ANALYSIS OF GEOPHYSICAL DATA TO EXAMINE THE FEASIBILITY OF DEEP-WELL INJECTION OF BRINE NEAR LOGAN, NEW MEXICO

Final Report

HYDRO GEO CHEM, INC.

Groundwater Consultants

ANALYSIS OF GEOPHYSICAL DATA TO EXAMINE THE FEASIBILITY OF DEEP-WELL INJECTION OF BRINE NEAR LOGAN, NEW MEXICO

__Final Report__

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EXECUTIVE SUMMARY

Brine flowing into the Canadian River system near Logan, New Mexico has degraded the quality of water in Lake Meredith, located downstream near Amarillo, Texas. The U.S. Bureau of Reclamation is considering several saltwater abatement schemes, all of which require the disposal of brine. Deep-well injection has been proposed by the Bureau of Reclamation as the most preferable method of brine disposal. The available subsurface geophysical and geological data from the Logan area have been analyzed and reviewed to identify those geologic units in which brine injection is feasible.

Potential horizons for brine disposal may exist within the Permian San Andres and Yeso Formations and within the deeper Permo-Pennsylvanian Abo and Sangre de Cristo Formations. The Permian units are the source of salt entering the river and may be hydraulically connected to the surface. Because brine injection might increase upward leakage from the San Andres and Yeso, these units have been excluded as possible injection zones. The focus of this analysis, therefore, is on the arkosic sandstones of the Abo and Sangre de Cristo formations.

Analysis of the well logs obtained from the nearby Ute Anticline No. 1 Well shows the arkosic sandstones have total porosities of 10 to 17 percent. Cross-sections, based upon geophysical well-log data, show that the Abo Formation is regionally extensive. The Abo and Sangre de Cristo sands are quite

thick, but individual sandstone horizons are difficult to correlate given the present well spacings.

Detailed information regarding these sandstones was obtained from seven subsurface miles of seismic reflection data. The data show that the fault-bounded Tucumcari Basin extends further north than indicated by previous studies. A minimum of 1500 feet of Abo and Sangre de Cristo Formation sediments can be found near Logan. The Abo Formation sandstones, located 3800 to 4400 feet below land surface in the vicinity of the seismic lines, are the most laterally extensive and the least structurally disrupted of the arkosic sandstones.

Locally, the deeper sandstones have sufficient porosity, thickness, and extent for the injection of brine. Selecting an optimal location for a disposal well will require identifying areas with maximum formation thickness to minimize injection pressures while minimizing the distance to the disposal well. The seismic data indicate that areas with sufficient sand thickness to permit brine injection lie within three to six miles of the area of brine inflow. One of the best areas to place a well appears to be between sections 29 and 30 along line B (please refer to Figure 13). Care must be taken, however, not to intercept any of the fracture and fault zones found at depth that may be hydraulically connected to the surface. The area most prone to fracturing in the injection zones is upsection of faults mapped in the subsurface by the seismic survey.

A design criterion of 450 gallons per minute (approximately one cubic foot per second) into a 9 5/8 inch diameter well has been proposed by the Bureau of Reclamation. From a hydraulic standpoint, the permeability of the deep arkosic sandstone has not been measured in the area and can only be estimated. The formation fluid pressure is unknown as well and should be tested during the completion of any disposal well. The pressure will determine the effective head or fluid pressure that can be applied to flow into the injection horizon. Initial estimates show that a well rated at 450 gallons per minute can be supported by a 200 foot thick section of sandstone for the range of hydraulic conductivities and formation pressures that can be expected in the area. It is also important to carefully examine the chemistry of the pore fluid and the rock matrix within an injection horizon because of the possibility of the swelling of clay minerals or the precipitation of calcite or gypsum which will adversely affect the performance of the well.

