UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Seismic-refraction survey to the top of salt in the north end of the Salt Valley anticline, Grand County, Utah

by

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Open File Report 79-1212

1979

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ILLUSTRATIONS

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Abstract

A seismic-refraction survey, consisting of three lines about 2700, 2760, and 5460 meters long, was made at the north end of the Salt Valley anticline of the Paradox Basin in eastern Utah. The target was the crest of a diapiric salt mass and the overlying, deformed caprock.

The interpretations reveal an undulating salt surface with as much as 80 meters of relief. The minimum depth of about 165 meters is near the location of three holes drilled by the U.S. Department of Energy for the purpose of evaluating the Salt Valley anticline as a potential site for radioactive waste storage. Caprock properties were difficult to estimate because the contorted nature of these beds invalidated a geologic interpretation in terms of velocity layers. However, laterally varying velocities of the critically refracted rays throughout the area suggest differences in the gross physical properties of the caprock.

INTRODUCTION

A seismic-refraction survey was made in May 1978 at the north end of the Salt Valley anticline in the Paradox Basin of eastern Utah (fig. 1), as part of an integrated geological-geophysical evaluation for the U.S. Department of Energy (DOE) of the buried salt anticline as a potential nuclear waste repository. The purpose of this study was to determine variations in the depth to the top of the salt mass in the vicinity of three exploratory wells, DOE 1, 2, and 3, drilled into the salt and to estimate lateral variations in the physical properties of the overlying caprock from lateral variations in its compressional velocity. Recorded depths to the top of salt were also available from three other exploratory wells in the area. They were drilled in 1961, 1956, and 1931 and are labeled 9, 12, and 15 in figure 1.

The geology of the study area and its relationship to that of the Paradox Basin is given in reports by Hite and Lohman (1973), Hite (1977), and Gard (1976). Several interesting seismic-reflection sections of the immediate area are shown in a report by Stockton and Balch (1978). The following brief geologic description, taken essentially from the above reports, is presented to help understand the seismic-refraction interpretations.

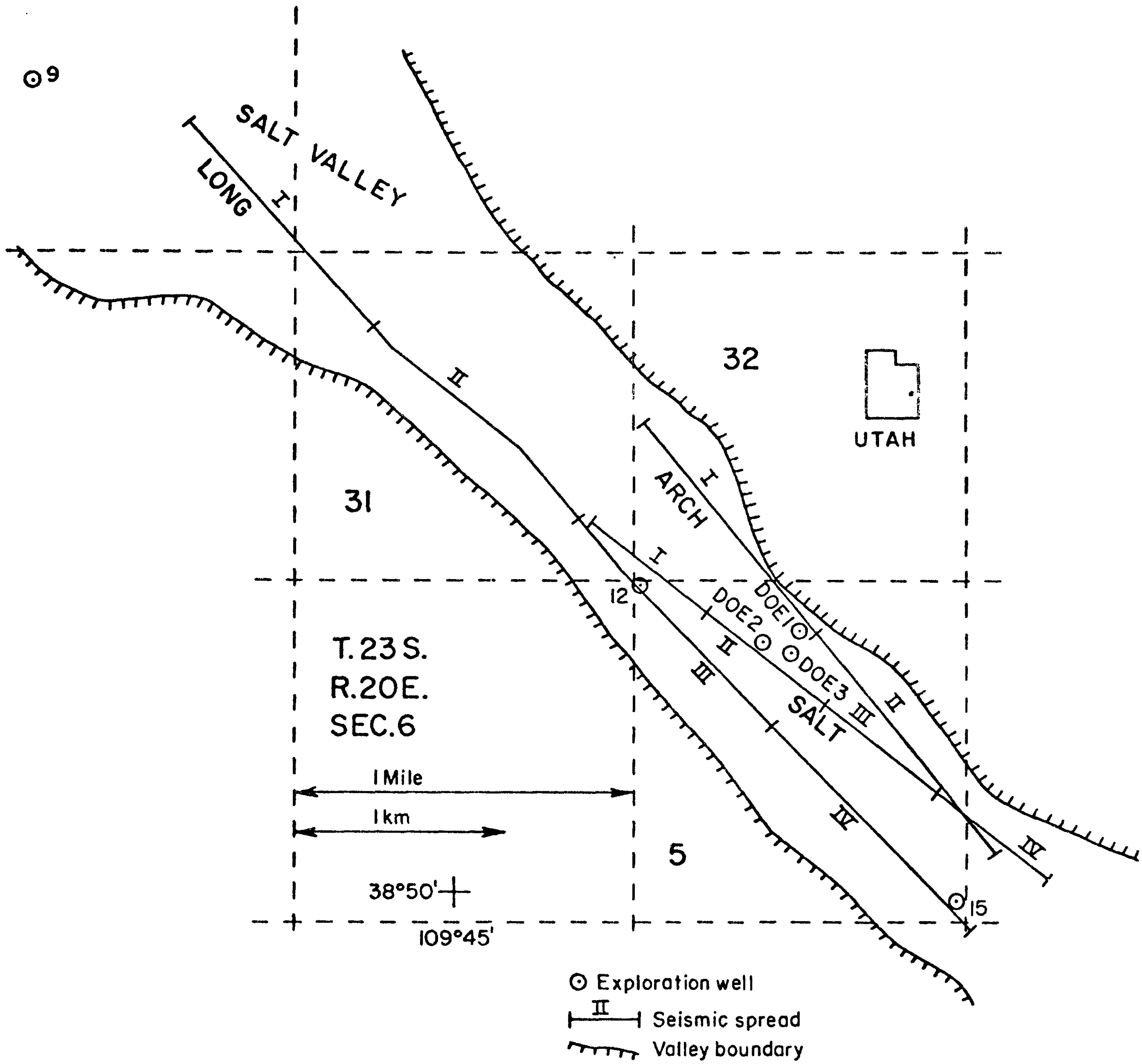

Figure 1.--Spread locations for lines Arch, Long, and Salt.

