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Analysis of borehole geophysical data in an evaporite sequence at Salt Valley, Utah

by

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ABSTRACT

Interpretation of the lithology of an interbed sequence (thin-bedded sediments between thick layers of salt) is often difficult due to the presence of dolomitic sandstones and halite inclusions. The most useful well logging measurements in an evaporite sequence are gamma-ray, neutron-neutron, density, and acoustic velocity. The high resistivity of salt and the low resistivity of commonly used drilling fluids (brine muds) make it difficult to obtain measurements of electrical properties in an evaporite sequence. Tests of a single-coil induction probe at Salt Valley show good resolution of the interbed lithologies and may be useful in determining moisture in the halite.

Complex structural features (faulting and folding) are difficult to interpret with individual well logs. Interpretation of complex folding can be aided by plotting the percent frequency of occurrence of well log response values for the interbeds. Limbs of a fold that intersect the drill hole at different dip angles yield similar distribution patterns on these percent-frequency plots.

INTRODUCTION

Evaporite sequences are an important potential medium for the storage of radioactive wastes. In order to ascertain the viability of a proposed waste isolation site, the physical properties and the mineralogy of the rocks in the evaporite sequence must be determined. Cores can provide specific information about the lithology of a formation, but borehole geophysical measurements are more useful than cores for establishing the in-situ physical properties of the rocks. It is necessary to determine the geological viability of a rock sequence without extensive drilling that might destroy the structural integrity of the site, and let radioactive materials escape into the environment. A complete analysis of the geology of a repository site should include the use of deep penetrating borehole geophysical tools, like the borehole gravity and receivers. Interpretation of data acquired with deep penetrating borehole geophysical tools requires knowledge of physical properties obtained from conventional well logs.

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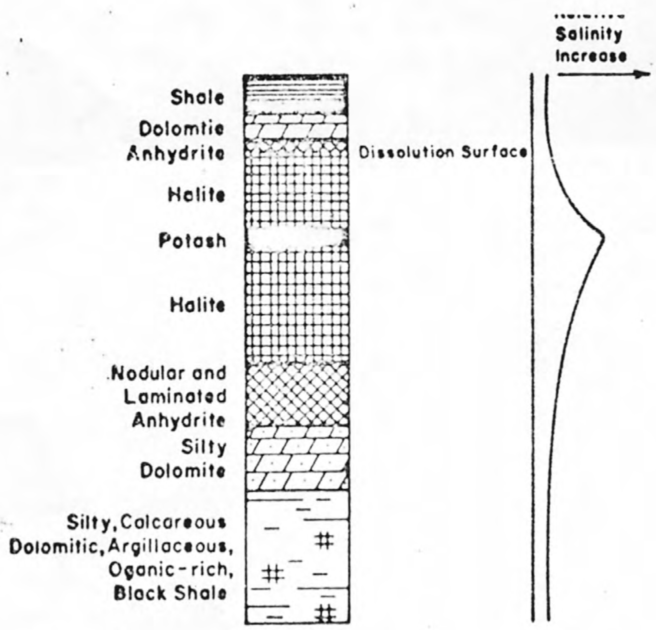
Previous investigators (Tixier and Alger, 1970; Nurmi, 1978) have described the basic physical properties of an evaporite sequence. These general properties, summarized in figure 1, appear to apply to the Salt Valley evaporite sequence. However, although the intrinsic physical properties of the individual mineralogic units are similar from one geographic area to another, the overall makeup and structural complexity of evaporite sequences are often dissimilar.

Figure 1 illustrates an idealized geologic section showing typical evaporites in the Paradox basin. This evaporite sequence is repeated in a cyclic manner as the result of salinity changes in the basin. The original evaporite sequence may be changed by tectonism that may occur several times during, or after deposition.



	(grams/cc) Density	(km/sec) Velocity	Natural Radioactivity	Water Content
Halite	2.16	4.4 - 6.5	None	Very Low
Sylvite	1.99	4.6 - 6.5	High	Low
Anhydrite	2.96	4.1	None	Very Low
Carnallite	1.61	4.4 - 6.5	Low	High
Dolomite	2.87	3.5 - 6.9	None	Low
Gypsum	2.32	2 - 3.5	None	Intermediate
Shale	2.2 - 2.6	2.3 - 4.7	High	Intermediate - High

Figure 1.--Lithology and physical properties of an idealized evaporite sequence in the Paradox basin. (Hite and Lohman, 1973; Tixier and Alger, 1970)

The borehole geophysical information presented in this paper was obtained in a well drilled to a depth of 1238 m in the Salt Valley Anticline in the Paradox basin of southeast Utah. The deposits are in the Paradox Member of the Hermosa Formation. The Salt Valley Anticline is a diapiric structure, with a very complex internal structure (Hite and Lohman, 1973). The core structure of the anticline is a result of both regional compression and flowage of the Paradox Member into the anticlines. Migration of Paradox strata from flanking synclinal areas to the salt anticline involved movement of both halite layers and the interbeds as a single mass. Recumbent folds and low-angle reverse faults are typical structures in the salt core. The complex geologic structure makes it difficult to trace individual lithologic units in the diapiric mass.

Well Log Responses in Evaporite Sequences

The evaporite sequence at Salt Valley can be divided into three different stratigraphic regimes as follows: (1) a weathered cap rock, (2) halite sections below the caprock, and (3) interbeds below the caprock. These divisions are shown in figure 2 for the well that is discussed in detail in the remainder of this paper. Halite has a nearly zero gamma-ray response, a high neutron-neutron response, a low density, and a high p-wave velocity. Halite is easily distinguished from the interbeds and caprock at Salt Valley. The high gamma-ray response in the interbeds and caprock is caused by potassium-rich clays and possibly uranium, in the shaley interbeds, while the low neutron-neutron response indicates a general increase in water in the interbeds and caprock. The density log shows the relatively high grain densities of the interbeds compared to the halite, while the acoustic log reflects the low p-wave velocity of the caprock and interbeds. The density, neutron-neutron and acoustic log responses reflects the hydration of anhydrite to gypsum in the caprock.

In theory, resistivity should be an excellent tool to use in an evaporite sequence. The dc-resistivity of consolidated halite is generally greater than ten-thousand ohm-m, which contrasts markedly with the 10 to 200 ohm-m resistivities of the caprock and interbeds in the Paradox basin. Conventional resistivity probes are not designed to operate in holes drilled through evaporites. The resistivity contrast between the drilling fluid and the salt formation is approximately 200,000 to 1, resulting in a resistivity response that is dominated by the low resistivity of the drilling fluid. This results in a normal resistivity log that lacks detail in defining lithologies within the interbeds, as well as yielding apparent resistivity values that are several orders of magnitude different from the true resistivity of the salt. Conventional induction logging tools are also inadequate for measuring the high resistivities encountered in an evaporite sequence.