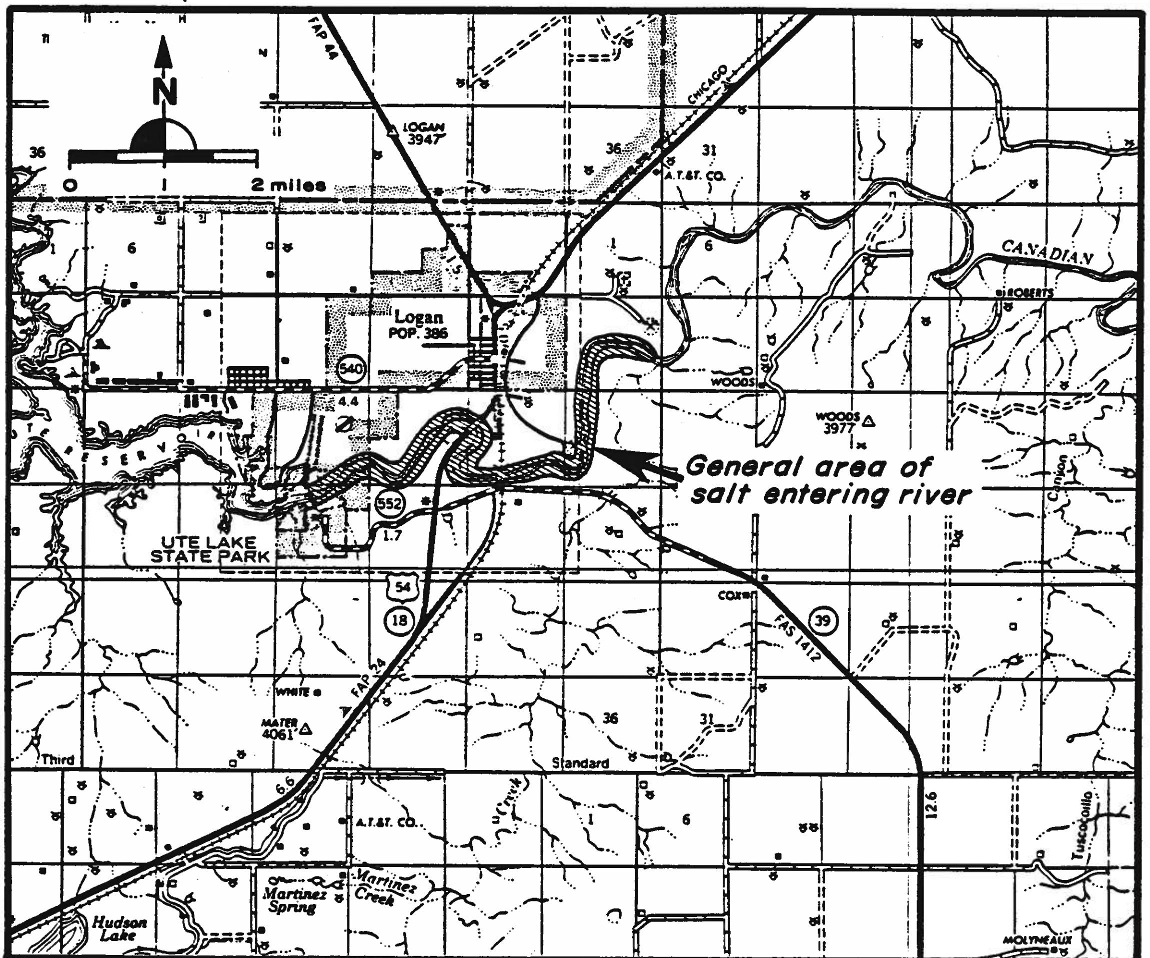
CHAPTER 1

INTRODUCTION

This report contains results of analyses of seismic reflection and geophysical well logs to guide the location and design of a deep-well system for brine injection near Logan, New Mexico. It has been prepared by the staff of Hydro Geo Chem, Inc., Tucson, Arizona, for the U.S. Bureau of Reclamation, Southwest Region, under Modification No. 1 to Contract No. 3-CS-50-01580.

The limiting factor in any saltwater abatement program proposed for the Canadian River is an acceptable disposal method for the brine removed from the river's hydrologic system. Deep-well injection appears to be the most feasible disposal method. Therefore, to explore for potential injection horizons in the area southeast of Logan, New Mexico, eleven surface miles of seismic reflection data (Figure 1) were collected by Grant Geophysical Co. of Midland, Texas and processed by Norpac Processing Company of Englewood, Colorado. The work was conducted between July and October, 1984. The seismic field data tapes are being stored by the U. S. Bureau of Reclamation Engineering and Research Center, Lakewood, Colorado. These data, combined with the available deep well-log data and the results of our previous study (Hydro Geo Chem, Inc., 1984) form the basis of this report.

The area of investigation was limited to a distance of about six miles from the area of brine inflow (Figure 1), based primarily on the cost of transporting brine from the river to a disposal well system. The survey area



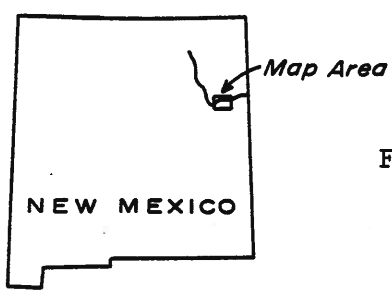


Figure 1. Location of study area.

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chosen is near the source of brine discharge into the river and is south of the limit of evaporite dissolution as determined from well-log and surface mapping.

An injection horizon must have sufficient permeability, effective porosity, and lateral extent to accept large quantities of disposed brine. Presently, the Bureau of Reclamation is proposing an injection well rated for a flow rate of 450 gallons per minute. The mineralogy of the formation and the chemistry of the pore fluids must also be compatible with the injected fluids. For example, clays within a unit may swell or migrate and plug the pore spaces within the rock when a fresher water is introduced into a formation already in equilibrium with saline water. The disposal zone must also be isolated from the surface so that the injected fluids "... do not result in the degradation of underground drinking water sources..." under the 1974 EPA Safe Drinking Water Act.

