Effect of Geology on the Hydraulic Fracturing of Salt

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ABSTRACT

The paper is presented with the intent of bringing into focus a few of the many problems surrounding the successful fracturing of bedded salts. The results of hydraulic fracturing early in the history of the art left many unanswered questions. Based on continuous gathering and evaluation of data over the last ten years, some explanations are beginning to take form. Some of the individuals having the most experience have a "rule of thumb" which specifies, "If two wells do not connect in twenty-four hours, stop pumping." We believe that the major portion of these failures are based on geological irregularities.

A number of our questions concerning our fracturing operations at Watkins Glen, New York, have been answered by recent geological interpretations of salt disposition and subsequent deformation. Initial interpretation of structures based on the plastic flow and leaching of salt by ground water have given way in light of additional geological information to a theory of a system of thrust and normal faults. Former isopach and structural maps depicting folds and which failed to explain fracturing results have been completely discarded for the Watkins Glen area.

Areas such as Wayne County, Michigan, which are underlain by relatively flat dipping beds with gentle monoclinic folds can be shown by isopach maps. These beds, in some cases, have been disturbed by the ground water leaching of the salt with resulting secondary masses of crystalline salt being incorporated in the primary mass. In some locations, lithologic and/or chemical changes in the salt's composition are believed to be responsible for the erratic results obtained during hydraulic fracturing operations. Folding can develop fractures along the axis of the folds forming conduits along which solutions have a tendency to travel. Thus, both in salt beds which have been subjected to relatively sharp movement and those with only minor disturbance, the local geology plays a permanent role.

INTRODUCTION

A large percentage of the companies engaged in the extraction of salt from subsurface deposits by the solution method of mining have practiced the art of hydraulic fracturing with varying degrees of success. Very little has been written or otherwise divulged about any of these fracturing operations except those that are successful. A successful fracturing operation receives less attention, study and technical analysis than do the ones where difficulties are encountered.

Based on the information gathered in the Watkins Glen and Ludlowville, New York, areas over the last ten years, some explanations for our failures and difficult fractured connections are beginning to develop. For the purposes of this article which relates to bedded salt deposits, we have classified them into three major types. These are (1) The flat-lying deposits such as those in the vicinity of Wayne County, Michigan; (2) Folded deposits which are typified by the Ludlowville, New York, area; and (3) Faulted salt beds are represented by Watkins Glen, New York.

In all cases brought forth in this paper, we are basing our statements on virgin salt deposits in which there are no solution mining operations in relatively close proximity. It is known that solution mining operations adjacent to a new fracturing operation will have a direct bearing on the outcome of the fracture.

BEDDED SALT -- FLAT LYING

Wayne County, Michigan. The salt deposit underlying Wayne County, Michigan Metropolitan Airport was explored by drilling in 1955. The two and one-eighth inch slim hole cores delineated a flat-lying series of salt beds apparently disturbed only by minor monoclinic folding. Figure 1 is a stratigraphic cross section hinged on Hole # 2. This cross section illustrates the termination or "zero line" of the salt beds in the Michigan Basin. The lettering system used in Fig. 1 is a carry-over from a system used locally prior to 1900.

Between Core Hole # 2 and Core Hole # 3, an approximate distance of 2,800 feet, six salt beds have been leached out completely by ground water. Using the thickness of the intervening rock layers, the collapsed breccia zones of these leached out salt beds were actually correlated in Core Hole # 3 and Core Hole # 4. The drilling of salt wells along the perimeter of the Michigan Basin

