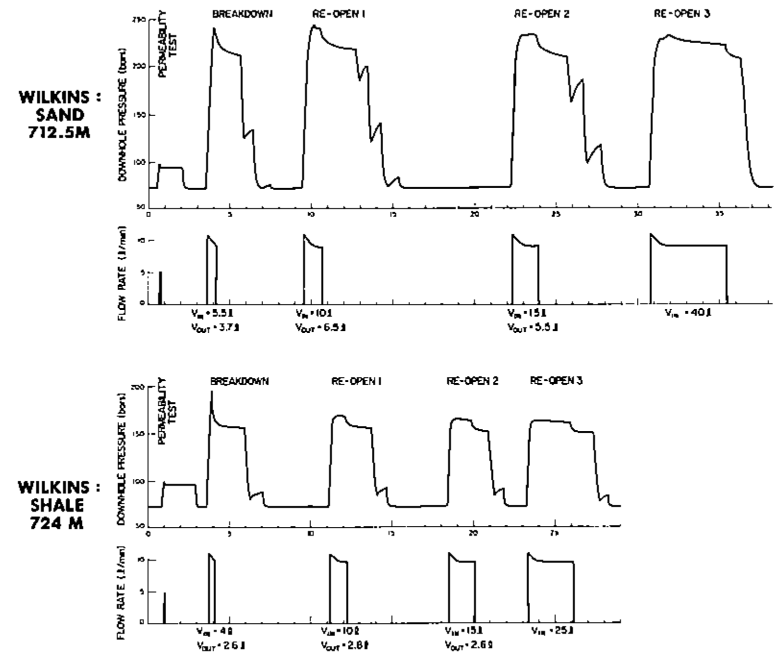

Fig. 6—Pressure-time and flow input-time records for two holes in the Wilkins well.

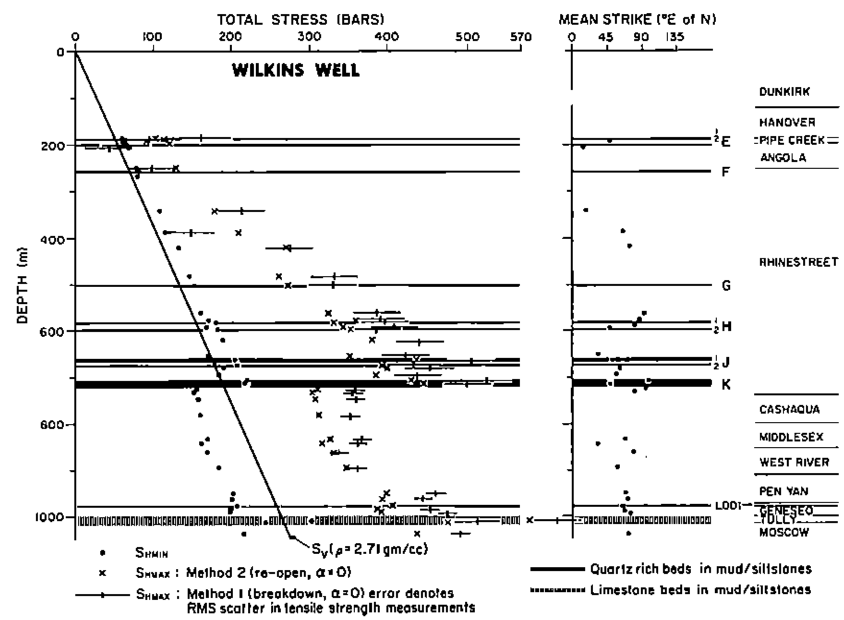

Fig. 8—Summary of total stress data for the Wilkins well.

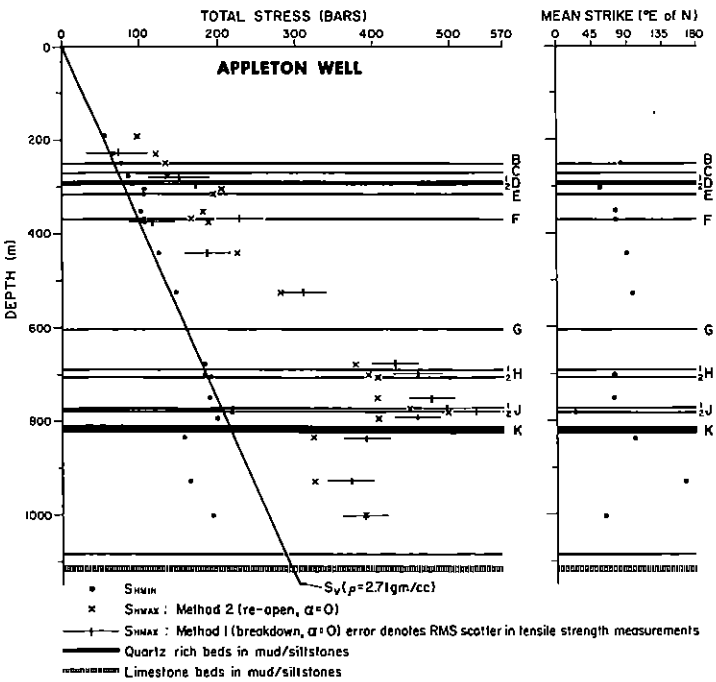

Fig. 9—Summary of total stress data for the Appleton well.

