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INTER-OFFICE MEMORANDUM

SUBJECT: AMAX No. 1 Livermore well DATE April 23, 1979

TO: A. M. Dolan
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FROM: J. E. Deymonaz

SUMMARY AND CONCLUSIONS

Lithology

The well was spudded in Upper Franciscan graywacke, and continued in interbedded graywacke and argillites down to 5150 feet. There an 85 foot thick unit of greenstone marked the boundary between the Upper and Lower Franciscan Units. The well was continued to 8760 feet in graywacke with minor argillites, greenstones, blueschists, and chert.

Structure and fluid movement

The rapid change in the drift direction of the well from 3200-4200 feet, and the fractures, fracture filling material, brecciation, and mineralization below 5100 feet, together with the results of temperature logs indicate the well entered a fault zone between 4000-5150 feet, and remained within the influence of the fault zone at least to a depth of 8600 feet.

While temperatures in the upper 5500 feet of the well have equillibrated in a normal manner, the lower 3000 feet of the well is apparently experiencing a long term temperature drift.

A possible explanation is a near vertical permeable plane, consisting of one or more open fractures. This would allow a natural upward movement of warm ground water, causing some of the aberrations noted in the temperature logs (roll-overs, positive increases followed by lower than normal gradients, and the apparent increase in gradient near the bottom of the well). Also, it would permit both a vertical and lateral movement of drilling fluids along a plane roughly paralleling the well, causing an equillibration period disproportionate to the amount, and location, of fluid lost.

Temperatures

From the confusing array of temperature data thus far gathered, an average gradient of 60-65°C/km, perhaps slightly higher, seems justified. Assuming a bottom hole temperature of 170±5°C, and a gradient of 70°C/km, the 240°C isotherm would be intercepted at about 12,000 feet (12,500 feet with a 60°C/km gradient).

Future exploration

It appears that temperature projections can reliably be made from shallow gradient holes in this area. Therefore, the present plan to drill additional shallow gradient holes, and better define the anomaly before deciding on the future course of deep drilling is the most prudent plan of action.

Any future deep drilling should involve a three-dimensional model, which would be modified during the course of drilling, and used to determine the need, if any, for directional drilling to intercept a specific target.

STRATIGRAPHY

Drill site description

The well was spudded in a small "window" of Upper Franciscan graywacke. To the east, west, and north is a thin cap rock of silica carbonate rock emplaced by a low angle thrust fault. The northerly dipping sole of the thrust is visible in the cut bank along the east side of the site. About 1200 feet west of the drill site, more extensive exposures of silica carbonates and related serpentinites occur and continue on to the west for several miles.

About 200 feet south of the wellhead is a small dacite dike of the Sonoma Volcanic Series(?) lying along an east-west trending fault. Silicic tuffs of the Sonoma Volcanics lie south and about 600 feet east of the well. The tuffs to the east appear to form a thin veneer overlying the Franciscan, while to the south they are in fault contact with the Franciscan and have an unknown depth.

Generalized downhole lithology

From the surface to 3500 feet the well passes through a monotonous sequence of light- to medium-gray, fine- to very fine-grained graywacke with micas often imparting a phylittic sheen, and minor amounts of quartz and calcite fracture filling material. Minor, localized alteration to chlorite, and rare pyrite mineralization are also associated with the graywacke. Interbedded phylittic argillites comprise 0-30% of the rock.

Nearby surface exposures of graywacke closely resemble cuttings from the upper portion of the well, and have numerous thin beds (2mm to several cm. thick) of argillite comprizing 20-30% of the rock. It is likely that the rock encountered in the upper 3500 feet of the well is very similar to these surface exposures.

From 3500-5150 feet the amount of argillite increases rapidly, often comprizing 75-90% of the cuttings. Except for a 27 foot section of greenstone at 4763 feet, and a few traces of greenstone at other depths, the lithology remains quite uniform down to 5150 feet.