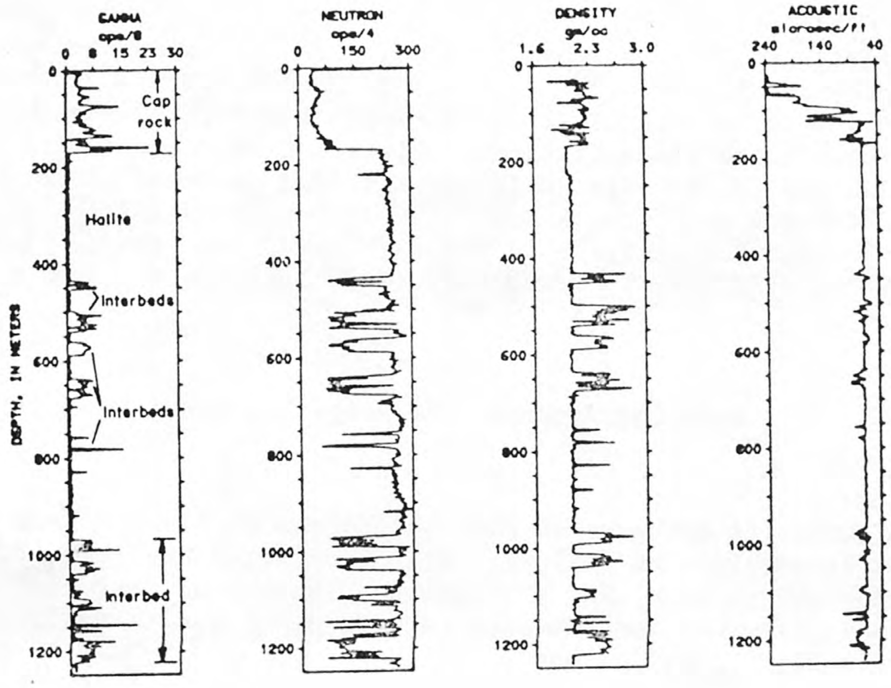


Figure 2.--Gamma-ray (GAMMA), neutron-neutron (NEUTRON), compensated density (DENSITY), and acoustic interval transit time (ACOUSTIC) well logs for the well discussed in this paper. The interbed, caprock, and halite intervals are indicated on the gamma-ray log. Units are counts/second (cps) for the gamma-ray and neutron logs, grams/cc (gm/cc) for the density log, and microseconds/foot (microsec/ft) for the acoustic log.

An experiment using widely-spaced electrode arrays was performed in the test well at Salt Valley. Electrode configurations and the resulting apparent resistivities are shown in figure 3. Increasing the source-receiver separation increases the apparent resistivity. The widely-spaced configurations also show more detail than the conventional long-normal resistivity tool. This paradox is a result of penetration of current beyond the invaded zone of the interbeds. If the electrode separation were increased further the resolution of the interbeds would diminish, and the apparent resistivity would increase as the ratio of salt-to-interbed thickness increased. True resistivity values of the evaporite layers can only be achieved by removing the effect of the borehole from the apparent resistivity response by detailed computer modeling.

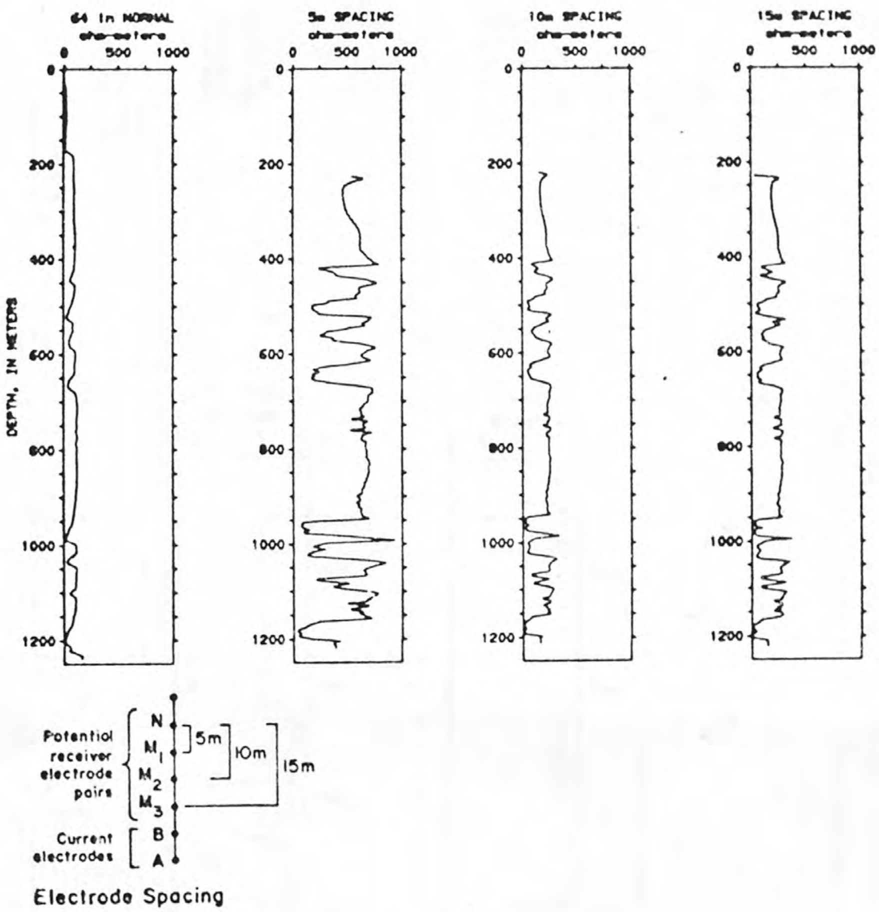


Figure 3.--DC-resistivity well log responses for the Salt Valley Well. The long normal array (64 in) is the conventional 1.6 m logging array. Spacings for the other arrays are shown in the figure. Plot position for the widely-spaced arrays is halfway between the potential electrodes.

High frequency electromagnetic methods, such as radar, can be used in dry holes drilled into evaporites, and could be adapted to work in fluid-filled holes. More experimental work is needed to determine the usefulness of subradar-frequency electromagnetic measurements in salt environments. Figure 4 shows an uncalibrated experimental conductivity log that was made at Salt Valley by measureing the in-phase self-inductance of a single coil driven at a frequency of 1000 Hz. The quadrature component of this inductance signal is normally used to measure magnetic susceptibility and has been described by Scott and others (1976). The usefulness of this conductivity measurement is not yet fully established, but the measurements do correlate with conductivity changes that would be expected in an evaporite sequence, and show conductivity anomalies in the salt that may be related to moisture variations.