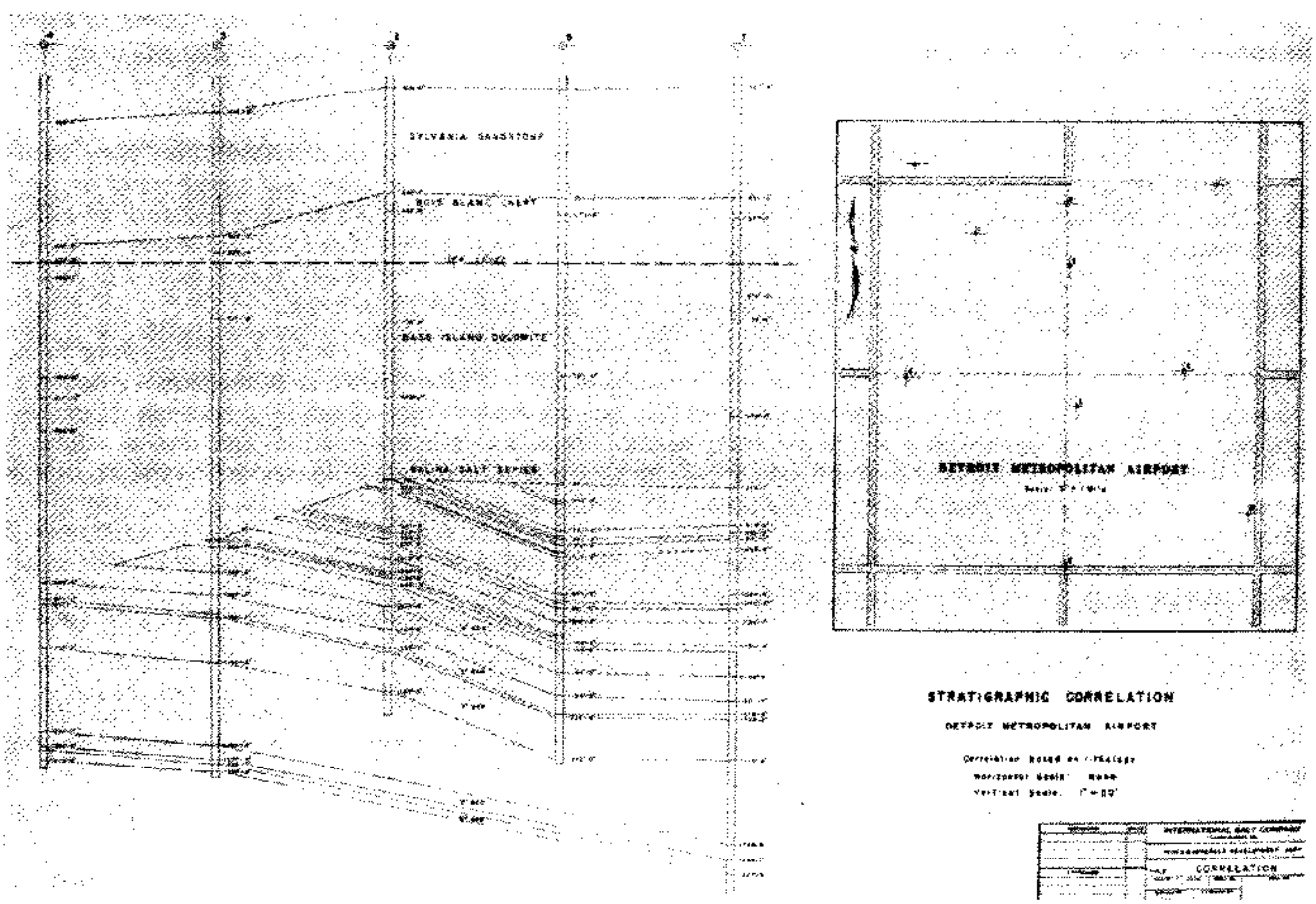

Figure 1

could have negative results unless careful correlation of the salt beds and their termination points are developed well in advance of any fracturing operations. Wells in which the salt beds were to be fractured could conceivably be drilled and penetrate large thicknesses of salt and yet be near enough to the termination point or zero line of these wells as to have the fracturing fluid travel to the zero line and be lost in the adjacent rock mass.

This possibility is illustrated in Fig. 2 which is an isopach of the "AA" bed. The strike of the zero line of this bed is approximately N52W. Core Hole # 8 disclosed a thickness in this bed of 31 feet. Theoretically, at a distance of less than 1,900 feet due west of Core Hole # 8, the bed is nonexistent.

It is our belief that in cases such as this, the direction of travel of the fracturing fluid would be perpendicular to the zero or line of termination if no other factors dominate. The truncation of this salt bed closely parallels the axis of the Howell anticline and may have resulted from its formation.

There are a number of other factors which in our opinion would influence the direction of flow of a fracturing fluid in flat-bedded salt deposits. Figure 3 shows horizontal laminae exposed in a 24-foot face in the Detroit Mine. It will be noted that these laminae terminate in a mass of salt crystal which constitutes secondary deposition. The laminated salt is primary. Where the seal of the salt bed has been ruptured after primary salt has been deposited, meteoric waters give rise to solution cavities with the resultant formation of included crystal masses.

This mass of crystal shown in Fig. 3 extends from the roof of the mine to the floor. Since the salt bed at this point was only 29 feet thick with four feet of salt in the roof and one foot remaining in the floor, we may assume that the zone extends from the top to the bottom of the bed. A fracturing fluid that migrated along a lamina of this bed would intercept this crystal mass. It is