The Salt Valley anticline is a salt diapir which formed, more or less continuously, from Pennsylvanian through Jurassic time. The anticline is one of many salt anticlines which formed in the Paradox Basin during this period. The core of the Salt Valley anticline, contained in the Paradox Member of the Hermosa Formation of Pennsylvanian age, is estimated to contain 87 percent halite. The remainder consists principally of numerous included folded and faulted bands of shale, dolomite, and anhydrite which are called marker beds. These beds represent cyclic deposits within the original, undeformed salt which were squeezed up along with the salt mass. At Salt Valley, clastic sediments were deposited along the flanks of the growing anticline. Contemporaneous solution of near-surface salt left, as an overlying rsidue, insoluble marker beds, with the anydrite being chemically converted into gypsum. This residue forms a caprock which can be seen in exposures elsewhere as a mass of tortuously folded and faulted beds.

During late Jurassic and Cretaceous time, the area was covered by a thick section of sedimentary rocks. However, continued salt solution and its removal resulted in collapse, producing large graben-type block faults on the anticlinal crest. Subsequent uplift during Miocene time and contemporaneous fault-controlled erosion breached the anticline, re-exposing caprock. Locally, huge blocks of the overlying sedimentary sequence were left foundered into the caprock, possibly penetrating into the salt mass itself. Such blocks form some of the isolated hills within the northwestern portion of the otherwise level valley of the study area.

A diagrammatic sketch of the present valley in cross section, taken directly from Hite (1977), is shown as figure 2. This sketch could represent the location of the three DOE test wells.

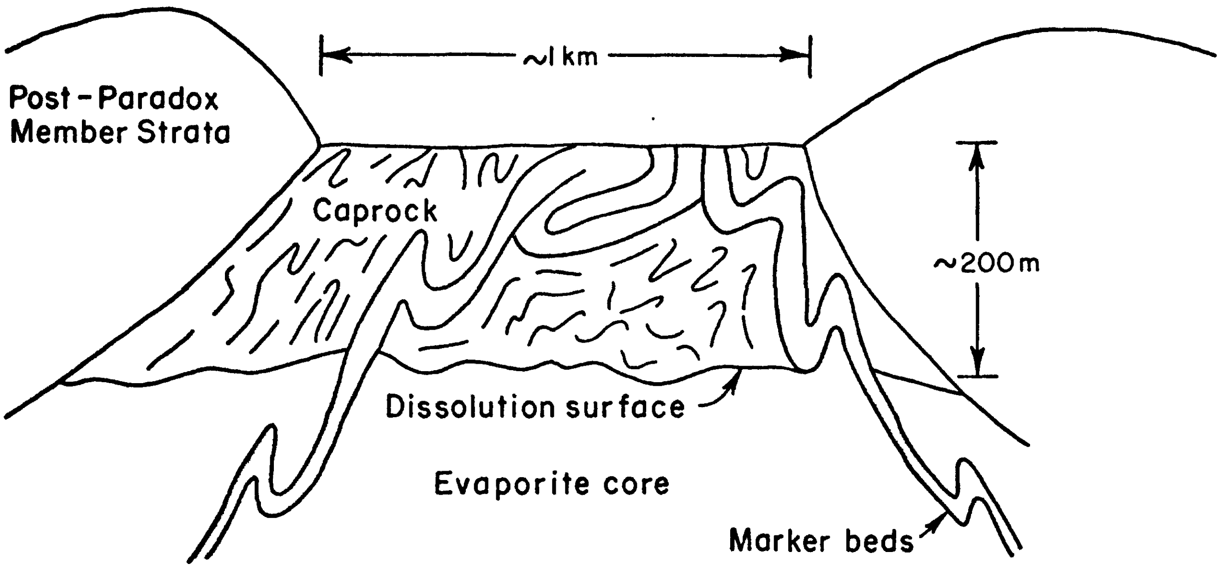

Figure 2.--Diagrammatic cross section through Salt Valley anticline (Hite, 1977) showing interpretive relationships between caprock, evaporite core, and marker beds.

THE SURVEY

Three seismic-refraction lines, named Arch, Long, and Salt (fig. 1), were recorded. Lines were on the valley floor along traverses avoiding the major isolated hills. Lines Arch and Salt, each approximately 2700 meters long, straddled the three DOE well sites. Line Long, 5460 meters long, passed through the two earlier exploration wells in the area and extended several kilometers, parallel to the valley, northwest of the DOE drilling sites. The northwest half of this line skirted some of the hills of foundered downdropped blocks of Cretaceous rocks.