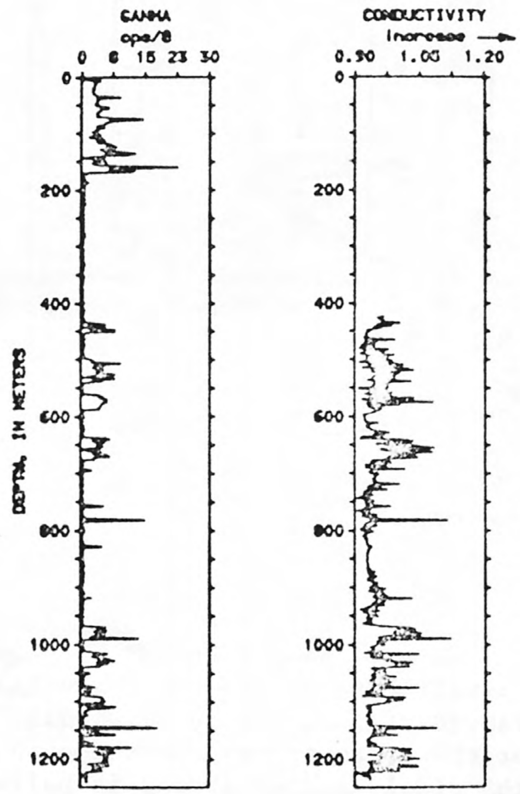


Figure 4.--Gamma-ray and conductivity well logs for the Salt Valley well. Conductivity values are uncalibrated.

Figure 5 illustrates the well-log measurement response for a typical halite-interbed sequence from the well logs shown in figures 2 and 4. Halite, shale, potash, and anhydrite can be easily identified by individual well logs as follows:

(1) Most shales have a high gamma-ray response, low neutron response, intermediate densities, high interval transit times, and high conductivities.

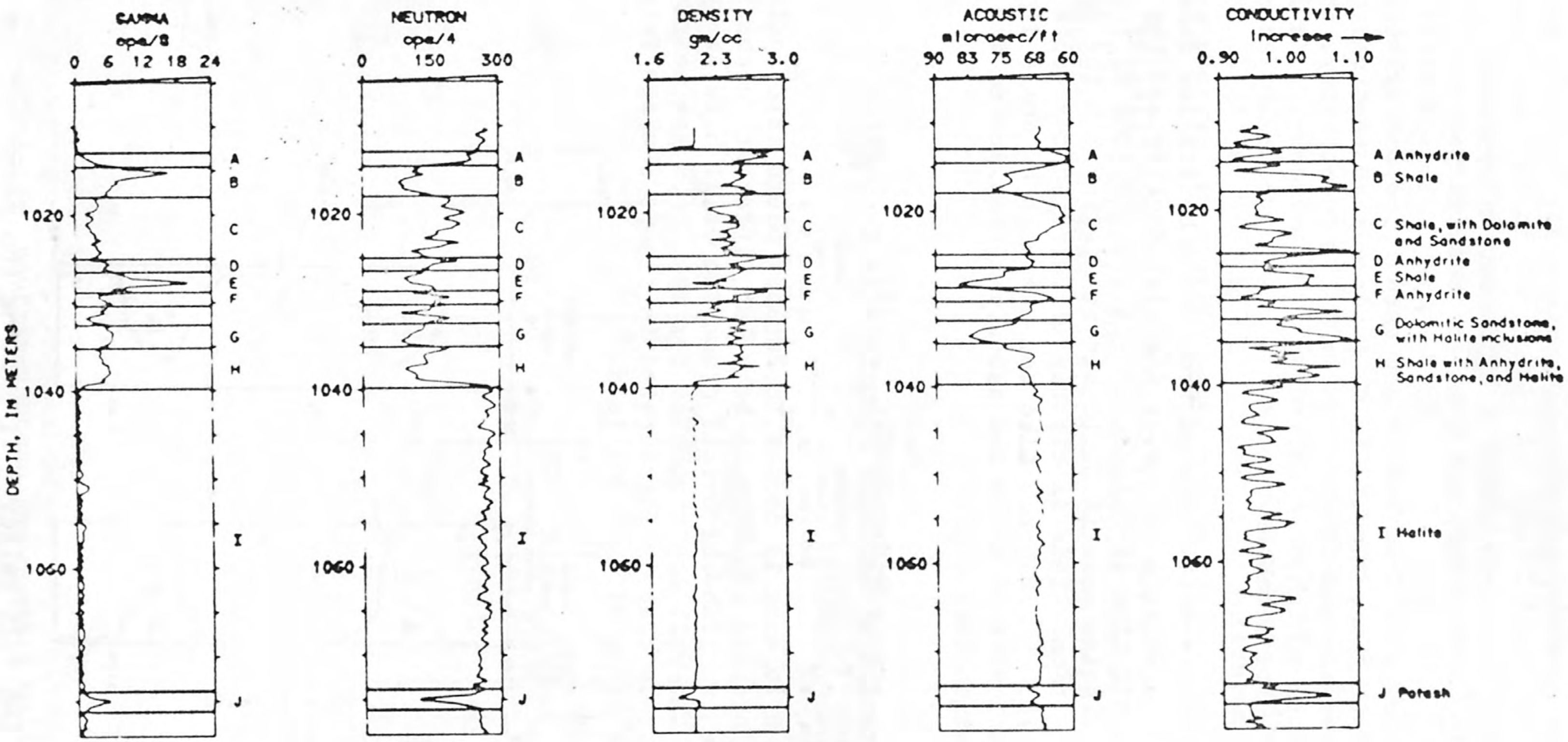


Figure 5.--Lithologies corresponding to response values for the gamma-ray, neutron-neutron, density, acoustic velocity, and conductivity well logs.

(2) Anhydrite has a low gamma-ray count, high neutron response, low interval transit time, high density, and low conductivity.

(3) Halite has a low gamma-ray count, a high neutron response, a low density, a high interval transit time, and a low conductivity.

(4) The potash minerals at Salt Valley are carnallite and sylvite. Carnallite has an intermediate gamma-ray count, an intermediate neutron response, a low density, a low interval transit time, and a high conductivity. Sylvite has a high gamma-ray count, a high neutron response, a low density, a low interval transit time and a low conductivity.

Carnallite can usually be distinguished from shale by its low density. Anhydrite can be distinguished from halite by its high density and the nearly constant interval transit time of halite. There are sections of the interbeds where multiple lithologies make it difficult to distinguish the mineralogic components of the section. This is clearly illustrated for depth intervals 1018 to 1025 m and 1030 to 1040 m. Like the presence of shale in sandstone, the presence of dolomite in shale and sandstone complicated the interpretation of evaporite sequences.