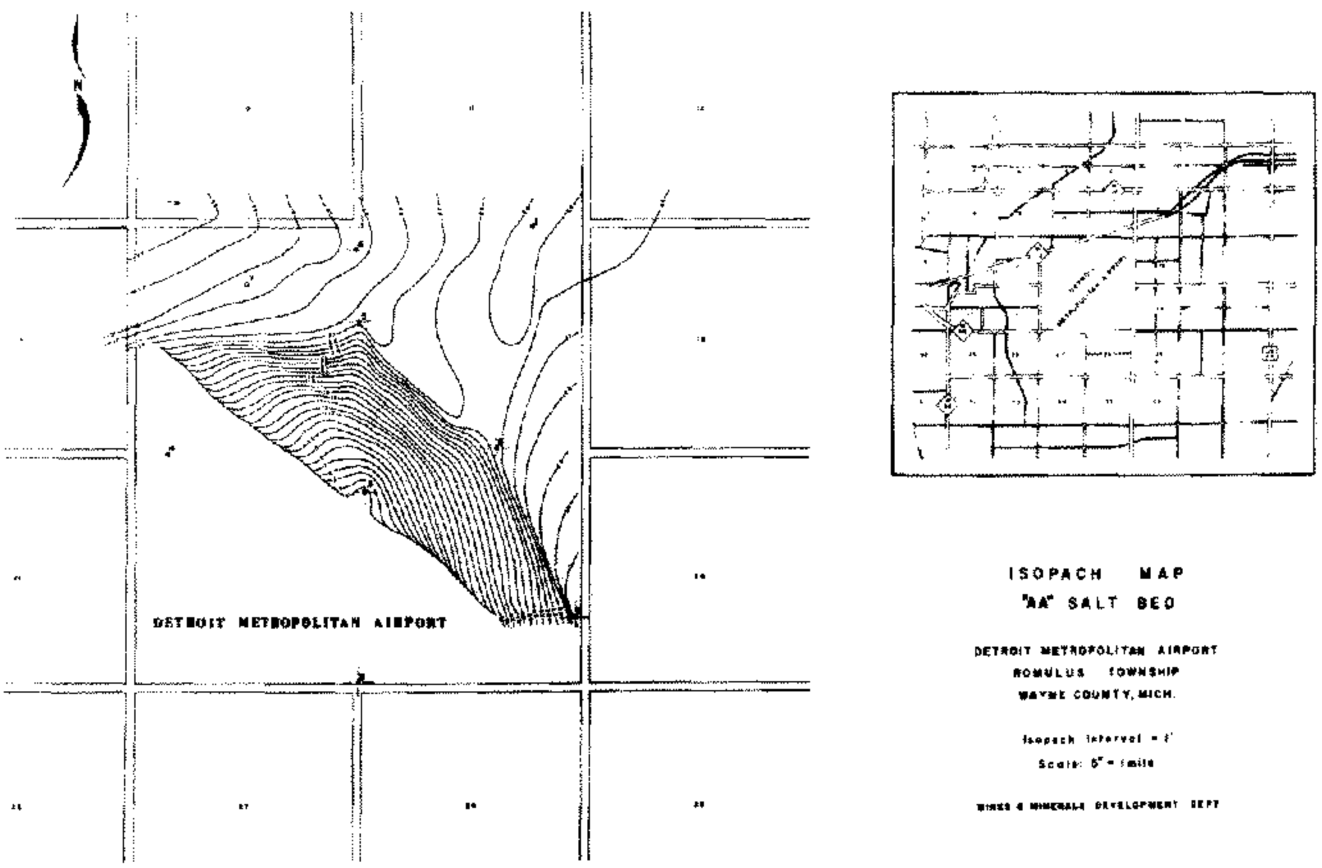

Figure 2

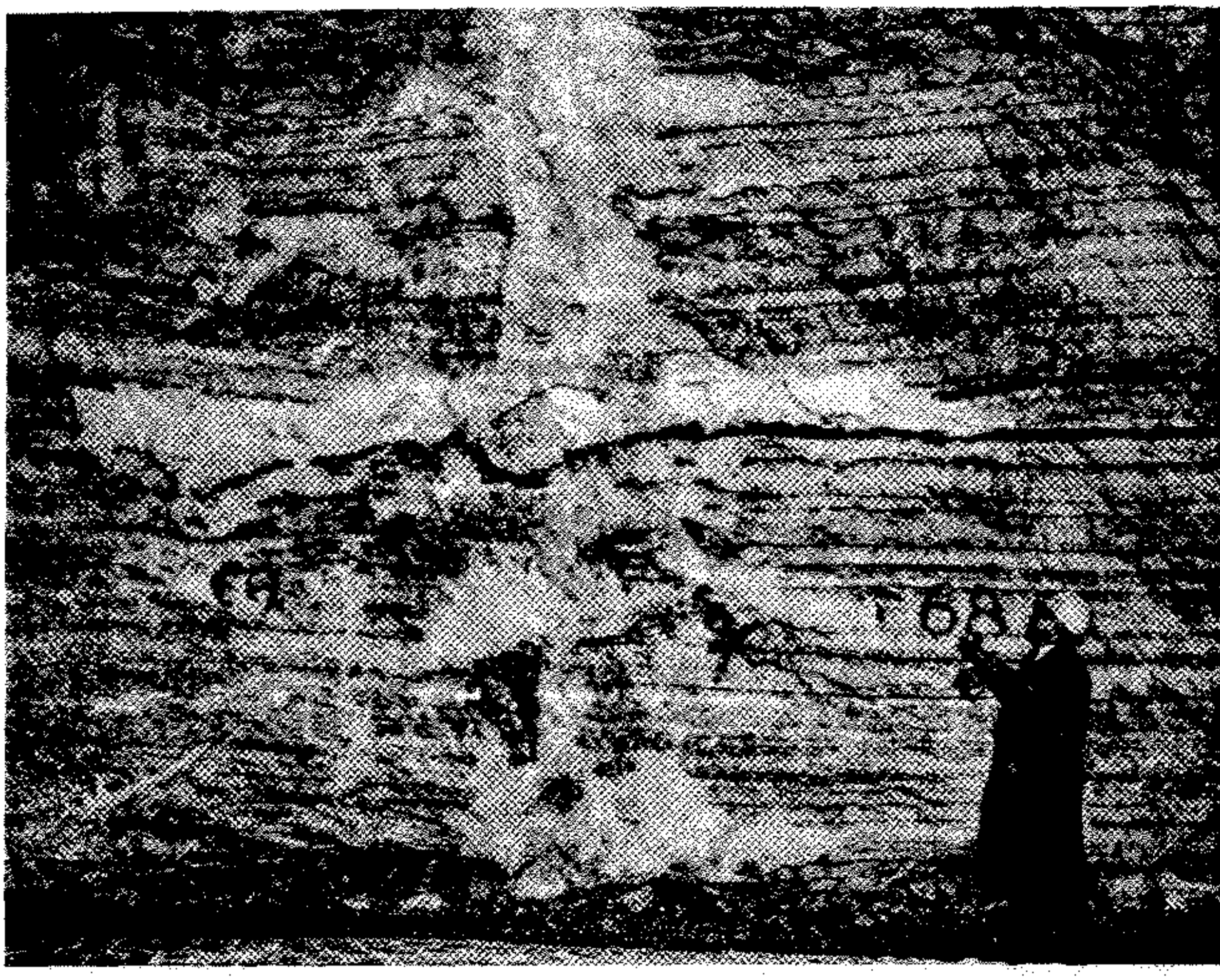

Figure 3

our opinion that at this point, the fluid would have a tendency to either travel parallel to the horizontal direction of the crystal mass or vertically to the top of the salt bed. At the top of the salt bed the fluid would follow the first major plane of weakness that it encountered, thus bed jumping would occur.

In isolated instances, these masses of crystal salt and their accompanying rock masses of solidified impurities have sufficient lateral continuity so that their rock inclusions have been termed "Rivers of Rock," Fig. 4 shows such an enclosed mass. We would not expect a fracturing fluid to split this mass but rather to follow its lateral direction. It may be noted that the salt in the upper portion of the bed is primary with horizontal laminations.

Lithological changes are known to occur in salt beds. An example of the occurrence of such a lithological change is associated with the shaft area of the Detroit Mine. When the shafts penetrated the Salina beds one was logged as "dolomite with salt inclusions." Within a few hundred years of the shaft area, the bed is a "salt, dirty with dolomitic inclusion and at a distance of 2,000 feet runs 95% NaCl. In the case of the "A-2" bed,[1] which is anhydrite in the area of the Metropolitan Airport, it becomes a bed of very pure salt in areas adjacent to and north of Detroit.

Fracturing fluids encountering a gradual change in the lithology of the salt would have a tendency to be deflected from their original direction into a new course. Likewise, impurities