Lines consisted of either two or four spreads, laid end to end, each containing 24 equally spaced, single seismometer arrays (4.5 hertz). Shots were recorded with amplifiers at fixed gain (no automatic gain control). Shots varied between 1 and 20 pounds of gelatin dynamite at depths between 1 and 3 meters. Recordings were made using analog equipment and individual gains were set to prevent overdriving initial arrivals.

Field recordings were of good quality. The internal consistency of the arrival-time plots inferred a 5 millisecond, or better, digitizing accuracy of initial arrivals.

Line Salt consisted of four spreads having a 30-meter seismometer interval. Spreads were recorded at 11 or 12 in-line shot-point locations. Figure 3 shows the shot-seismometer configuration for one of these spreads. The use of common shot-point locations for the individual spreads provided many continuous arrival-time plots across the entire length of the line.

Sixty-meter seismometer intervals were used for lines Arch and Long. Shot-point locations for line Arch were approximately 460 meters apart, and for line Long, 690 meters. These larger spacings produced less detailed data than for line Salt.

The purpose of the numerous shot locations for each spread was to obtain complete reversed data from as many different depths as possible to a total depth considerably into the salt mass. Good coverage was achieved for line Salt. However, for lines Arch and Long, which employed the larger shot-seismometer intervals, only partial data were obtained from the section overlyig the salt.

Arrival-time plots and interpretations were made using interactive computer programs written by the author. Well information was not used in making computations.

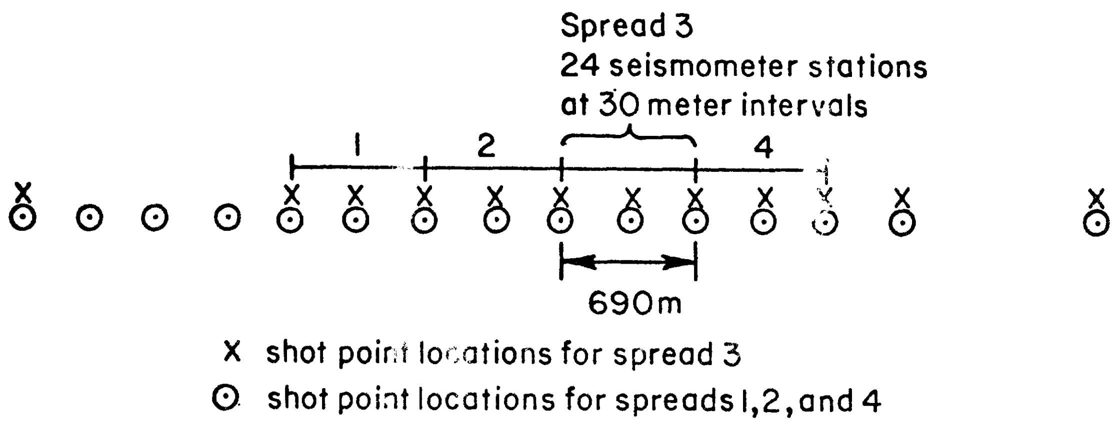

Figure 3.--Shot-seismometer configuration for spread 3 of line Salt. Spreads 1, 2, and 4 are also numbered.

INTERPRETATIONS

Hand-smoothed versions of the sonic logs from the upper 220 meters of the three closely spaced (less than 200 meters apart) DOE test wells are shown in figure 4. The interval transit-time axis of the original logs has been converted to velocity, resulting in curves showing velocity versus depth. The top of salt is inferred by the onset of the plateaus of velocity between 4.3 and 4.6 km/sec. Simple inspection of these three curves indicates a widely fluctuating caprock velocity which varies both laterally and vertically. A case can probably be made for a general velocity increase with depth. Nevertheless, it appears invalid to attempt a geologic interpretation for the rocks overlying salt in terms of the classical seismic model of discrete velocity layers.