The parameters that can be determined from seismic and borehole data are the porosity, thickness, and lateral extent of sandstone sequences. Seismic data are most useful in examining the structure of potential disposal horizons and can help identify faulting that may lead to upward leakage of brine. Downhole geophysical data are used in this report to identify individual sandstone units in the area and to correlate potential disposal zones over the region. Three important parameters, the in-situ hydraulic conductivity, the formation pressure, and the chemical composition of pore fluids within the deep sediments, cannot be deduced from the geophysical data and can only be determined from well tests.

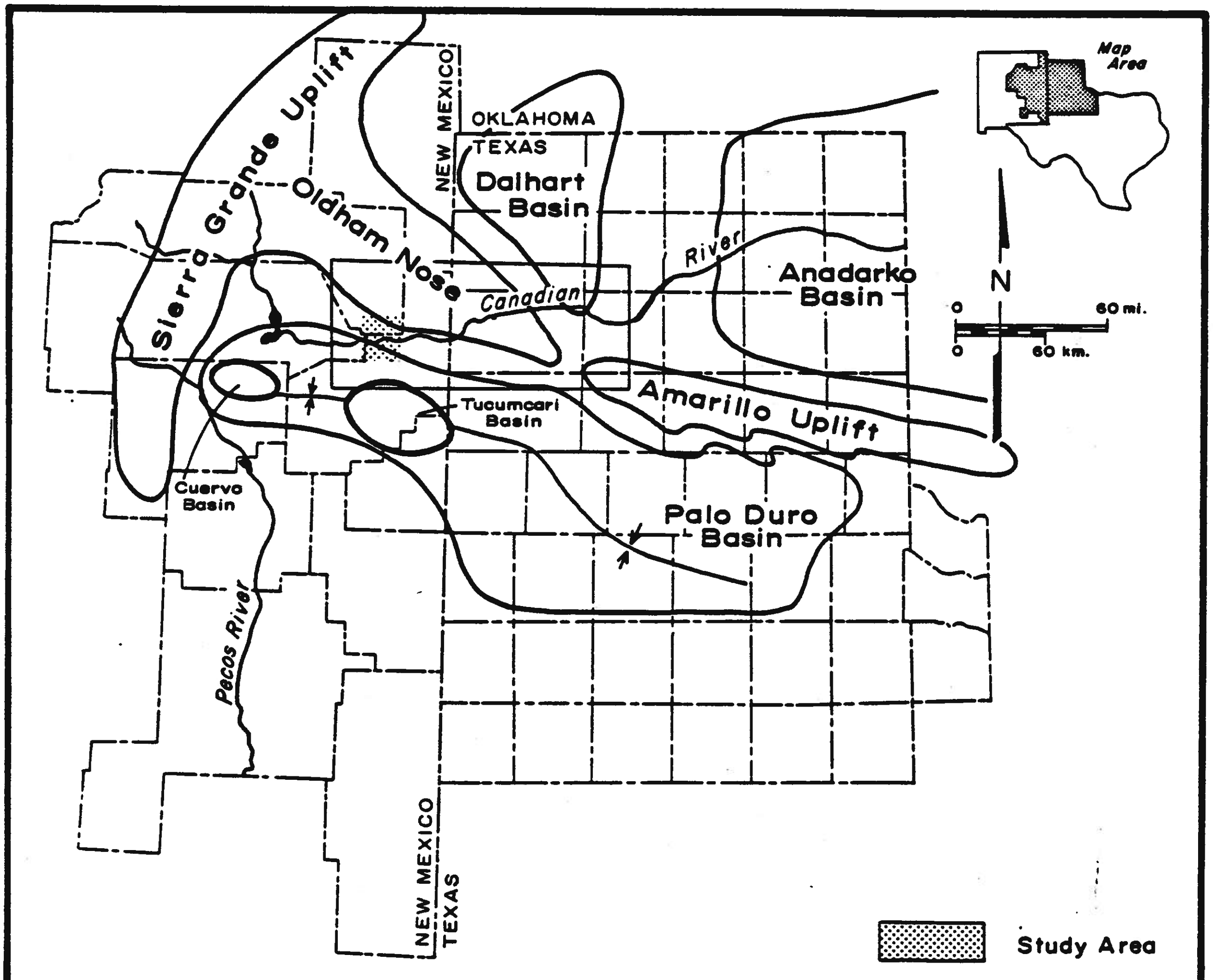
This report is structured by first presenting an overview of the regional geology. Then, using the data from a well located near Logan, an assessment is made of potential reservoir sands. These results are extended into a regional well-log analysis. Finally, the interpretation of the seismic data is presented to detail the structure and continuity of potential brine reservoir sands. From this study, recommendations are made regarding the location of potential disposal horizons as well as testing considered necessary to determine the properties of the horizons.