[1] According to Dr. K.K. Landes.

Figure 4

suspended in the fracturing fluid as a result of the dissolving of the salt, enter the crevice and alter the direction of fluid flow. As these insoluble impurities in the salt increase, their influence on direction increases.

FOLDED BEDS

In 1957 construction was begun on a new brine field at Ludlowville, New York. Based on the results of previous hydraulic fracturing operations at Watkins Glen, New York, we had come to the conclusion that the direction of fluid flow in fracturing operations where folded salt beds were involved, was parallel to the axis of these folds. It was our belief that in anticlinal structures the fluid flows more readily parallel to and at the top of any structural unit or member. Conversely, in a syncline, the bottom of a bed has a tendency to be in tension which would facilitate fluid flows along the bottom of the bed and, also, parallel to the axis of the fold. Desiring to conduct our brining operations as near the bottom of the salt bed as possible, we attempted to find a synclinal trough.

This was done by extrapolating from known geological information on the area adjacent to our proposed field and the adjoining wells of the old brine field. The data from this adjacent area, Fig. 5, showed the folding associated with the top of the 4th Salt which was the bed in which we were to attempt our proposed fracture. It was known that the soft rocks underlying the 4th Salt had suffered parallel but much more severe distortion. In some cases, recumbent folds exist at the contact between the bottom of the 4th Salt and the underlying rock. Trough to crest distances of