At 5150 feet an 85 foot section of greenstone marked, what will be considered in this report, the base of the Upper Franciscan and the top of the Lower Franciscan Units. Below the greenstone, graywacke again becomes the predominant rock type, although it is of a considerably different character than above. The graywacke is medium- to fine-grained with common alteration to chlorite, and minor amounts of epidote. Pyrite is widely dissiminated throughout the rock, though comprizing less than 1% of any one sample. Rare, small concentrations of pyrite are found in some vein quartz. 10-30% of most samples are composed of quartz and calcite fracture filling material. Fractures generally cut across grain boundaries, and less often follow grain boundaries, or form halos of quartz around clusters of grains. Some samples appear to have been brecciated and silicified, however, the brecciation occurs randomly throughout the lower portion of the well and does not seem to be associated with any specific fracture zones encountered.

Argillite, common above 5150 feet, generally conprizes less than 10% of the lower 5000 feet of samples.

Greenstone (5150-5285, 5510-5518, and common traces 5550-8760) encountered is usually mottled light- to medium-green, fine-grained to aphanitic, with occasional white, pink, and rarely clear quartz filling small fractures. Pyrite occurs as a trace mineral dissiminated throughout most samples.

Light-gray, green, brown, and yellow chert appears in trace amounts in several portions of the well and often contains small amounts of pyrite.

Small amounts of dark-blue, dense, aphanitic to schistose blueschist occur at several depths (6361-6368, 6385-6395, 6685-6693, 7123-7128, 7490-7501, and 7900-7918), and in each case is associated with small amounts of greenstone. The 2.9-3.15 gm/cm^3 density of the blueschist makes it possible to outline small lenses of the rock from the Schlumberger density log (2500-8230 feet). The logs agree fairly well with the cuttings taken, although, individual intervals are more limited in thickness than is indicated by the cuttings. The density log outlines some dense areas 10-18 feet thick, and in cuttings they occur over intervals of 30 feet, however, the blueschist never accounts for more than a few percent of any one sample. This may indicate that the blueschist is emplaced in clusters of small stringers along with minor amounts of greenstone in the graywacke rather than as homogeneous lenses.

STRUCTURE AND FLUID MOVEMENT

Subsurface structural influences

Rocks of the Franciscan Formation have undergone intensive tectonic deformation, making projection of down hole structural trends from surface exposures difficult. Evidence pretaining to bedding attitudes, folding, and faulting can, however, be interpreted from drilling irregularities, cuttings, and downhole logging. In examining these trends downhole, certain assumptions concerning the drilling must be made:

a. In a purely homogeneous material, gravity and the force exerted by the clockwise rotation of the drill bit would be the major factors influencing the drift of the drill hole. The result would most likely be a hole gently spiriling to the right, with a radius dependent upon the flexiability of the drilling assembly.