CHAPTER 2

STRUCTURAL AND STRATIGRAPHIC SETTING

REGIONAL GEOLOGY

The area of investigation lies near the edge of the Tucumcari Basin, which can be considered to be an extension of the Palo Duro Basin of Texas (Figure 2). The sedimentary units dip gently southward towards the depositional axis of the basin. Prior to the formation of the basin in mid-Pennsylvanian times, the Panhandle region was the site of shallow water carbonate deposition. As the basin developed, arkosic sandstones and shales originating from uplifted granitic highlands north and west of Logan were initially deposited as irregular clastic units. These units later became more developed and continuous as the basin filled. These sediments are represented by the Pennsylvanian/Permian age Sangre de Cristo and Abo Formations. Conformably overlying the sandstones are the Permian Yeso, San Andres, and Artesia Formations. All three Permian age formations contain fine-grained siltstone, dolomite, anhydrite, gypsum, and halite, and represent shelf and shelf margin depositional systems that existed in an arid environment. Upsection, the units generally grade from fine-grained sandstones and interbedded mudstone and salt to bedded halite, gypsum, anhydrite, and carbonate. Unconformably overlying the evaporitic sediments are the fluvio-deltaic Dockum Group sediments of Triassic age that are exposed throughout the study area. A veneer of alluvial sands, gravels and irregularly exposed caliche deposits cap the highlands and terraces above the river channel. A stratigraphic section (Figure 3) is included to illustrate the relation between the units.



Adapted from Nicholson, 1960; Gustavson and others, 1982

Figure 2. Geologic setting.

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		NE NEW MEXICO STUDY AREA			PALO DURO BASIN	
SYSTEM	SERIES	GROUP	FORMATION	GROUP	FORMATION	General Lithology & Depositional setting
QUATERNARY	HOLOCENE				alluvium, dune sand Playa	
QUATERNARY	PLEISTOCENE				Tahoka cover sands, Tule/"Playa" Blanco	Lacustrine clastics & windblown deposits
TERTIARY	NEOGENE		Ogallala		Ogallala	Fluvial & lacustrine clastics
CRETACEOUS					undifferentiated	Marine shales & limestones
TRIASSIC		DOCKUM		DOCKUM		Fluvial-deltaic & lacustrine clastics
PERMIAN	OCHOA		Alibates?		Dewey Lake (Quartermaster)	Sabkha salt, anhydrite, red beds, & peritidal dolomite
PERMIAN	OCHOA		Alibates?		Alibates	Sabkha salt, anhydrite, red beds, & peritidal dolomite
PERMIAN	OCHOA	ARTESIA	Bernal *	ARTESIA	Salado/Tansill *	Sabkha salt, anhydrite, red beds, & peritidal dolomite
PERMIAN	GUADALUPE	ARTESIA	Bernal *	ARTESIA	Yates	Sabkha salt, anhydrite, red beds, & peritidal dolomite
PERMIAN	GUADALUPE	ARTESIA	Bernal *	ARTESIA	Seven Rivers *	Sabkha salt, anhydrite, red beds, & peritidal dolomite
PERMIAN	GUADALUPE	ARTESIA	Bernal *	ARTESIA	Queen/Grayburg	Sabkha salt, anhydrite, red beds, & peritidal dolomite
PERMIAN	GUADALUPE		San Andres *		San Andres *	Sabkha salt, anhydrite, red beds, & peritidal dolomite
PERMIAN	LEONARD		Yeso *	CLEAR FORK	Glorieta *	Sabkha salt, anhydrite, red beds, & peritidal dolomite
PERMIAN	LEONARD		Yeso *	CLEAR FORK	Upper Clear Fork *	Sabkha salt, anhydrite, red beds, & peritidal dolomite
PERMIAN	LEONARD		Yeso *	CLEAR FORK	Tubb	Sabkha salt, anhydrite, red beds, & peritidal dolomite
PERMIAN	LEONARD		Yeso *	CLEAR FORK	Lower Clear Fork *	Sabkha salt, anhydrite, red beds, & peritidal dolomite
PERMIAN	LEONARD		Yeso *	CLEAR FORK	Red Cave	Sabkha salt, anhydrite, red beds, & peritidal dolomite
PERMIAN	LEONARD		Yeso *	WICHITA		Sabkha salt, anhydrite, red beds, & peritidal dolomite
PERMIAN	WOLFCAMP		Abo		?	Shelf & shelf-margin carbonate, basinal shale, & deltaic sandstone
PENNSYLVANIAN	VIRGIL	MAGDALENA	Sangre de Cristo "granite wash"	CISCO		Shelf & shelf-margin carbonate, basinal shale, & deltaic sandstone
PENNSYLVANIAN	MISSOURI	MAGDALENA	Madera	CANYON		Shelf & shelf-margin carbonate, basinal shale, & deltaic sandstone
PENNSYLVANIAN	DES MOINES	MAGDALENA	Madera	STRAWN		Shelf & shelf-margin carbonate, basinal shale, & deltaic sandstone
PENNSYLVANIAN	ATOKA			BEND		Shelf & shelf-margin carbonate, basinal shale, & deltaic sandstone
PENNSYLVANIAN	MORROW			BEND		Shelf & shelf-margin carbonate, basinal shale, & deltaic sandstone
MISSISSIPPIAN	CHESTER		SECTION PARTIALLY MISSING			Shelf carbonate & chert
MISSISSIPPIAN	MERAMEC		SECTION PARTIALLY MISSING			Shelf carbonate & chert
MISSISSIPPIAN	OSAGE		SECTION PARTIALLY MISSING			Shelf carbonate & chert
ORDOVICIAN				ELLENBURGER		Shelf dolomite
CAMBRIAN						Shallow marine (?) sandstone
PRECAMBRIAN						Igneous & metamorphic