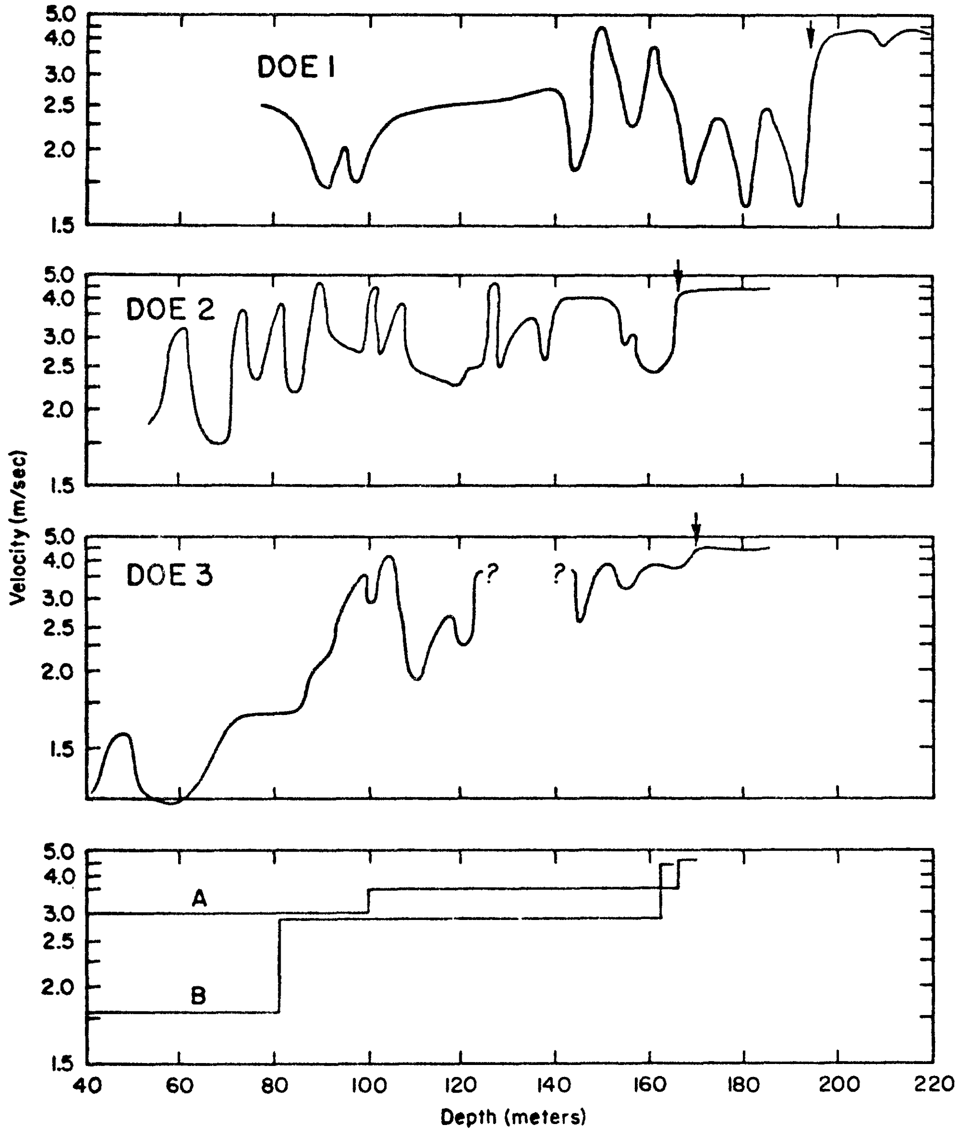

Figure 4.--Generalized velocity distributions from DOE 1, 2, and 3 as smoothed from the acoustic well logs, and the velocity distribution at the two locations A and B on line Salt, determined from the refraction data and used for calculating depths to the salt horizon. Curve A represents a fast distribution from near well DOE 2, and B, a slow distribution from near the northwest end of the line. Depth to top of salt from wells DOE 1, 2, and 3 is indicated by the vertical arrows.

On the other hand, seismic-refraction data, by their very nature, are interpreted in terms of a model consisting of discrete layers whose attitude and velocity may vary. These velocity layers frequently imply geologic layers, and velocity variations imply changes in their physical properties such as density, porosity, or rock type. In a true sense, however, a refraction-seismic layer simply represents the reconstruction of the more-or-less horizontal (critically refracted) segment of the path that a sonic ray traverses in propagating between a seismic source and a seismometer. The physics of the problem demand that this propagation path be one of minimum time. Hence rays "select," for critical refraction, paths that represent zones of successively deeper, higher propagation velocity. Low-velocity zones are "avoided" and, hence, remain undetected. In a common lithologic sequence, successive zones of increasig velocity may be represented by the zone of saturation in shallow, unconsolidated materials, bedrock, dense layers such as conglomerate or limestone, and, ultimately, the "basement," such as crystalline rocks. In this study, basement is represented approximately by the salt horizon. In the overlying materials, critically refracted rays follow some unpredictable minimum time path cutting through and across contorted bands of caprock.

The caprock

The more tightly spaced, shot-seismometer configuration for line Salt permitted clearcut delineation of critical refraction paths from several different horizons above the salt. Severe variations in the slopes of the plotted arrival-time data (not shown) are consistent with a subsurface mass of highly laterally varying velocity whch also tends to increase with depth. By applying necessary simplifying assumptions (that ray paths lie in a vertical plane and that critically refracted rays to successive seismometers follow a common path), approximate ray paths and their propagation velocities were calculated. The results show a rapid velocity increase from about 0.4 km/sec at the surface to velocities varying between 1.6 and 3.4 km/sec at a depth between 15 and 40 meters. The refracted ray path at this depth is shown in the velocity section of figure 5 as the first solid line beneath that representing the ground surface. The indicated velocities show the laterally varying speed of sound transmission. Below this level, velocities undoubtedly fluctuate to-and-fro as inferred by the sonic logs. A deeper, critically refracted raypath of higher velocity was computed at a depth between 70 and 120 meters. Velocities of ray propagation at this depth vary from roughly 2.8 to 4 km/sec. Once again, velocities undoubtedly continue to fluctuate below this level. The next deeper horizon indicated on the arrival-time curves correlates with the top of salt.