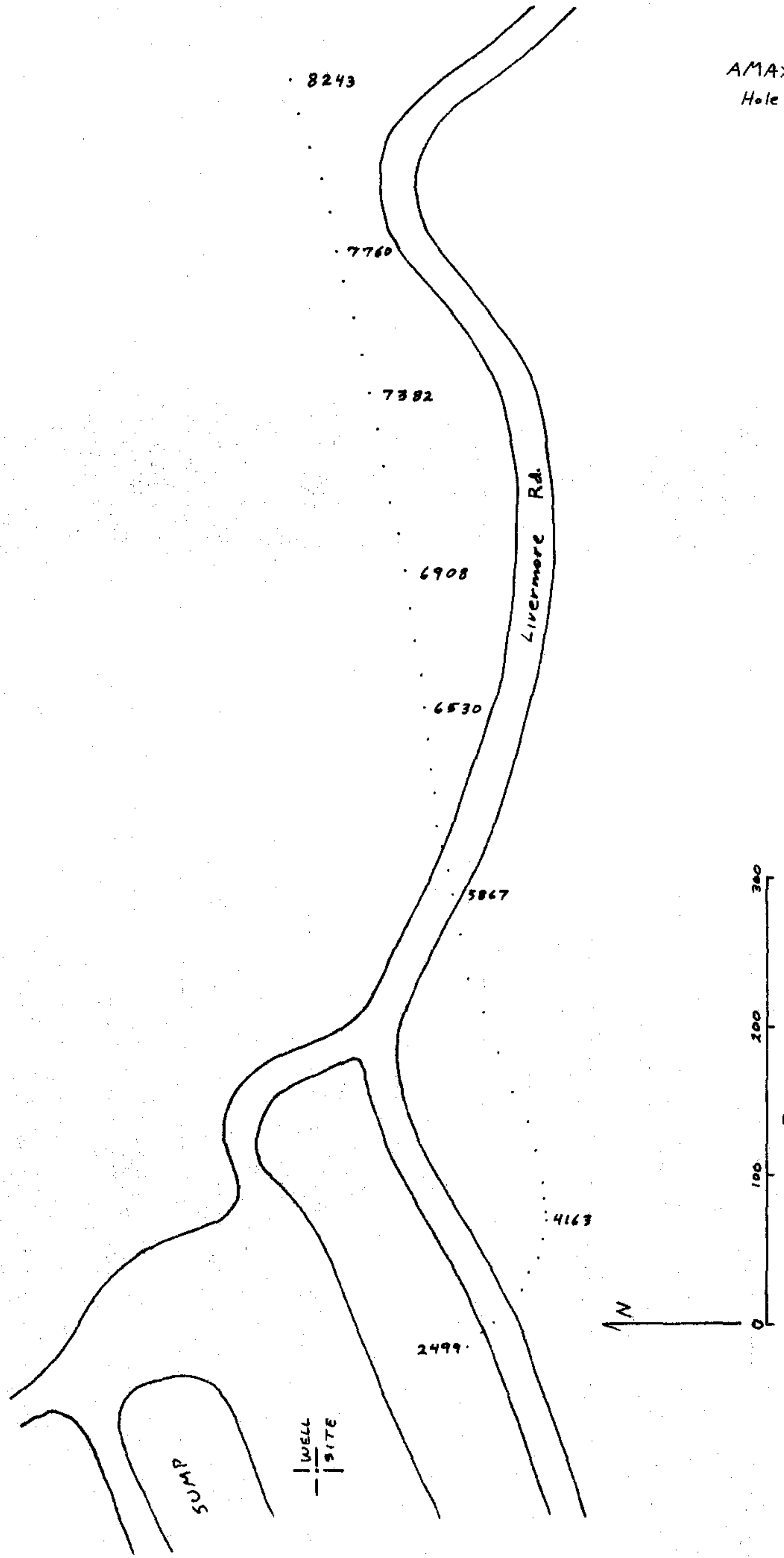
b. Any significant deviation of the drill hole from vertical which cannot be attributed to drill assembly rotation may therefore be caused by some internal structure in the rock (bedding, fractures, formational contacts, schistosity, etc.).

While drilling, the hole deviated to the southeast at 2°-3° down to about 3500 feet. At that depth the amount of argillite increased substantially, deviation began increasing, and the hole started to turn east (Fig. 1). The hole stabalized in a N75-80E direction at about 4250 feet. The sudden change in drift direction can be attributed to a change in bedding dip from southeast at a moderate angle, to steeply dipping either north or south. Another possibility would be near vertical shearing, striking east-west. There is no indication of open fractures, or substantial amounts of fracture filling material between 3000-4650 feet. It's likely that this is a zone of drag folding or shearing passed through by the drill bit as it approached, or entered, a fault zone at a low angle from the upthrown block.

Although the hole direction stabalized by 4250 feet, the drift angle did not change substantially until nearly 5900 feet, increasing from 8° 30" to 15° 00" in about 1000 feet of drilling (from 4250-5874 feet the drift angle increased only from 4° 30" to 8° 30"). At 5874 feet the drilling assembly was reduced from 12 1/4 inches to 8 3/4 inches, and the larger, less flexiable drilling assembly is probably responsible for the lag.

At 5150 feet a major lithologic boundary was crossed. Below that point, the lithology consists mainly of graywackes with lessor amounts of argillites and minor greenstones, buleschist and chert. This change probably marks the contact between the Upper and Lower Franciscan, and in the well lies near or within a fault zone. Fluid movement indicated by temperature surveys just above this point

AMAX # 1 LIVERMORE
Hole drift / depth.
Fig. 1



(4650 feet), an increase in fracture filling material, brecciation, and the increase in open fractures encountered below 5150 feet indicate the existence of a fault zone beginning in this area.