Interpretation of Geologic Structure in Evaporites

Complex faulting and folding is common in Paradox basin salt anticlines, and can cause the same interbed sequence to occur at different depths in the same borehole. When the two limbs of a fold cross the drill hole at approximately the same angle, the well log responses for the limbs are nearly mirror images of one another. This case is illustrated in figure 6 where interbed sequences A and A' are the limbs of the same fold.

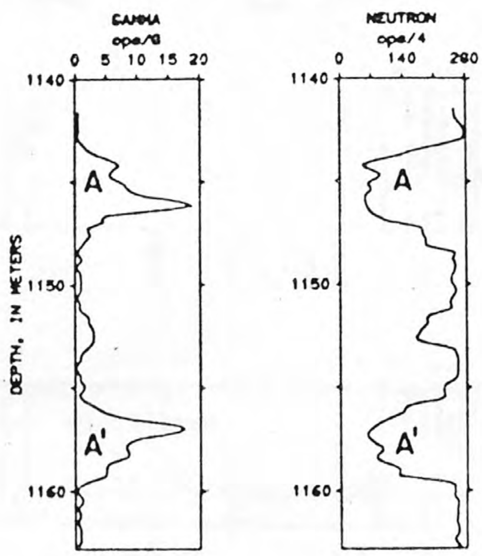


Figure 6.--A section of the Salt Valley well showing the gamma-ray and neutron-neutron well log responses for the limbs (A and A') of a fold.

Interbed A' is in its normal, or upright position, and interbed sequence A is the overturned limb of the fold. The dip of interbed sequence A-A' at the drill hole is approximately the same for each limb of the fold, and the two limbs of the fold have nearly identical well log responses. Unfortunately, folded beds rarely cross the drill hole at the same dip angle for both limbs of the fold. When a bedding sequence does cross the drill hole at different depths and dip angles, the resulting well log responses can lead to a misinterpretation of the geologic structures. Faulting often results in a dissection of an interbed sequence. The general structural style at salt valley causes reverse faulting, which results in repetition of interbed sequences. However, normal faulting also occurs and results in the ommission of interbeds from the normal evaporite sequence observed in a drill hole.

A typically complex structural situation encountered at Salt Valley is illustrated in figure 7. Some interbeds in this section are folded, while other interbed sequences are disturbed by faulting.

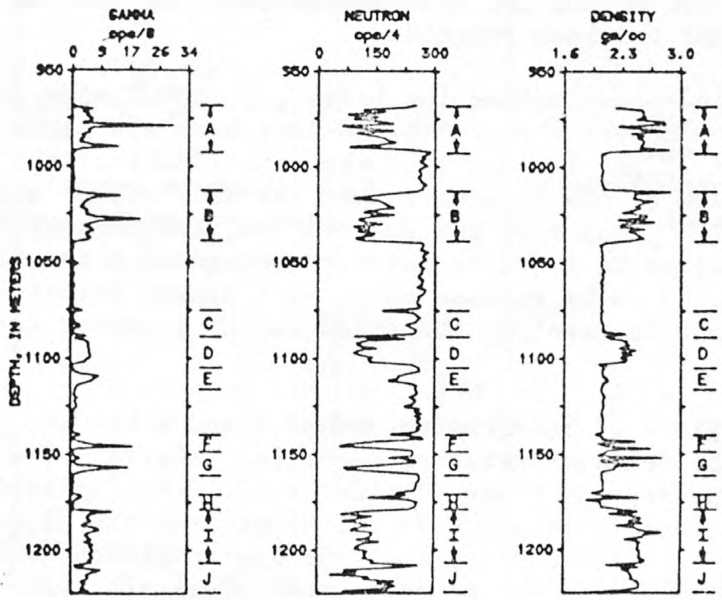


Figure 7.--Gamma-ray, neutron-neutron and density well logs in complex structural section of the Salt Valley well. Interbed sequences that are analyzed in this paper are indicated by the letters A through J.

Interbed sequences A and B in figure 7 are the limbs of a fold involving the same interbed. The limbs of the fold cross the drill hole at about the same dip angle, (approximately 30° from core description) resulting in similar well log response patterns. The structural relationship of the remaining interbeds in this part of the section (interbeds C through J) is not as simple as the fold represented by interbed sequences A and B.

In order to compare the well log responses of the various interbed sequences, it would be hlpful to rotate the interbeds from their present dip angles to a common dip angle. An alternative solution is to normalize the well log response values. This can be done by plotting the percent frequency of occurrence of well log response values (digitized at 0.15 m intervals) for the interbed. Figure 8 shows the results of plotting the percent of occurrence for the gamma-ray, neutron-neutron, and density well log values in depth intervals A and B. The slight amplitude discrepancies in the gamma-ray plots are caused by a greater depth interval being sampled for interbed sequence B, resulting in some non-interbed halite response values being included in the analysis of interbed sequence B.

The other interbed sequences (C through J) were analyzed individually and in various combinations. The percent frequency plots for intervals D and E are shown in figure 9. These plots indicate that intervals D and E are not similar to each other and are either two independent beds, or are two unfolded sections of the same bed that has been faulted.

The well log response values for beds C, D, and E were combined and the percent-frequency plots of these combined interbeds are shown in figure 10. Both sets of plots (figs. 10a and 10b) show the effect of the salt that is present between each of the sequences. If the salt values are ignored, the general shape of the gamma-ray, neutron-neutron, and density-frequency patterns would be similar to those of interbed sequences A and B. The combined sequence C, D, and E can be considered to be a single interbed sequence that has been faulted and is possibly connected to the interbed sequences in intervals A and B.

Independent plots of interbed sequences F and G are shown in figure 11. A comparison of the density-frequency plots for intervals F and G shows that these sequences may represent the same interbed. The distribution of points in the frequency plots for F and G is different from the plots for other intervals in the section. Combining the well log responses for sequences F and G (fig. 12) also yields a percent frequency pattern whose distribution is different from percent frequency plots for the other interbed sequences. Interbeds F and G are independent interbed sequences that are limbs of a common structural fold.