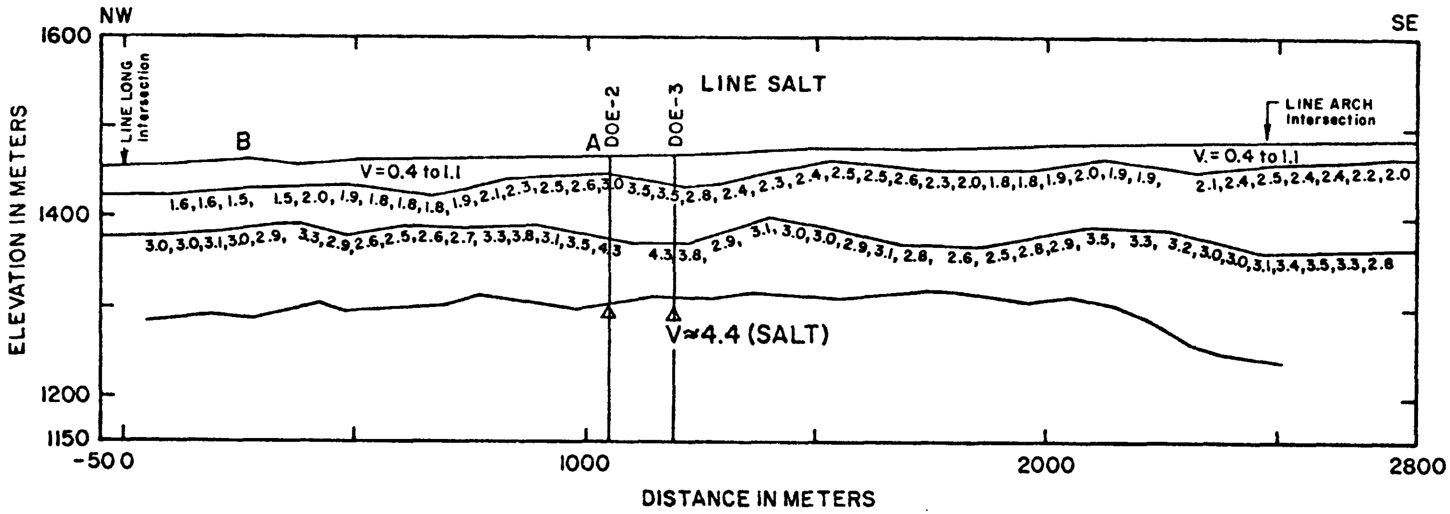

Figure 5.--Interpreted velocity section for line Salt showing the ground surface, two horizons representing critically refracted rays within the caprock, and the salt horizon. Velocities are in meters per second. The apex of the triangle at the locations of wells DOE 2 and 3 shows the top of salt as picked from various geophysical logs and core.

Similar velocity sections (figs. 6 and 7) show the refracted ray paths and their corresponding, laterally varying velocities for lines Arch and Long.

Although these computed caprock velocities are, at best, fragmental, they may provide important clues for estimating an average generalized velocity distribution in the rocks overlying the salt. Such information can be important for determining the hydrologic properties throughout an area, because velocity is closely related to both porosity and bulk density. For an example, two points on line Salt, labeled A and B in figure 5, have been selected. Point A is near the location of the three test wells and B is near the northwest end of the line. The velocities along the critically refracted raypaths at A are significantly higher than at B, particularly for the shallower event. This suggests that the average velocity beneath point A is greater than at point B. Although the caprock at both locations is probably similar, the section beneath B may be more fractured than at A. It is thus recommended that any drilling program undertaken to ascertain variations in hydrologic conditions throughout the area be directed, in part, by the available velocity information.

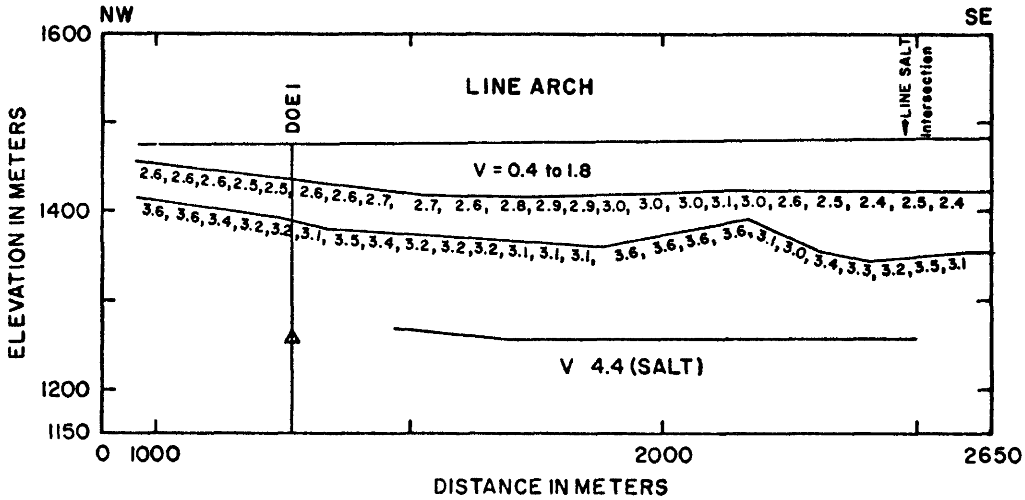

Figure 6.--Interpreted velocity section for line Arch showing the ground surface, two horizons representing critically refracted rays within the caprock, and the salt horizon. Velocities are in meters per second. The apex of the triangle at the location of well DOE 1 shows the top of salt.

Figure 7.--Interpreted velocity section for line Long showing the ground surface, one horizon representing a critically refracted ray within the rocks overlying salt, and the salt horizon. The dashed line at approximately the salt horizon near the northwest end represents arrivals from within high-velocity rocks foundered into caprock. The extension of the salt horizon beneath this foundered block, also shown dashed, is drawn to intersect top of salt recorded from earlier exploration well 9, approximately 700 meters northwest of the line. The apex of the triangles at the location of wells 12 and 15 represents recorded depths to salt.