From at least 5150 feet, the well continues within the fault zone and possibly passes through it at a very low angle (<5°). The slight decrease in fracture filling material around 8700 feet, and the increased gradient beginning at 8500 feet may mark an exit from the fault zone, or possibly reflect the influence of another intercepting fault zone.

Two faults mapped at the surface could concieveably intercept the well at around 5000 feet, and a third may exert some indluence on the well at about 8500 feet:

a. The Corona Fault, striking approximately N55W has a surface trace 1700 feet southwest of the drill site. Plotting the well as a line across the plane of a fault striking N55-65W, the fault would be required to dip north at 75°-80° to intercept the well at the proper depth and attitude. Although it is possible that the fault zone drilled into is the Corona Fault, several factors argue against it:

   1. Mercury mineralization is associated with the Corona Fault. Except for one small (¼mm) sample of cinnabar at about 7300 feet, no such mineralization was noted in the cuttings.
   2. Silica carbonate and serpentinites occur along the trace of the fault for several miles to the south and southeast. No serpentine or silica carbonate rock was encountered in the drilling.
   3. Surface investigations indicate the Corona Fault is nearly vertical south of the drill site, and dipping gently to the south about 2.5 miles southeast of the drill site.

b. An unnamed east-west trending, nearly vertical fault with a surface trace about 200 feet south of the well. The surface trace of this fault has its eastern most exposure a few hundred feet southeast of the drill site, and from there it can be followed about ½ mile to the west. At both ends, the fault disappears into tuffs of the Sonoma Volcanics, and the fault may continue in or beneath these tuffs. A fault which intercepts the Twin Peaks Fault northeast of the Livermore Ranch homes may be a western continuation of this fault. Displacement along the fault is not known, although, it does appear to seperate rocks of the Franciscan Formation from those of the Sonoma Volcanic Series in the vicinity of the drill site. A small dacite dike of the Sonoma Volcanics(?) lies along the fault just south of the drill site. The faults relationship with the Sonoma Volcanics, and the lack of mercury mineralization associated with the volcanics in the area could account for the absence of mineralization in the fault zone down hole, while providing a source of silica bearing waters responsible for sealing most of the fractures within the fault zone. A fault plane striking N77-90E and dipping north 86° fits the line of the well very nicely.

c. An unnamed, curving, north-south trending fault with a surface trace about 1400 feet east of the wellhead. The fault appears to be nearly vertical and is associated with a zone of hydrothermal alteration which trends northward towards the Magnola Mine. The type and amount of displacement along the fault is unknown. At 8243 feet the measured drift of the well is about 950 feet east of the wellhead. Continuing the deviation at 15° the well would bottom about 1080 feet east of the wellhead, and 300-400 feet west of the surface trace of the fault. There is a remote chance that the fractures encountered below 8400 feet mark the intersection of this fault and the east-west striking fault zone, along which, the well is tracking.

Movement of fluids

Assuming over 3500 feet of hole was drilled in a fault zone, relatively little fluid was lost, less than 2000 bbls. between 5150-8760 feet. Nearly half of this volume was lost below 8400 feet, although open fractures were encountered at intervals throughout the fault zone. This indicates that most fractures in the fault zone have been sealed, or are of limited extent.

The most perplexing problem associated with the well, is that four months after moving off location, temperature logs indicate that the fault zone is still not fully equillibrated and suggest fluid movement, while the upper 5500 feet has nearly reached equillibration. A possible explaniation for the lenghty down hole equillibration time is one or more vertical permeable zones within the fault zone providing for a natural upward movement of warm fluids, and a conduit for the movement of drilling fluids.