Percent frequency plots for combined beds I and J, and H, I, and J, are shown in figure 13. These combined plots show similar patterns to the plots for beds A and B. This relationship is not apparent on the individual well logs. The conclusion can be drawn from these plots that combined interbed sequence H, I, and J is the same interbed sequence as that represented by

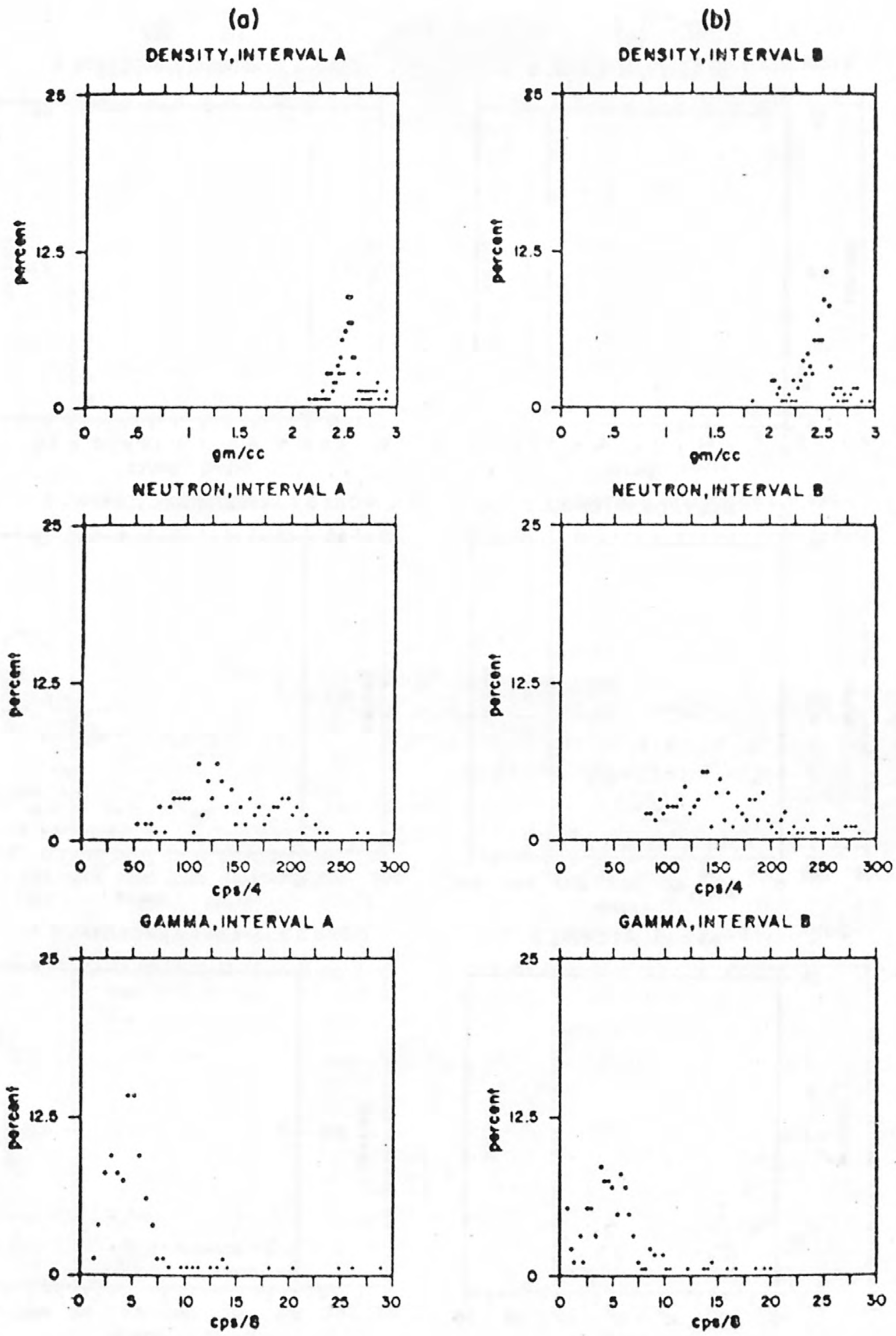


Figure 8.--Gamma-ray, neutron-neutron, and density plots for depth intervals (a) A, and (b) B. The abbreviation "cps" is counts/second; abbreviation "gm/cc" is grams/cubic centimeter.

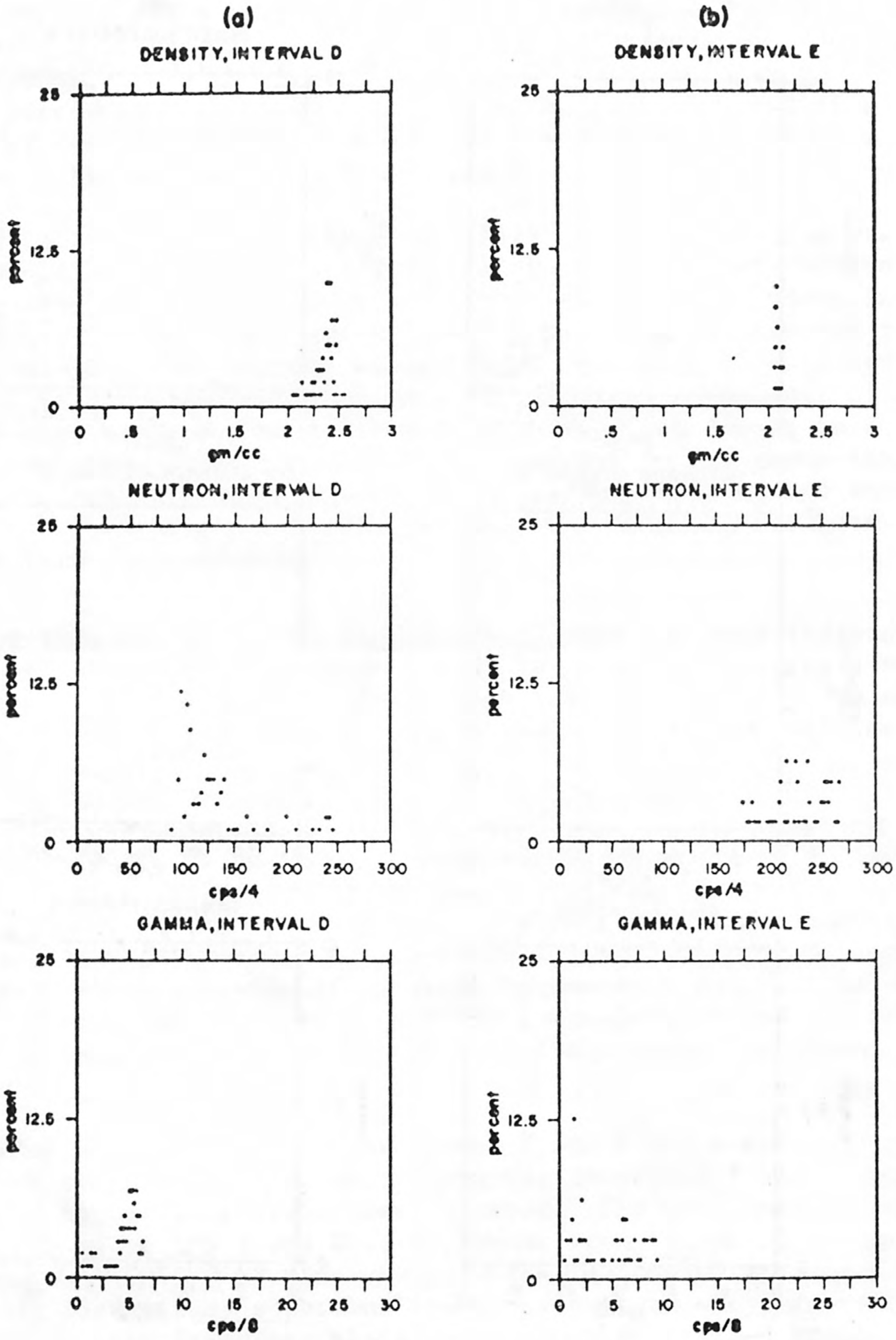


Figure 9.--Gamma-ray, neutron-neutron, and density percent frequency plots for depth intervals (a) D, and (b) E. The abbreviation "cps" is counts/second; abbreviation "gm/cc" is grams/cubic centimeter.