*SALT PRESENT

Figure 3. Stratigraphic column.

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The structure of the basin and the geometry of the deep sediments is controlled by the structure of the Precambrian basement rocks. The dominant structural features are northwesterly trending high angle normal faults found deep in the subsurface and a system of weakly developed northeast trending flexures observed at the surface. The edge of the Tucumcari basin (Figure 2) near Logan is defined by the northwest trending fault system. The seismic data acquired for this study show the position of the northern edge of the Tucumcari basin to be closer to Logan than previously thought.

POTENTIAL DISPOSAL HORIZONS

Injection of brine requires a disposal horizon that is sufficiently permeable and areally extensive to accept large quantities of brine. The injection horizon must also be geologically isolated so that the chance of leakage back to the surface is minimized. In the study area, the shallowest stratum that could considered for brine disposal is a permeable dolomite within the San Andres that has been noted to be a lost circulation zone during the drilling of local oil wells. This zone is only 800 to 1100 feet deep in the Ute Anticline well and is within an area that is undergoing regional dissolution and contributing salt to the Canadian River system. Inasmuch as natural pathways for fluid movement from this unit already exist, it should not be considered for brine injection. Sandstones present in the Yeso Formation, most notably the Glorieta, Tubb, and Fullerton sandstones, may be suitable injection zones, but the strong possibility of upward leakage through fault and fracture zones still exists. These zones cannot be reliably mapped from the surface, but the analysis of the seismic data reveals fault displacement both below and occasionally within the Permian section. The upsection termination of these faults should be manifested as areas of increased fracturing.

Other potential injection zones which are relatively isolated from the upper evaporite sections are the Sangre de Cristo and Abo Formations. These formations are located 3800 feet and deeper below land surface in the study area. The arkosic sandstones within these formations are extensive and thicken toward the axis of the Tucumcari Basin. These formations contain the most suitable injection horizons because they are the thickest units available and appear to have the least risk of leakage. For this reason, the remainder of this report focuses on the characteristics of the Abo and Sangre de Cristo Formations.

ANALYSIS OF THE UTE ANTICLINE WELL LOG DATA

The well closest to the area of interest with a fairly complete set of well-logs is the National Oil Company's Ute Anticline No. 1 test well. It lies approximately 10 miles southwest of Logan, in Township 12 North, Range 32 East, Section 11 (see Figure A-1, Appendix A). Neutron porosity, bulk density, gamma, caliper, acoustic velocity, and resistivity logs were available for this well. These logs have been used to provide a lithologic description of potential disposal horizons in the well. The logs have been plotted in Figure 4 to show the sedimentary section from the top of the Abo and deeper.

The arkosic sandstones of the Abo and Sangre de Cristo Formations encountered in the Ute well were derived from granitic highlands located north and west of the study area. Therefore, the sandstone composition reflects the mineral content of the parent rock. As the basin filled, the sands became better sorted and appear to contain less clay. This is indicated by the trend of decreasing gamma activity observed in the gamma log from the bottom to the top of the section (Figure 4). Potassium feldspar derived from granitic rock will also contribute to the gamma response so the trend may also reflect a change in the ratio of feldspar to quartz in the sand, again a consequence of increased sorting and working of the deposited sands. A series of 17 sandstone units, representing the thickest sandstones in the lower section, were selected for quantitative analysis. These sandstones comprise the best injection horizon that can be identified within the arkosic sandstones in the vicinity of the Ute Anticline well. The log response of each unit is tabulated in Appendix B.

One important reservoir parameter that can be calculated from neutron, bulk density, and the electrical logs is porosity. The resistivity logs were not used for this calculation because the electrical resistivity of the formation fluids, a parameter necessary for quantitative calculation, is not known. The neutron porosity tool responds to hydrogen in the formation, which is interpreted as water, and thus provides a measure of the total porosity of a saturated rock. Chlorine in the formation water also has a minor influence on the tool response. Porosity determinations are strongly affected by the presence of clay minerals because clays contain hydrogen in their structure.