An angle of interception between the drill hole and fault zone of 5° or less would allow open fractures within the fault zone to deviate less than 9 feet laterally from the well per 100 feet vertically. A smaller angle, and more realistically, fractures following a slightly irratic course rather than a perfect plane could allow the well and fractures to remain in close proximity over a considerable distance. This would account for several occurances observed in the well:

a. A positive increase in the temperature gradient as the well nears a permeable area in the fault zone, as on the March 3 temperature log from 4800 to 5700 feet. This would be caused by the upward movement of warm fluids along a near vertical plane, which is approached by the well at a low angle.

b. The lowered gradient within the fault zone. Caused by slowly assending and cooling waters, forming an abnormally high temperature at the intercept depth, and a lower gradient within, or in close proximity to the convective system in the fractures. This is evident between 5750 and 8450 feet on the November 30 and March 3 temperature logs.

c. As the well leaves the fault zone, and the influence of the convective system, the gradient will tend to return to the pre-fault zone gradient. This may be occuring at about 8500 feet where the gradient is increasing slightly after passing through a permeable zone.

d. A continuous, near vertical permeable zone paralleling, and occasionally intercepting the well would allow drilling fluids to migrate vertically, displacing the natural fluids and disrupting temperatures parallel to, and outward from the well for considerable distances. Dave Blackwell concurs that, if this were the case, temperatures within the zone would require a longer equillibration period than if disrupted by fluid movement along a horozontal plane outward from the drill hole. This could contribute to the excessive length of time required for the lower portions of the hole to equillibrate. The equillibration period could also be extended if the drilling fluids sealed portions of the vertical conduit, and after an unknown period of time, movement reoccured for some reason.