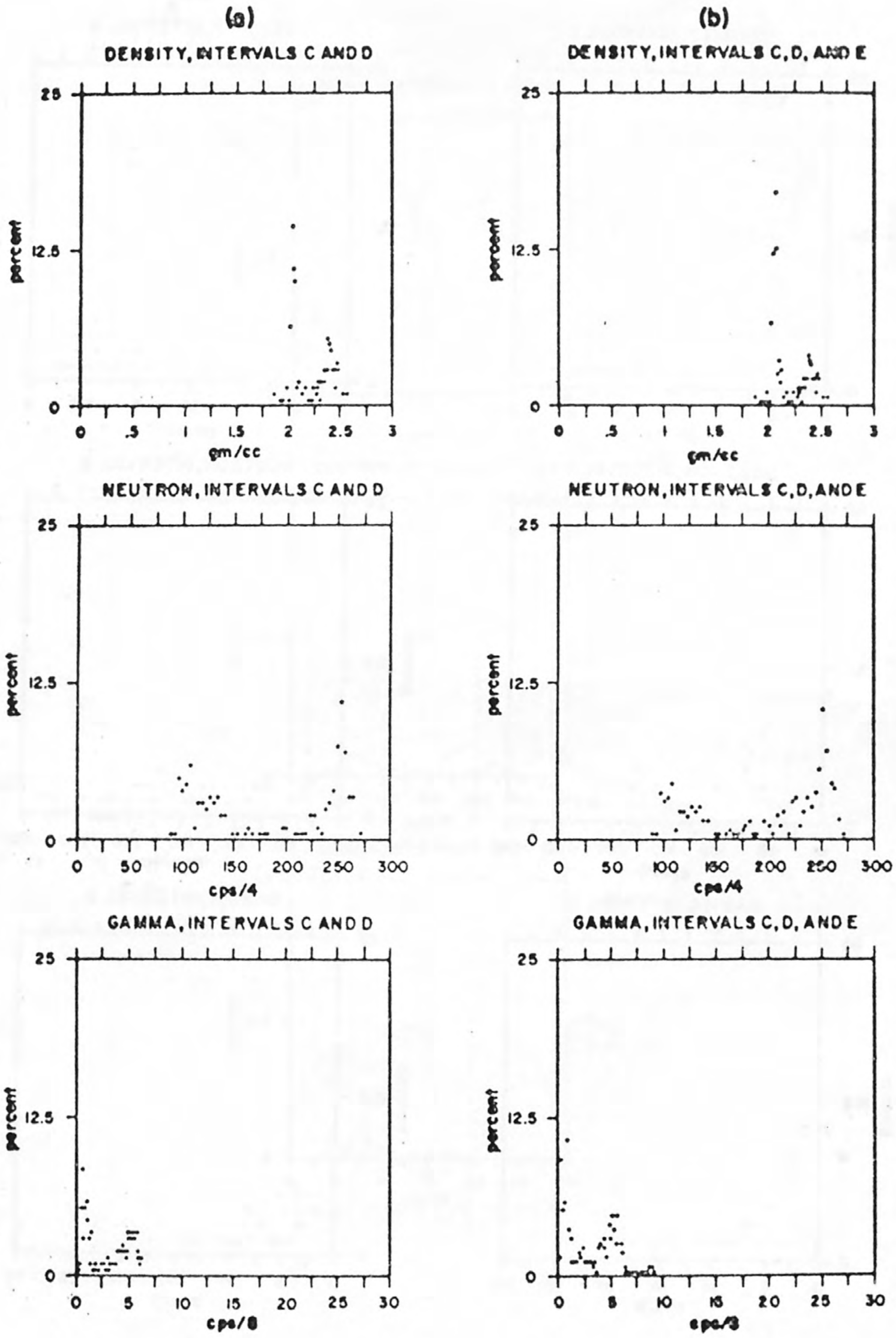


Figure 10.--Gamma-ray, neutron-neutron, and density percent frequency plots for combined-depth intervals (a) C and D, and (b) C, D, and E. The abbreviation "cps" is counts/second; abbreviation "gm/cc" is grams/cubic centimeter.