A standard technique to correct neutron porosity logs for the presence of clay is to simultaneously use the bulk density log data (which is unaffected by clay minerals) by constructing neutron porosity-bulk density crossplots

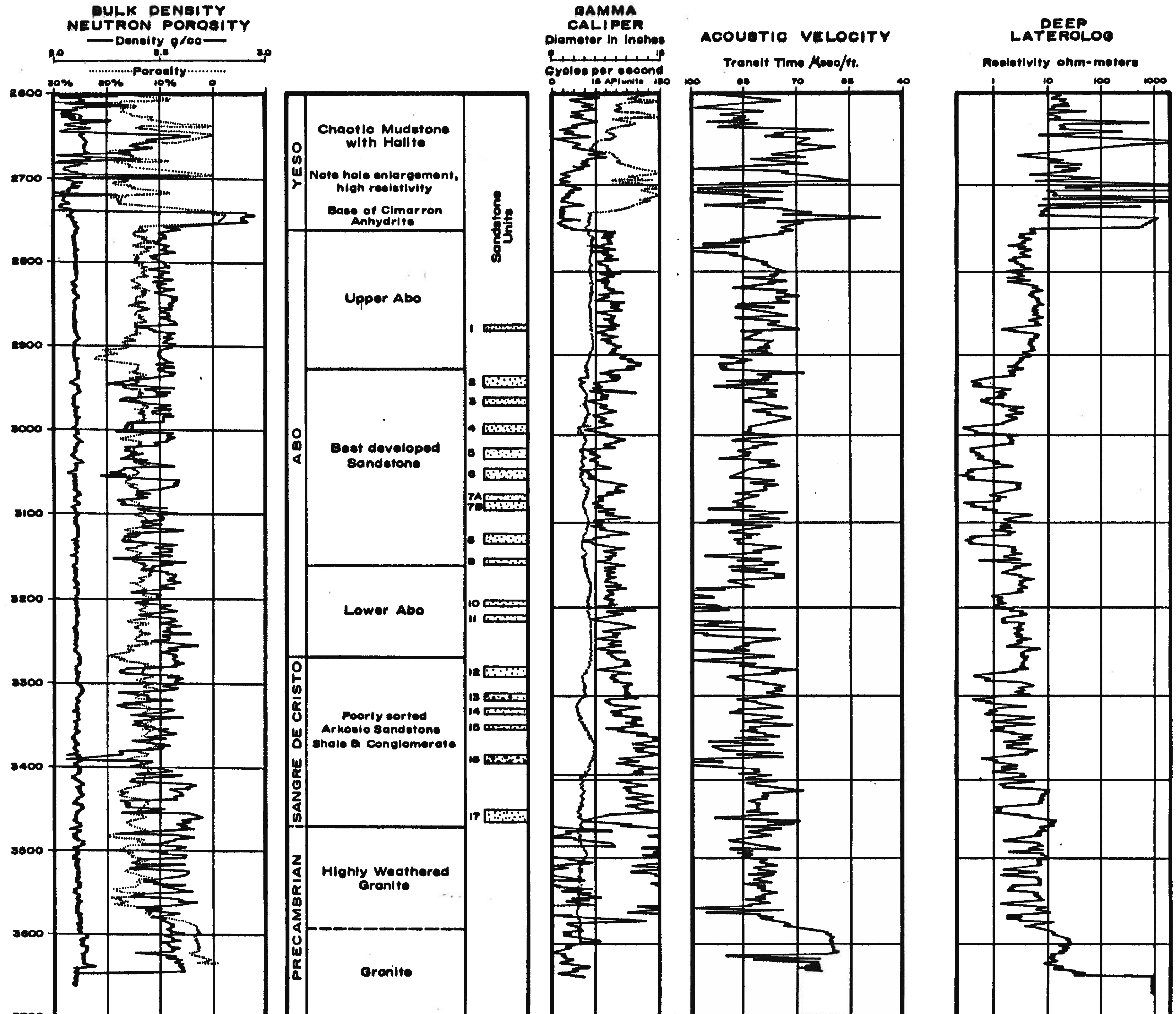

Figure 4. Ute Anticline well log comparison.

(Schlumberger, 1979). The response of a clean (clay-free) sandstone is plotted on the porosity-density graph using standard sandstone porosity values taken from Schlumberger log interpretation chart CP-1d (Schlumberger, 1979). A point corresponding to the response of pure shale is also placed upon the graph and a ternary plot of sand/shale/water is constructed on the graph (see the top of Figure 5 for an example of the overlay). The plot may then be scaled off in terms of the sandstone porosity and percent shale. This procedure assumes that the shale (or clay) is disseminated throughout the rock.