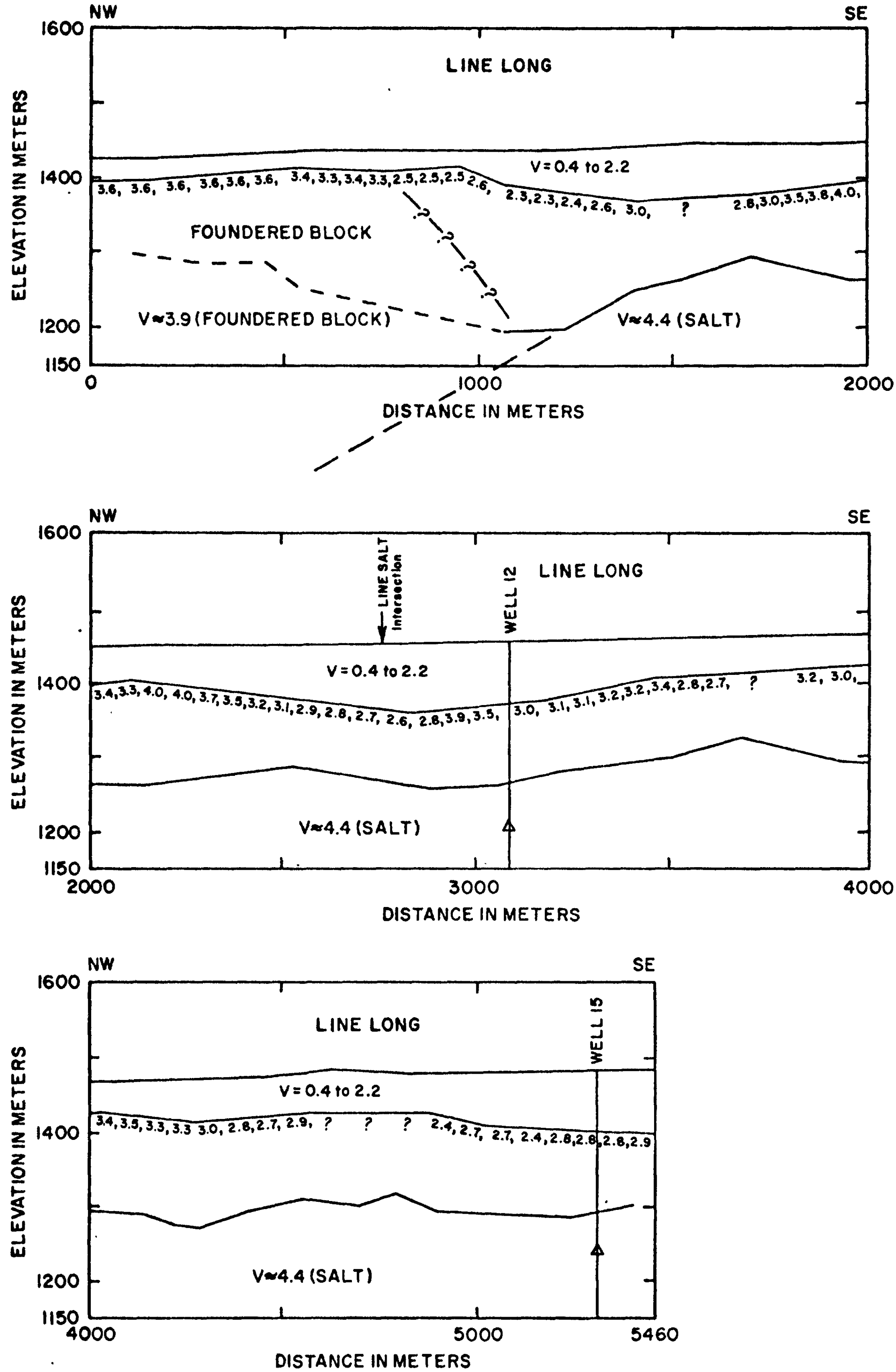
NW
SE
LINE LONG
V=0.4 to 2.2
FOUNDERED BLOCK
V≈3.9 (FOUNDERED BLOCK)
V≈4.4 (SALT)
ELEVATION IN METERS
DISTANCE IN METERS
LINE SALT Intersection
WELL 12
WELL 15
1600
1400
1200
1150
0
1000
2000
3000
4000
5000
5460

Figure 7

The salt

In order to determine accurate depths to a marker horizon from seismic refraction, a reasonably correct, overlying velocity function must be used. Thus, accurate salt-depth calculations hinge upon a valid model for the velocity distribution in the overlying caprock. The previous discussion has emphasized that caprock velocities are highly variable and not well known. Usually, the most reliable function to use is one obtained from well logs. However, the obvious, marked differences between the sonic logs from the DOE wells obviate using them to estimate a generalized velocity distribution for the entire area. Therefore, the velocity function used was one estimated from the critically refracted ray paths in the caprock. A layered model was assumed, with the top of each layer corresponding to the previously calculated, critically refracted ray path. The velocity in each layer was varied laterally as the velocity of the overlying ray path but smoothed somewhat to eliminate local high and low values. The velocity functions used beneath points A and B on line Salt have also been sketched in figure 4. This representation obviously ignores the fluctuations observed on the sonic log but instead attempts to substitute some average value. Comparing the function used at A with the sonic log from nearby DOE 2 suggests that the function used there is too fast. Therefore, the computed depth to the top of salt would be expected to be deeper than the actual well depth. However, the computed depth was remarkably accurate, as seen by comparing the final step on the velocity distribution at A with the recorded salt depth in DOE 2. Had the velocity distribution of the well log been used, the computed depth would have been too shallow.