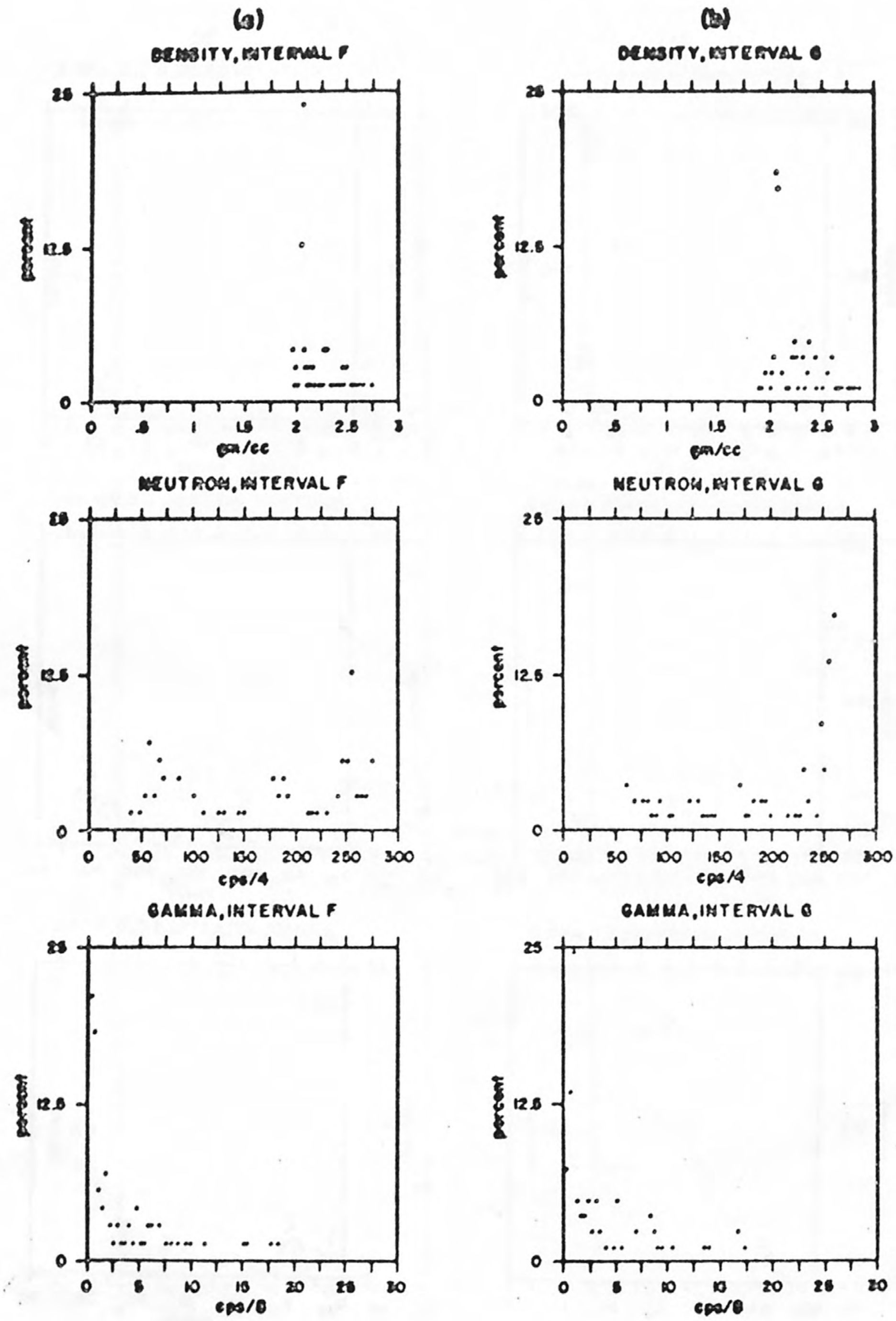


Figure 11.--Gamma-ray, neutron-neutron, and density percent frequency plots for depth intervals (a) F, and (b) G. The abbreviation "cps" is counts/second; abbreviation "gm/cc" is grams/cubic centimeter.

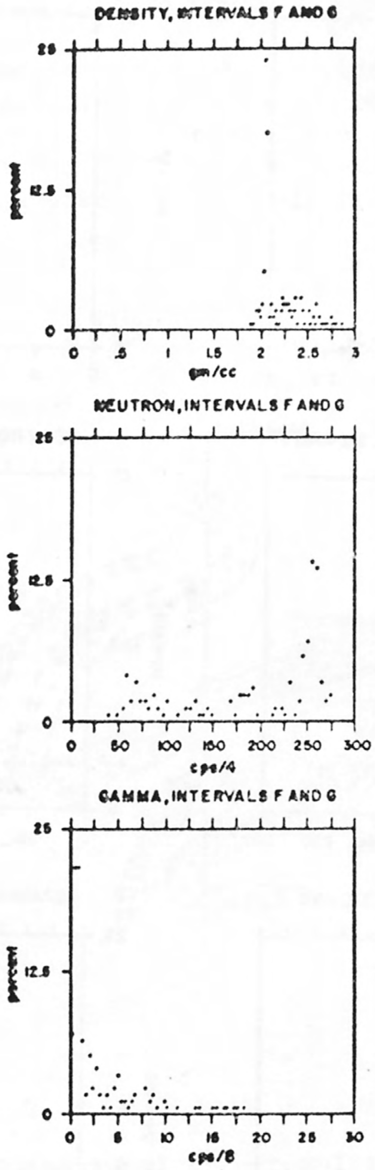


Figure 12.--Gamma-ray, neutron-neutron, and density percent frequency plots for combined-depth intervals F and G. The abbreviation "cps" is counts/second; abbreviation "gm/cc" is grams/cubic centimeter.