The values of porosity for the seventeen selected sand intervals are shown in Figure 5. Because the sandstone matrix contains a significant amount of feldspar, clay, and mica, the bulk density of "zero-porosity" sand has been set at 2.55 g/cm^3, rather than at 2.65 g/cm^3 as would be used for a pure quartz sand. This value of matrix rock density is lower than typically used for oil-field reservoirs, but it fits the observed cross-plot values fairly well. The effect of underestimating the grain density is to overestimate the porosity and shale content. The range of values show that <u>total</u> porosities range between 10 and 17 percent and shale contents range up to 30 percent. (The bulk density of sandstone unit 16, noted to be a conglomerate in the driller's log, is off-scale even after the grain density was adjusted). This analysis indicates that the Abo sands have a fairly high porosity and contain a low to moderate amount of clay in the rock matrix. These values, however, should be taken as approximate and any disposal well should be carefully cored and sampled to determine the true composition of sands in the well.

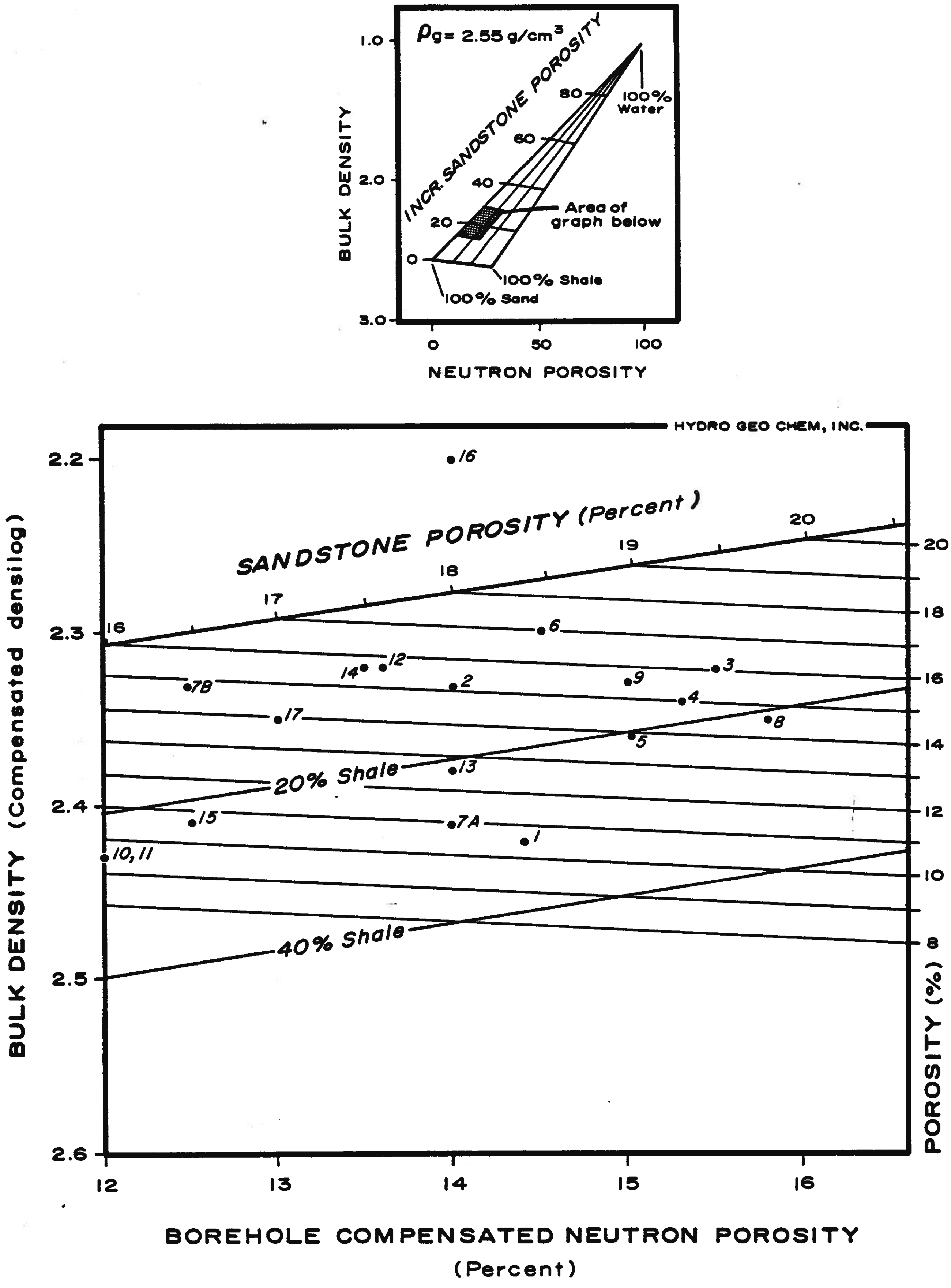

Figure 5. Neutron porosity-bulk density cross-plot.

In the Ute well, the sands that offer the best combination of high porosity and relatively low clay content lie in the middle of the Abo formation. Much of the 225 foot thick zone noted in the middle of the Abo in Figure 4 contains sands suitable for consideration as injection zones. Some of the deeper units also contain sands of similar composition. The geologic history of the arkosic formations suggests that the deeper sands should be more poorly sorted and contain a higher fraction of feldspar. Much of the feldspar may have been altered to clay, but this cannot be determined without samples from the well.