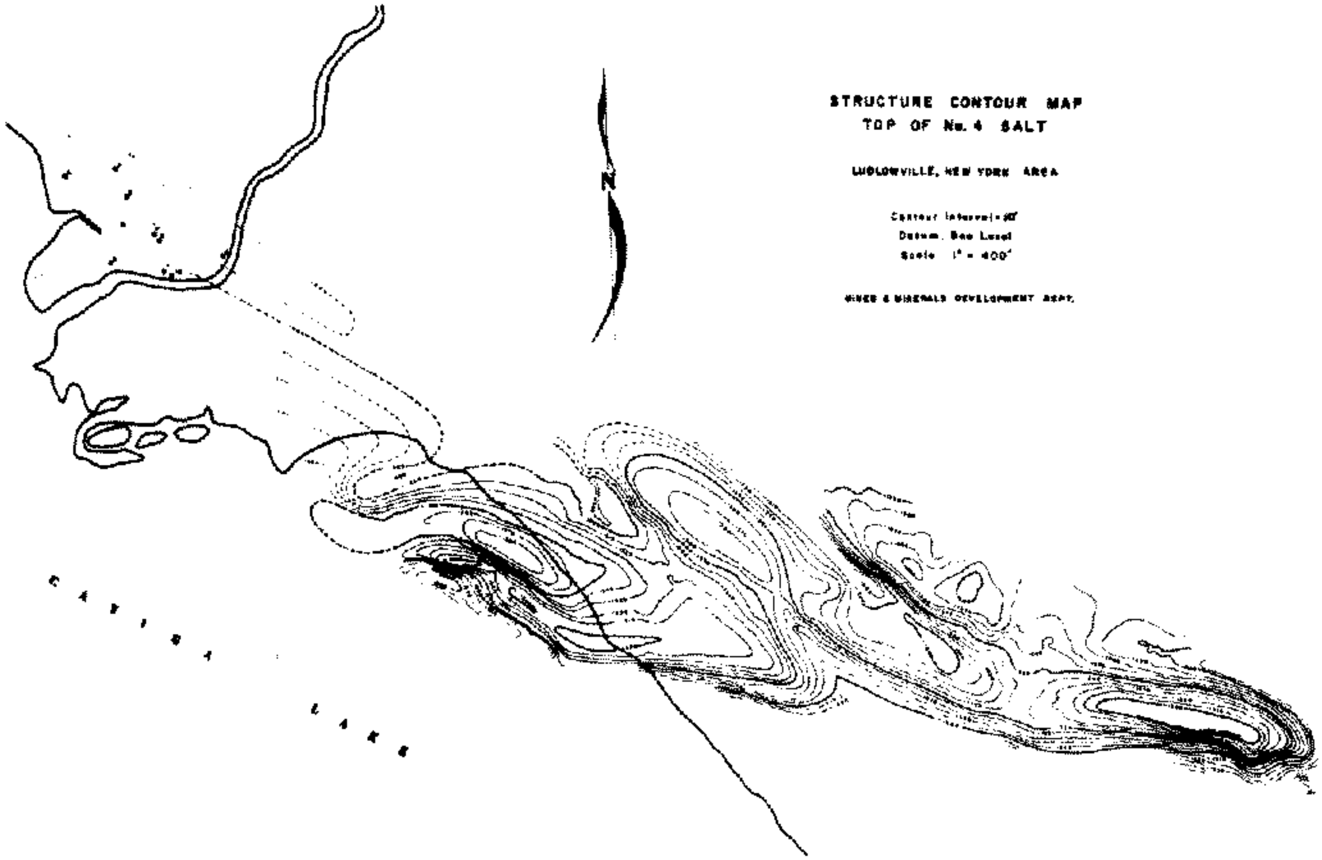

Figure 5

these folds on the bottom of the 4th Salt were as small as 200 feet with the isopach lines of the salt within this same distance ranging from six feet to 120 feet. This salt was considered as metamorphosed material. This made it imperative that both the injection well and the target well be located in the same trough.

The axial direction of the folds on the top of the 4th Salt was in an approximate direction of N65°W. By extrapolation we placed the center line of our injection well and our target well in this same orientation. The distance between these two wells was set at a nominal 500 feet.

Drilling on the injection well, Well # 20, was started by setting and cementing 20 feet of 16-inch conductor pipe. The hole was then continued with a 15-inch bit through this conductor string. Although the airline distance between Watkins Glen and Ludlowville, New York, is approximately 20 miles and the stratigraphy was thought to be the same. But the investigation showed a sharp difference in the character of the rock between the two locations. At Watkins Glen it normally required four to five 15-inch bits to penetrate 2, 100 feet. These footages included reaming of the salt sections after coring.

At a depth of 1, 500 feet, we started the coring of the Salina formation in keeping with our standard operating procedure of coring the salt sections of each new well. This is accomplished by use of a 50-foot double tube core barrel and a diamond bit. In the Watkins Glen area, this procedure with normal care has resulted in an average bit life of 3, 500 feet and a diamond salvage of 75%.

At a depth of 1, 584 feet ten and one-half inches our coring operations cut a periodotite sill which had a thickness of one foot six and one-half inches. This discovery was particularly disturbing in that, if the target well were on one side of the parent dike and the injection well on the other, we felt there could be no communication or coalescence of the two wells. Only one known dike existed in the area and none of the previous wells drilled in the area for oil, gas and salt had reported sills or igneous material. The closest point of the only dike known to exist in the area was 8, 500 feet.

The strike of the dike's trace was N15°W. No geophysical work had been done in the area and, thus, a field decision had to be made from the data on hand. The target well, Well # 21, was relocated in a direction of N10°W from Well # 20. With this change in direction from the original N65°W, the distance was also changed from 500 feet to 400 feet. It was our opinion that we could by this reorientation of target well location, take advantage of the same planes of weakness which gave rise to the dike and which it had subsequently caused. The target well was completed, the injection well fractured and a fractured connection established between the two wells.