The computed depths to salt beneath the three spreads Arch, Salt, and Long are shown in figures 5, 6, and 7 as the deepest horizon. Because of the numerous shot locations for each spread, several independent data sets for salt arrivals were recorded. Depth calculations, using different sets, generally resulted in differences of approximately 10 meters. Average values were used.

Salt velocities were computed along the critically refracted ray path within the salt at roughly 30-meter intervals. Some severe lateral variations, unexpected for a homogeneous salt mass, were noted. However, time-averaging these local, apparent variations over distances of approximately 2000 meters resulted, with one exception (to be discussed later), in salt velocities between 4.35 and 4.50 km/sec, in close agreement with values from the sonic well logs. The computed variations are probably due to inaccuracies in the velocity function used for the overlying caprock.

Salt depths were not calculated for the northeast half of line Arch. This portion of the line crossed an exposed foundered hill, and arrivals from the salt could not be distinguished from those of foundered, tilted, high-velocity Cretaceous rocks.

The salt horizon interpreted from line Salt (fig. 5) shows a slightly dipping layer punctuated by local highs and lows of 10 meters or less amplitude. These "bumps" may be due to error. The recorded salt depths from DOE wells 2 and 3, which are offset 25 and 95 meters northeast of the line, are shown. Recorded and calculated depths agree well. Toward the southeast end of the line, the roughly horizontal salt profile terminates, plunging 60 meters in a distance of approximately 300 meters.

Lines Salt and Arch intersect near their southeast ends. Independently calculated depths at the intersection agree within 8 meters.

The salt profile for line Arch appears to be nearly horizontal and, if projected northwestward (fig. 6), it approximately intersects the top of salt determined from well DOE 1. However, the profile is generally 40 to 50 meters deeper than for line Salt, indicating considerable dip between the two lines. Line Arch apparently parallels the strike of the plunging salt mass.

The center of line Long and the northwest end of line Salt are 25 meters apart. Calculated salt depths at these two points agree within a few meters. The salt horizon calculated from line Long (fig. 7) varies considerably. The calculations infer an undulating horizon with wavelengths of 600 to 1000 meters and amplitudes as large as 40 meters. Towards the northwest end, the salt horizon plunges approximately 80 meters in a distance of 400 meters. At the far northwest end, it falsely appears to rise again. Two lines of evidence indicate that this apparent rise is due to a very large, deeply foundered block. First of all, the computed ray velocity is 3.8 km/sec versus 4.35 to 4.50 km/sec elsewhere. Secondly, the shape of the arrival-time curve from shots offset progressively farther to the northwest varied systematically so as to suggest a deeply buried mass of velocity somewhat less than that of salt but significantly greater than that of caprock. Elsewhere in the study area, the shapes of arrival-time curves are independent of offset distance. Data are insufficient to prove whether or not this foundered block actually penetrates into the salt mass. An earlier exploratory well, numbered 9 in Hite's (1978) report (fig. 1), was drilled approximately 700 meters off the northwest end of line Long and had a reported depth to salt of 813 meters. The salt horizon, indicated in figure 7, has been extended with the slope which would intersect the top of salt from well 9.

Line Long intersected two exploratory wells (fig. 1), numbered 12 and 15 in Hite's (1977) report. The reported top-of-salt depths for these wells are indicated in figure 7. Both depths are significantly deeper than calculated from the refraction data. Well 12 mis-ties calculated depths by 50 meters, and well 15 by 35 meters. Neither hole was cored nor are geophysical logs available. Therefore, the apparent mis-ties are difficult to reconcile. Hite (oral commun., 1978) suggested that drillers' logs may be in error, with salt being penetrated shallower than logged. In fact, the salt depth for hole 12 is questioned in his report. On the other hand, depth calculations may well be in error due either to a combination of timing errors or to the use of an incorrect caprock-velocity function at these locations. With all these factors considered, this author is hesitant to attach important significance to the mis-ties without additional information from these two wells.

A contour map of the salt horizon, with seismic depth calculations for control, is shown in figure 8. This map indicates that DOE wells 2 and 3 were drilled along the edge of a high and that DOE 1 was drilled into its steeply dipping northeast flank. The salt horizon is shown to undulate and drop in elevation toward the northwest end of the study area.