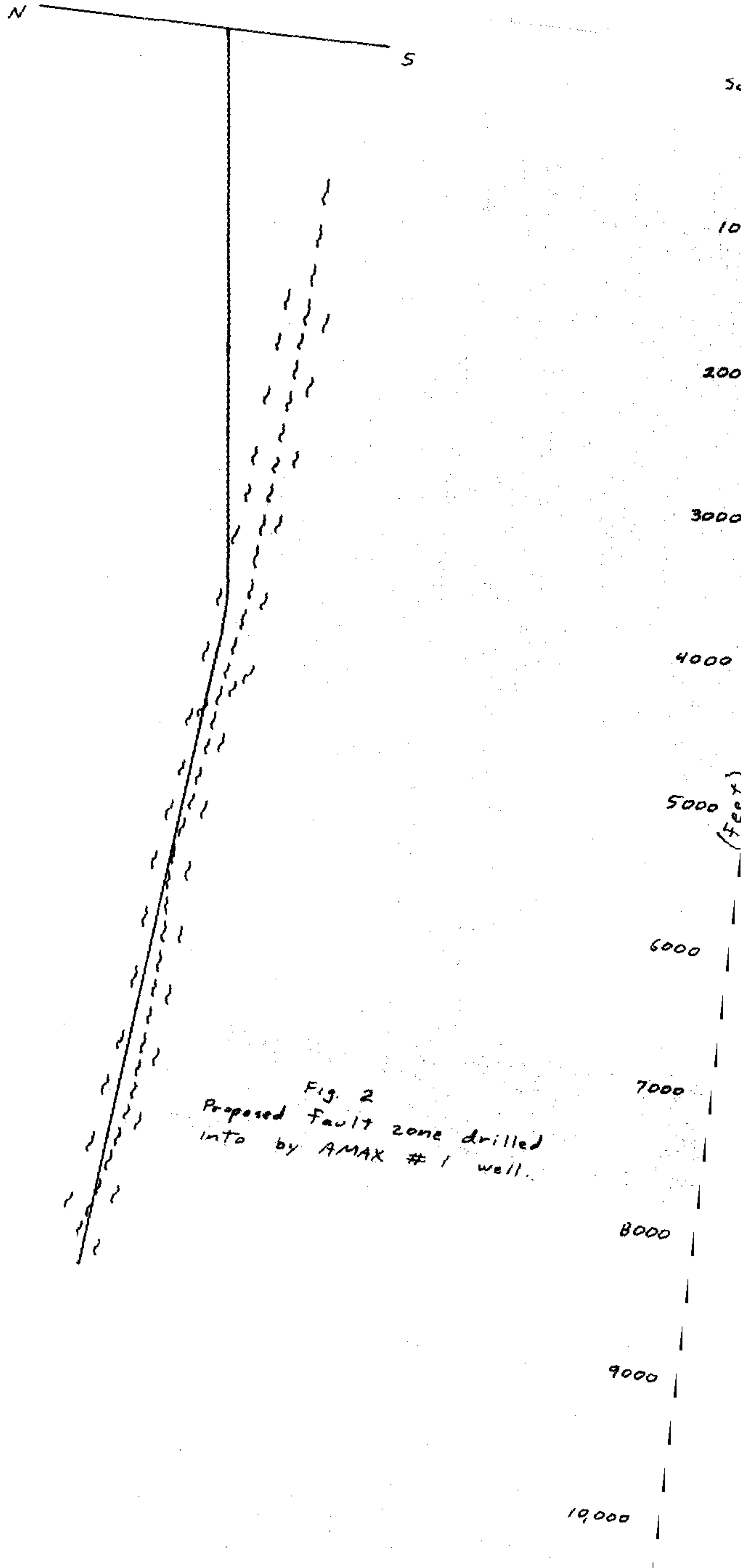


Fig. 2
Proposed fault zone drilled into by AMAX # 1 well.

e. Small aberations in the gradient within the fault zone (5925, 6360, 6500, and 8500 feet respectively) could be caused by fluid movement along open fractures connected to the main vertical fracture(s), by intersecting fault zones, or by the well re-entering the main fracture system.

A final possibility is that the well itself may have acted as a conduit, allowing the slow downward movement of fluids in the lower 2500 feet of the well, and their migration into the formation below 8400 feet. However, the expected dehydration of the drilling fluids, the length of time involved, and the lack of any noticeable effect on the upper 5500 feet of the well makes the mechanics involved difficult to comprehend.

TEMPERATURES

Absolute down hole temperatures have been elusive to date, however, the average gradient appears to be in the 60-65°C/km range, possibly a little higher. Five temperature recording instruments have been run in the well, providing a wide range of bottom hole temperatures. The most "beleaveable" being 170±5°C from the Nov. 30 and March 3 G.O. logs, the other instruments appear to have been influenced by either pressure or internal problems. The gradient varies substantially in the lower portion of the hole, and this may be attributable to rising and cooling waters within the fault zone mentioned earlier.

Prediction of dry steam temperatures from the data now available is questionable at best. Assuming the optimistic gradient of 70°C/km below 8690 feet, the depth to the 240°C isotherm would be nearly 12,000 feet (12,200 and 12,500 feet with 65 and 60°C/km gradients respectively).

FUTURE EXPLORATION

A few of the facts concerning future work in the area include:

a. Cost of deepening the existing well to 11,500 feet would be approximately $500,000, more if problems are encountered.

b. Drilling a second deep test, including road and pad construction is estimated to be 1.4-1.8 million.

c. From the limited amount of gradient data now available, the present well is on the edge of the high gradient "target area", and this "target area" is not well defined.

d. Gradients obtained from shallow gradient holes (less than 150m) in the area appear to provide realistic projections of temperatures at depth.

e. Additional shallow wells will better outline the anomally and allow a more intelligent decision to be made in regard to deepening the existing well or drilling a second well.

f. Cost of drilling 300 foot (78m) gradient holes by All Terrain Drilling is estimated to be $1500-2000 each.

Taking these facts into consideration, the most logical approach is to continue the present plan to drill additional gradient holes, further detail the "target area" and then decide on the next step in the deep test program.

As the heat flow map of the area becomes more detailed with the data from additional gradient holes, the broad anomalous area will become more involved, possibly outlining faults or fault intersections controling heat transfer. With the experience gained from the AMAX No. 1 well, and a better understanding of the structure and fluid movement in the area, a three-dimensional model of the next deep test target should be worked out in as much detail as possible prior to any drilling. This model should be kept in mind at all times, and revised as necessary during the drilling. In this manner the well would not only be aimed at a specific depth in a general area, but at a specific target. Directional drilling should be considered as a necessary expense to cut across certain structures and/or change the direction of drift if the hole is moving away from the prime target.