For reference in future development work, a magnetometer survey was run by Seismograph Services Corporation. This survey, Fig. 6, disclosed a dike due east of Well # 20 at a distance of 925 feet. The southern end of this dike had a trace of N10°W. The trace of this dike curved through a distance of approximately 1, 000 feet, which gave its northern end a direction of N40°W.

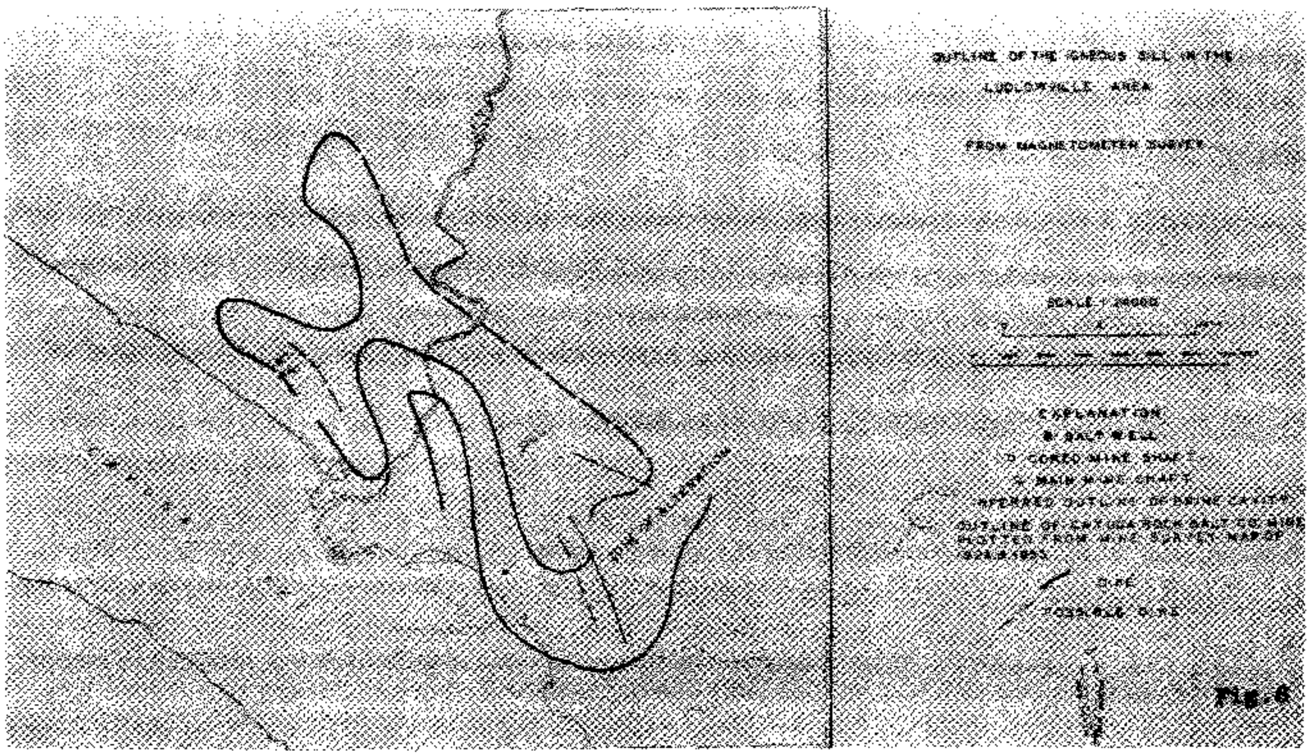

Figure 6

It is our opinion that if the two well locations had straddled this dike, no communication between the wells would have been possible. We believe that the fracturing fluid might have followed one of two courses. We consider that the most probable course would have been to encounter the dike, rise vertically to the first sill, and then flow under the sill in the line of least resistance. The second possibility would be to travel parallel to the dike in a horizontal direction.

FAULTED BEDS

The results of our initial fracturing operation at Watkins Glen were anything but desirable. In 1955 we fractured our first well, Well # 25. The target for this first injection well was a cavity which had one of its wells, Well # 24, just 200 feet north of Well # 25. A total of approximately 65, 000, 000 gallons of fluid was pumped into this well at an average rate of 400 gallons per minute over a nine-month period. Spaced intermittently during the 113 days were periods when we allowed the fracture to "cure." After a period of ten days to two weeks of pumping, the well was "shut-in" under pressure. It was during one of the "curing" periods that the pressure recorder fell to zero and we found the well on vacuum. At the time, three reasons were thought to be responsible for our difficulties. These were:

1. Geology of the immediate area, which was largely an unknown quantity at that time.
2. The stress concentration surrounding the cavity which might have deflected any fractures.
3. Rock movement which subsequently induced crevices in the strata overlying the cavity, allowing the escape of the fracturing fluid.

The continued development of this new brine field included the establishment of what is now a standard operating procedure, the coring of the salt sections in each new well. From this exploration work in each of the newly developed wells, there evolved a much better understanding of the local geology. Subsequent wells were located more properly. Structure-isopach maps were developed for each of the salt beds. These geological maps seem to show folded formations with distinct trends that appeared to explain the direction of fluid flow.