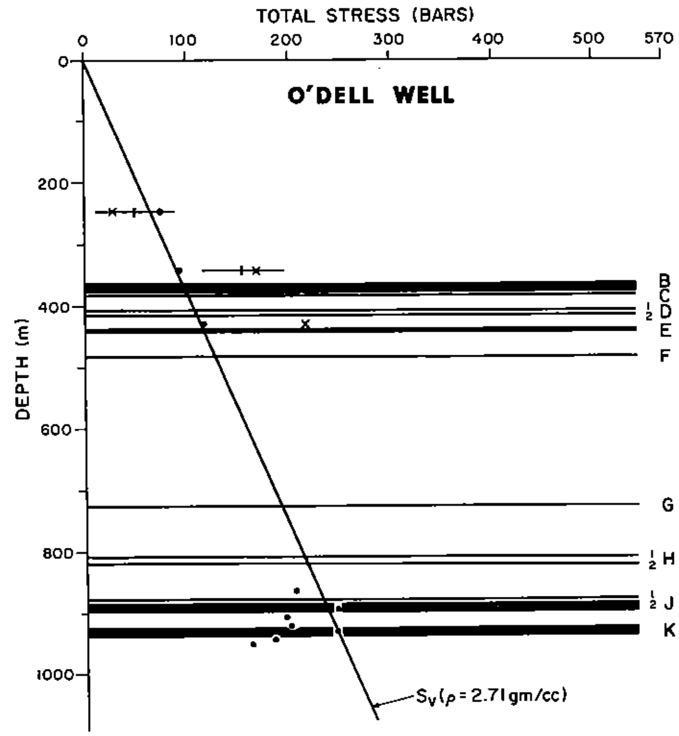

Fig. 10—Summary of total stress data for the O'Dell well.

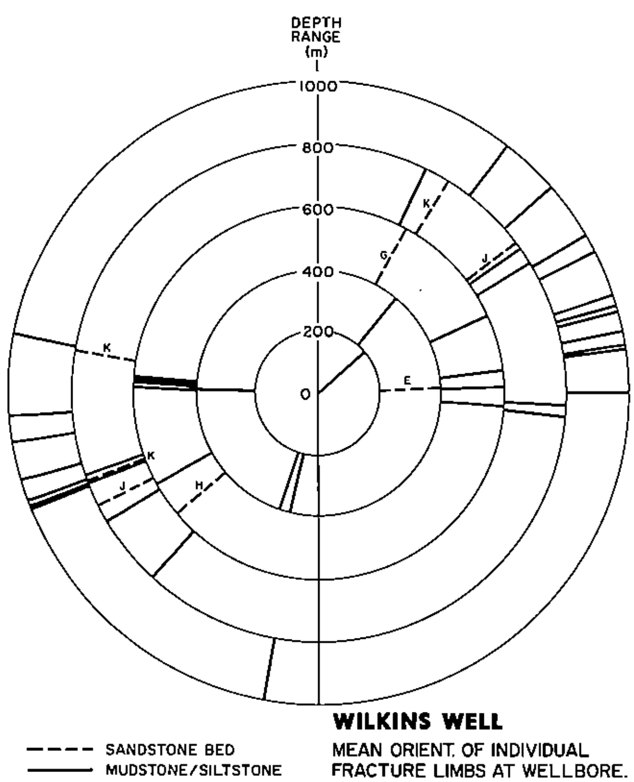

Fig. 11—Orientation of fractures as a function of depth for the Wilkins well.

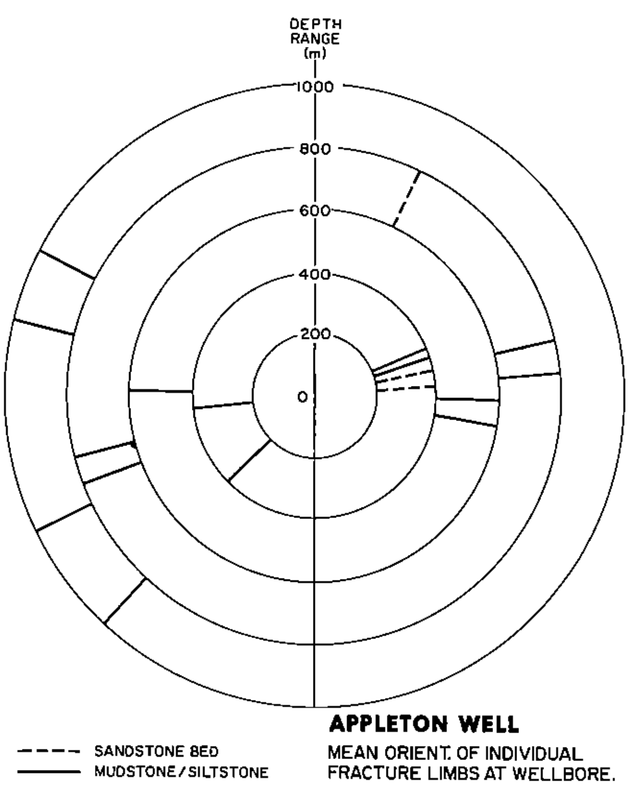

Fig. 12—Orientation of fractures as a function of depth for the Appleton well.