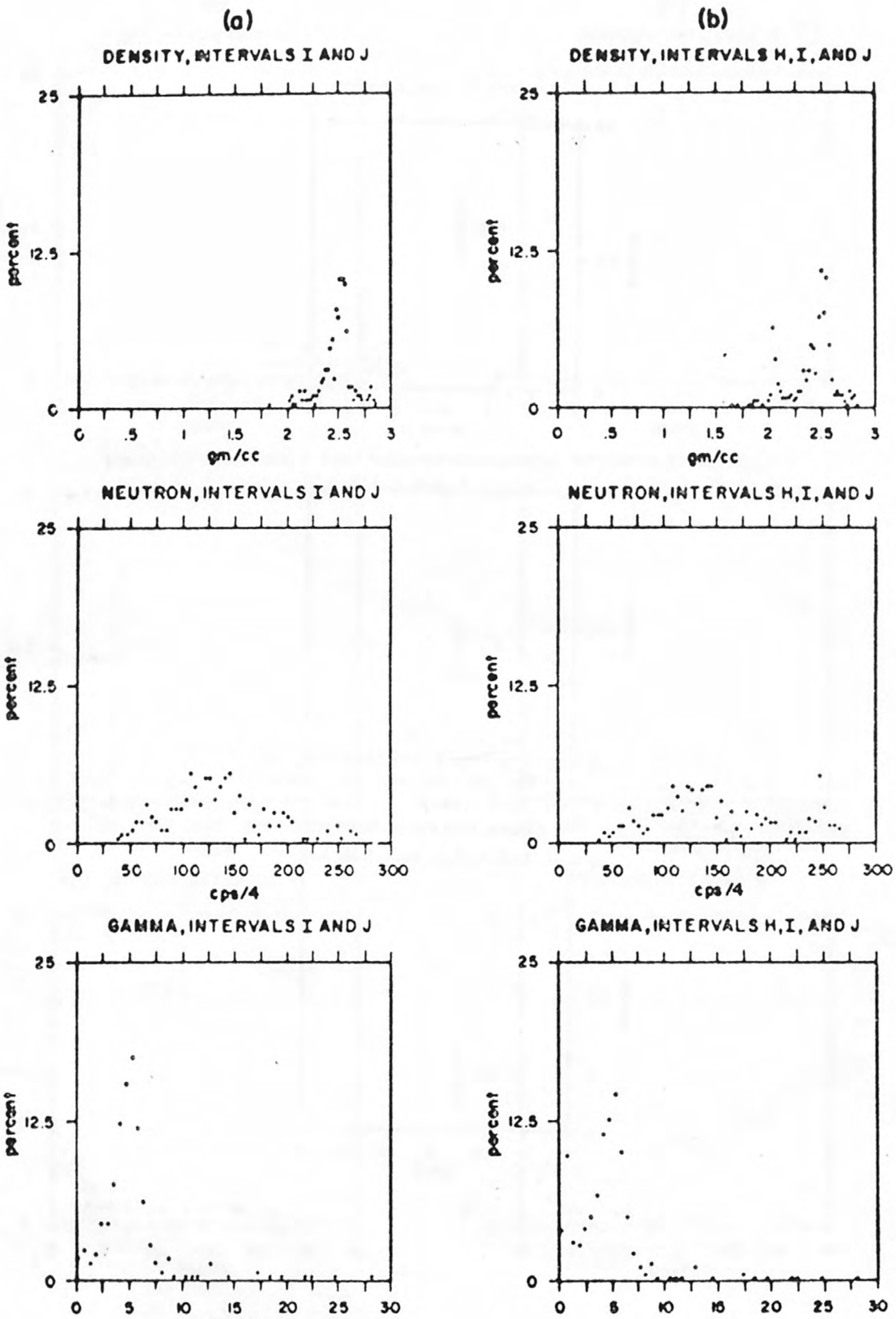


Figure 13.--Gamma-ray, neutron-neutron, and density percent frequency plots for combined-depth intervals (a) I and J, and (b) H, I, and J. The abbreviation "cps" is counts/second; abbreviation "gm/cc" is grams/cubic centimeter.

interbeds A and B. The well log responses indicate that beds I and J are separated by a thin halite layer. Therefore, interbed sequences I and J are probably limbs of a common fold.

A structural two-dimensional interpretation of evaporite sequences A through J is shown in figure 14. This interpretation is based upon the information contained in the percent-frequency plots. An interpretation based solely upon the individual well logs would probably not identify the interconnection of interbed sequences A and B with intervals H, I, and J.

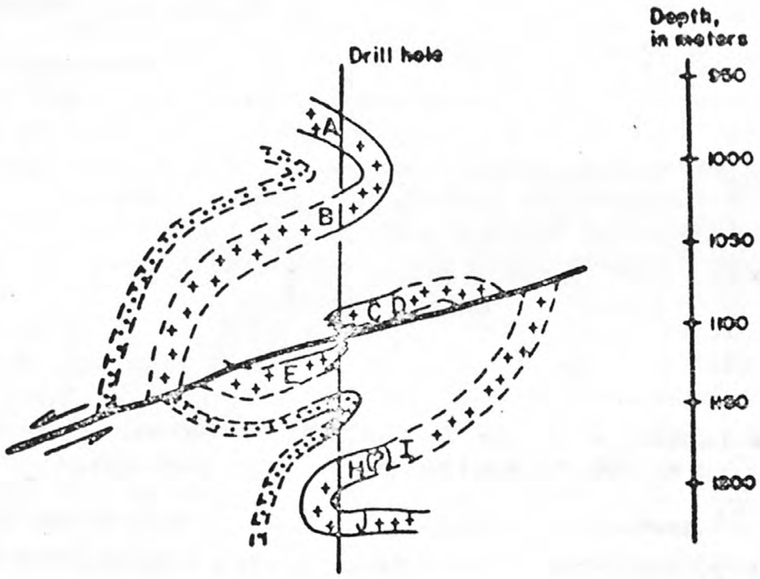


Figure 14.--Two-dimensional structural interpretation of the interbed sequence shown in figure 7 as interpreted from percent frequency plots.

Conclusions

The basic components of a normal evaporite sequence (halite, anhydrite, potash, shale, gypsum, and dolomite) are easily identifiable on conventional well logs. However, evaporite sequences rarely fit an idealized model. For example, the evaporite sequence at Salt Valley is lithologically and structurally complex. More work needs to be done on quantitatively identifying the mineralogic components within the complex interbed sequences. This may require the development and application of new borehole geophysical tools for use in evaporite environments. Some tools (such as the acoustic velocity probe) may be redesigned to better define thin beds in an evaporite sequence.

Borehole geophysical tools are needed to measure the large contrasts of electrical properties (dielectric constant resistivity) that are present between the individual lithologic components in an evaporite sequence. The single coil induction probe that was tested at Salt Valley may be useful in determining the moisture content of halite. Both dry-hole and wet-hole radar, and subradar-frequency electromagnetic borehole probes need to be developed.

The complicated geologic structure at Salt Valley makes it difficult to stratigraphically identify individual interbed sequences in a borehole. The frequency-plot technique, illustrated in this paper, may be useful in establishing stratigraphic sequences and assist in interpreting the complex geologic structure in a single borehole. The frequency-plot technique may also be useful for tracing marker beds in different holes. Hole-to-hole, hole-to-surface, and widely-spaced single hole acoustic and electrical techniques must be developed in order to interpret the three-dimensional structure of complex evaporite sequences such as Salt Valley.

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J. J. Daniels received his B.S. and M.S. degrees in geology from Michigan State University in 1969 and 1970, and a Ph.D. degree in geophysics from Colorado School of Mines in 1974. After graduating from CSM he worked for Chevron Oil Company until joining the U.S. Geological Survey in the fall of 1974. His research at the Geological Survey has involved the interpretation and evaluation of borehole geophysical methods in uranium and coal environments. He is a member of SEG, SPWLA, and CMA.

J. H. Scott received his B.S. degree from Union College in 1951, and has undertaken additional undergraduate and graduate study at the University of Kentucky, Pennsylvania State University, the University of Colorado, and Colorado School of Mines. His experience in exploration geophysics began with two years of seismic work for the Phillips Petroleum Company, followed by seven years of uranium exploration research, including gamma-ray logging studies for the Atomic Energy Commission (now the Energy Research Development Administration), six years of nuclear test site evaluation by surface and in-hole geophysical techniques for the U.S. Geological Survey, and seven years of development of surface and borehole mining geophysical techniques for the U.S. Bureau of Mines. For the past 5 years he has been engaged in borehole geophysical research for the U.S. Geological Survey. He is a member of SPWLA and SEG.

Robert J. Hite graduated from Wichita State University in 1954. Graduate work, University of New Mexico from 1954-1956. Employed by the U.S. Geological Survey in 1956. From 1956 to 1964 geologic investigations of phosphate, potash, coal, and petroleum in the Rocky Mountains. 1964 to present includes studies of domestic potash deposits especially in the Paradox basin, and also international investigations in Brazil, Thailand, and Laos. Current projects include marine evaporites and petroleum, and emplacement of radioactive wastes in salt deposits. Forty-six publications in the field of marine evaporites, potash deposits, oil shale, uranium and structure in the Rocky Mountains. Member of GSA, SEG, RMAG, and the New Mexico Geological Society.

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