In 1962 a pair of two-well galleries were drilled and fractured. Instead of the fracture proceeding in an east-west direction as had been previously experienced and in keeping with the structure maps, the fractures developed in a north-south direction. Well # 33 was an injection well with an intended target of Well # 32 across a distance of 735 feet. Unexpectedly, it connected with Well # 34, or almost due north, a distance of 745 feet. Within 24 hours after the fracture had been initiated, brine was being produced by the target well. The volume of brine produced quickly reached a point where it was proportional to the volume of water injected. The quality of brine with respect to calcium and magnesium chlorides was extremely high, thus being relatively poor for the production of evaporated salt. Pump pressures remained extremely high despite the fact that large quantities of salt were extracted. No second plateau ever developed.

It was surmised that fracturing fluid had passed horizontally along a faulted zone with at least a portion of the travel route being in shale layers. It was in these layers that the brine picked up the large percentages of calcium and magnesium.

Similarly, Well # 29 fractured to Well # 32 or in an approximate north-south direction rather than the anticipated preferred direction of east and west. The original target for Well # 29 was Well # 34 located some 490 feet to the west. Well # 32 was located 810 feet to the south of Well # 29. Again, a high pressure connection between the two wells was established quickly. The brine produced had approximately the same chemical composition as that developed by the fracture between Well # 33 and Well # 34.

All four of these wells were finally abandoned as fractured galleries. A modified Trump-type single well was developed. At this point the brine produced quickly began to improve with respect to its chemical composition, gradually assuming the characteristics of a high purity brine. This conversion required that the main string of casing be perforated near the top of the cavity; a hook-wall packer on a string of casing be set below these perforations and above the end of the casing and that water be circulated down the annulus and back up the tubing.

In view of this unexpected development, our first step was to reëvaluate our geological data. Gradually, there emerged a theory of a double system of faults which controlled the direction of flow of our fracturing fluid. A careful study of our gamma-neutron logs which we had developed previously in Well # 27 and Well # 28, disclosed the # 4 Rock which underlies the 4th Salt, Fig. 7, repeats itself. The gamma-neutron logs from Well # 30 and Well # 31 demonstrated that the # 3 Rock repeated itself. The repetition of rock sequences was not found in any of the wells north of a line between Well # 30 and Well # 27, although there was a material thickening of the 1st Salt in Well # 34. This repetition of beds indicated faulting. The diastrophism which has occurred in this area was probably due to the tectonic force which created the Appalachian Uplift.

Two of our older facilities were relegated to storage of propane. These, two well galleries, were replaced by similar installations, the construction of which was started in October 1963. Based on the geology developed up to that point, we adhered to an east-west line. This was partially due to our geological findings, Fig. 8, and partially to our previous successful fracturing in an east-west direction in this southern portion of the field. Well # 35 was used as an injection