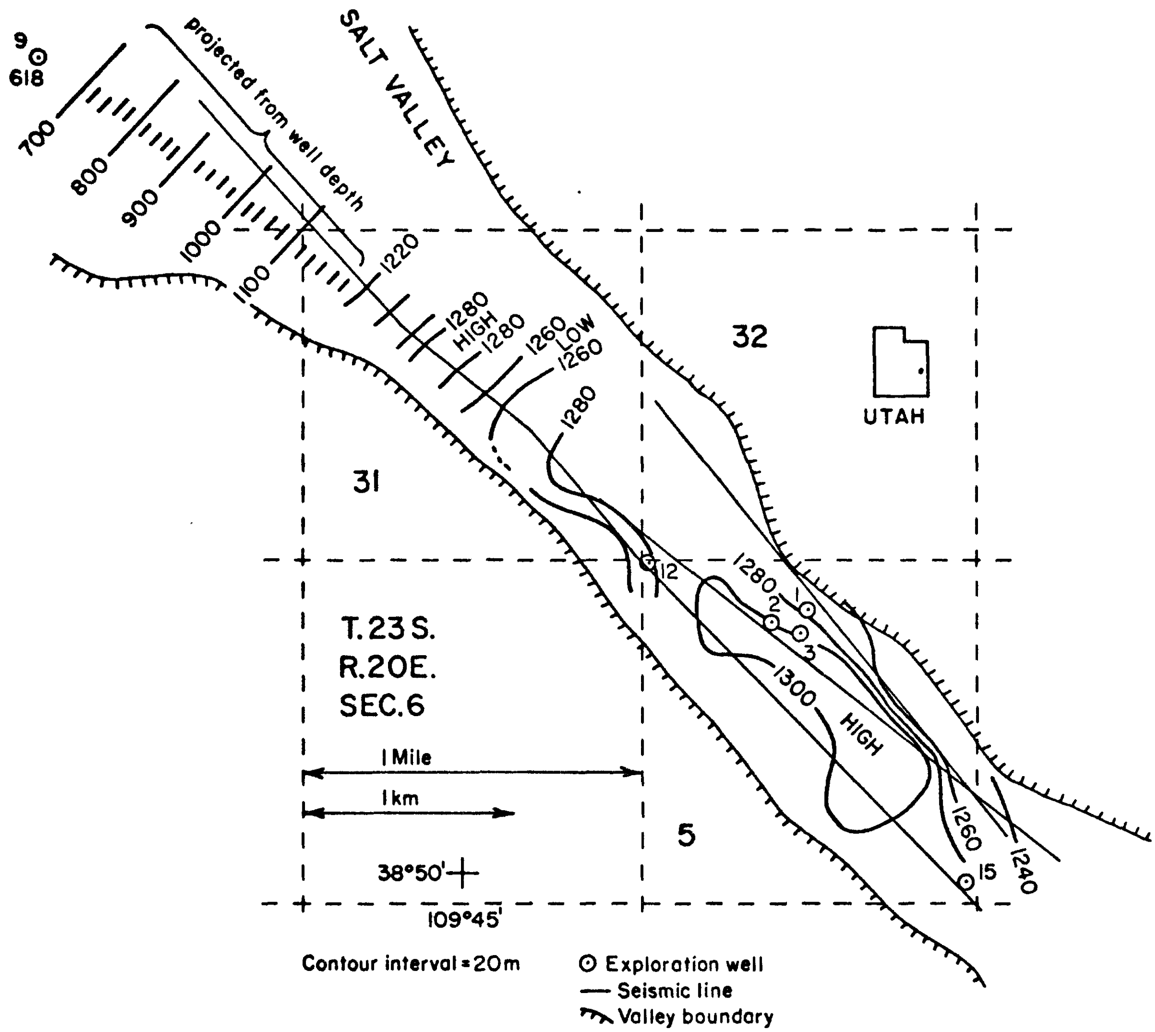

Figure 8.--Generalized elevation contours in meters for the salt horizon as interpreted from the seismic-refraction data. Contours are continued to the northwest from the top to salt recorded for exploration well number 9.

DISCUSSION

The seismic-refraction survey consisted of three lines, each with a different shot-seismometer configuration. Many shots were recorded for each individual spread. The shorter shot-seismometer spacings, used for line Salt, were necessary to delineate ray paths and their varying velocities in the overlying caprock. The many offset shots generally resulted in redundant data from the salt layer. However, they were essential in proving that arrivals from the northwest end of line Long originated from a deeply foundered block rather than from a dipping salt layer.

Caprock heterogeneity precluded a geologic interpretation of critically refracted rays in terms of a layered medium. However, the results suggest that the gross physical properties of the caprock may vary and that the hydrologic conditions in the vicinity of three DOE drill holes may not be representative. These holes may have been drilled where caprock velocity is anomalously high.

The three DOE test wells were drilled near the edge of a ridgelike salt high. Elsewhere, the elevation of the salt horizon also varies considerably, as much as 80 meters toward the northwest end of the study area.

A laterally varying, overlying velocity function was used to calculate depth to salt. It was obtained from the velocity of critically refracted rays within the caprock, which may not be representative of the entire mass. Therefore, the accuracy of the function used is questionable, which may have led to errors in depth calculations. Calculated depths to salt agreed well with those determined at the three DOE test wells for which geophysical logs were run but large, apparent mis-ties (35 and 50 meters) occurred at two old exploration wells in the area. This author believes that these differences may be due to incorrectly recorded salt depths in these wells. There can be little doubt that the major features on the map of figure 8 are correctly shown.

ACKNOWLEDGMENT

The author thanks R. H. Hite of the U.S. Geological Survey for leading a very useful field trip related to some of the structures in the Paradox Basin and for helpful discussions of the geology of the area.

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