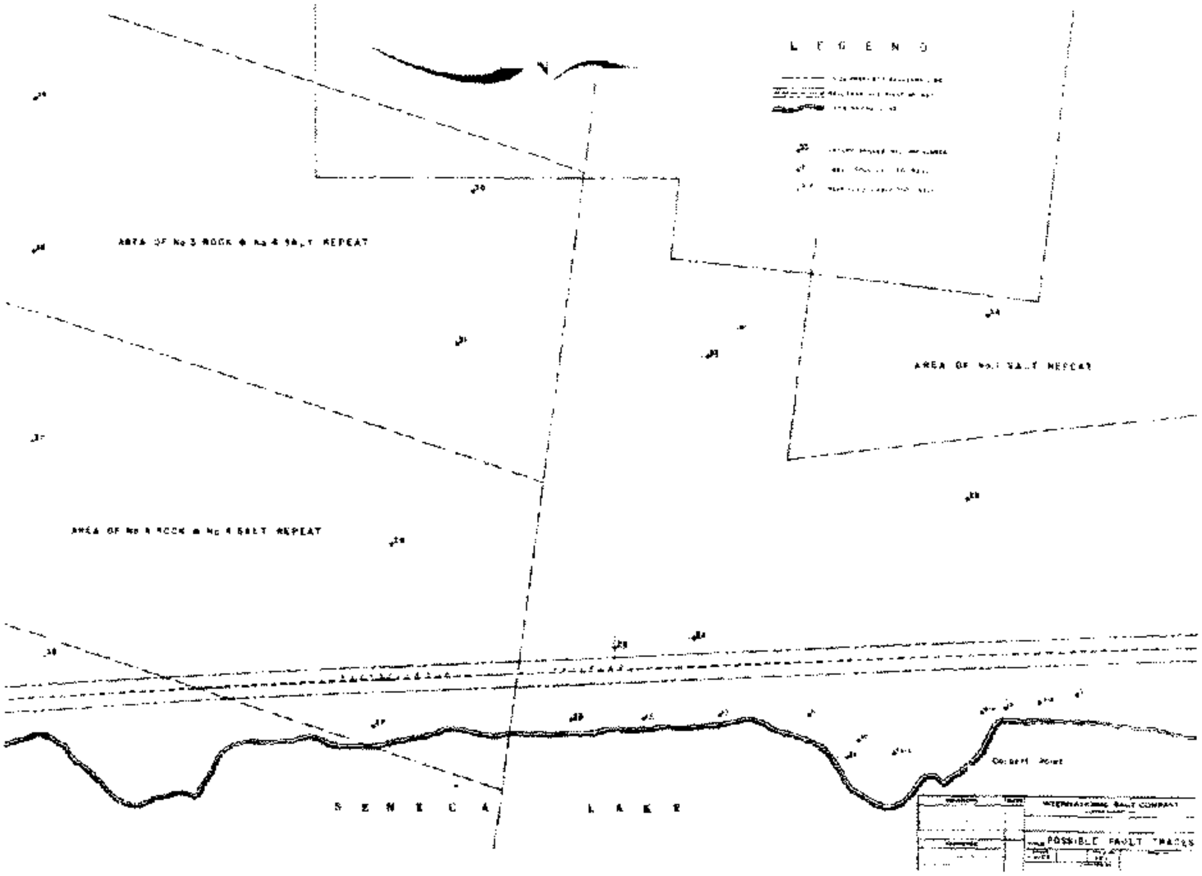

Figure 7

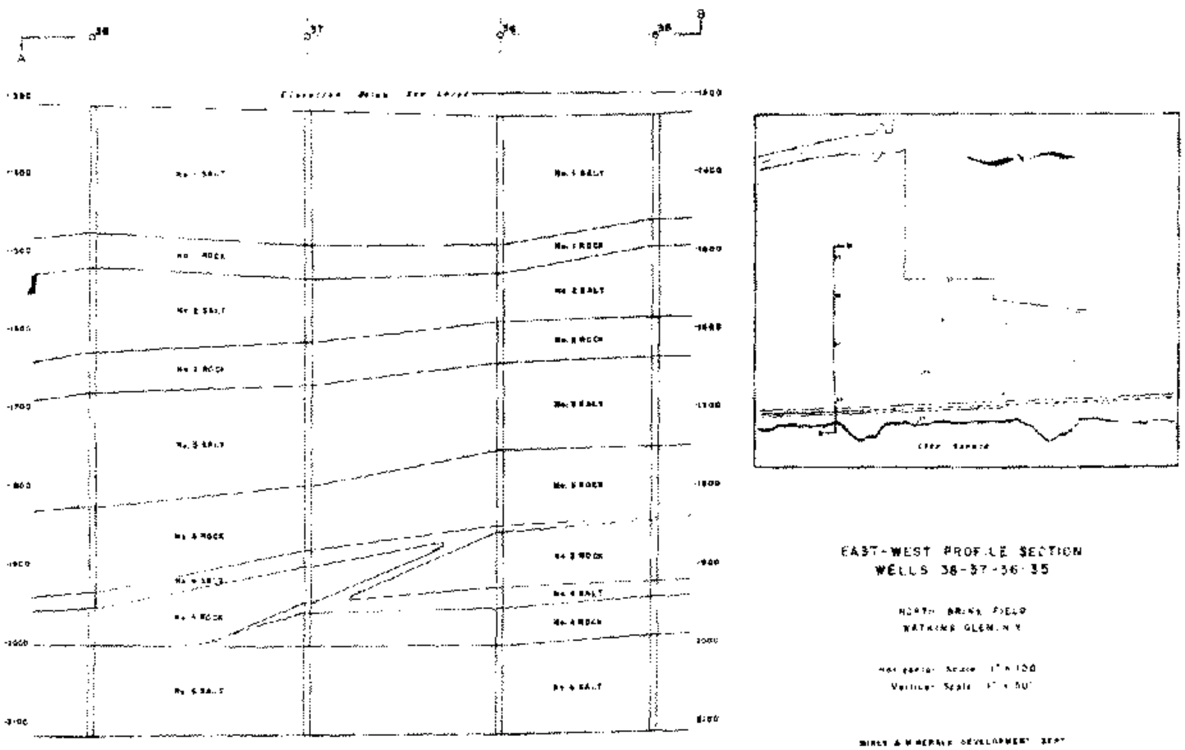

Figure 8

well with Well # 36 forming the target well. This was designed to form a gallery 410 feet in length. The second new gallery, Well # 37 and Well # 38 were spaced 550 feet apart with Well # 37 forming the injection well. The gallery formed by # 35 and Well # 36, together with the one formed by Well # 37 and Well # 38, were both fractured, connected and washed down to less than 100 p. s. i. in less than 24 hours.

CONCLUSIONS

From the field results we have experienced, we may conclude that an accurate interpretation of the local geology will eliminate a majority of the difficulties that we have encountered during our fracturing operations. These results also point up a number of facets of the geology at Watkins Glen which are not thoroughly resolved.

It is our opinion that except on a hit-or-miss basis, your results experienced during hydraulic fracturing are only as good as your geology is accurate.