REGIONAL CROSS-SECTIONS

To establish the regional continuity of the deep sandstone sequences within the Abo and Sangre de Cristo Formations, we have constructed cross-sections to illustrate the relationships of these formations between wells. All the logs are referenced to the top of the Abo Formation, marked by a transition zone of thinly bedded shale and sandstone in the upper section. The locations of the sections are shown in Figure 6.

A northwest-southeast cross-section, A-A', that includes the Ute Anticline Well is shown in Figure 7. Between 150 and 500 feet below the top of the Abo lies the sand sequence that was identified in the Ute well and can be correlated across the regional cross-section. Two internal shale horizons can also be traced between the wells. Correlations of individual units within the Sangre de Cristo was not possible with the available well control. The lower Abo and

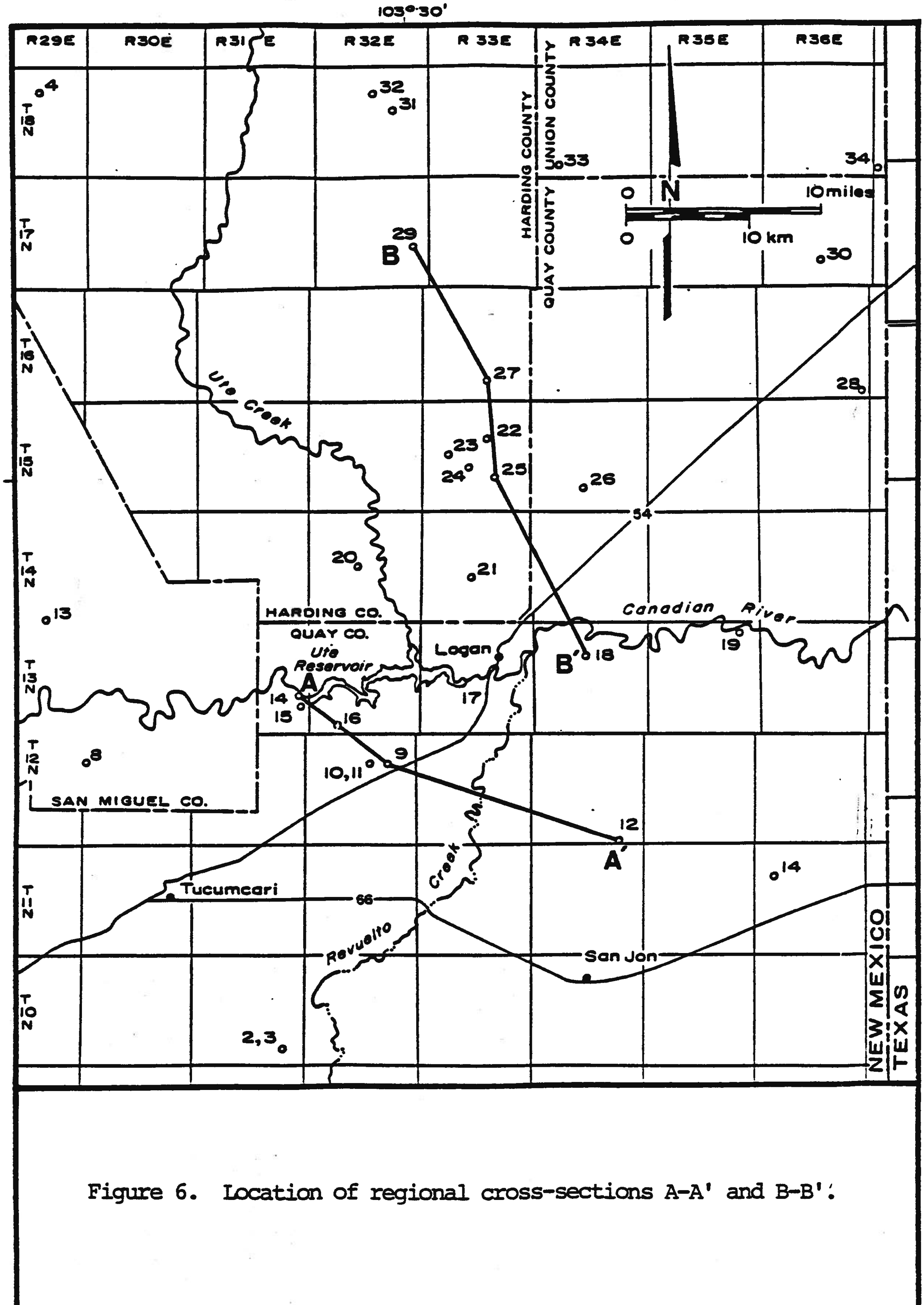

Figure 6. Location of regional cross-sections A-A' and B-B'.

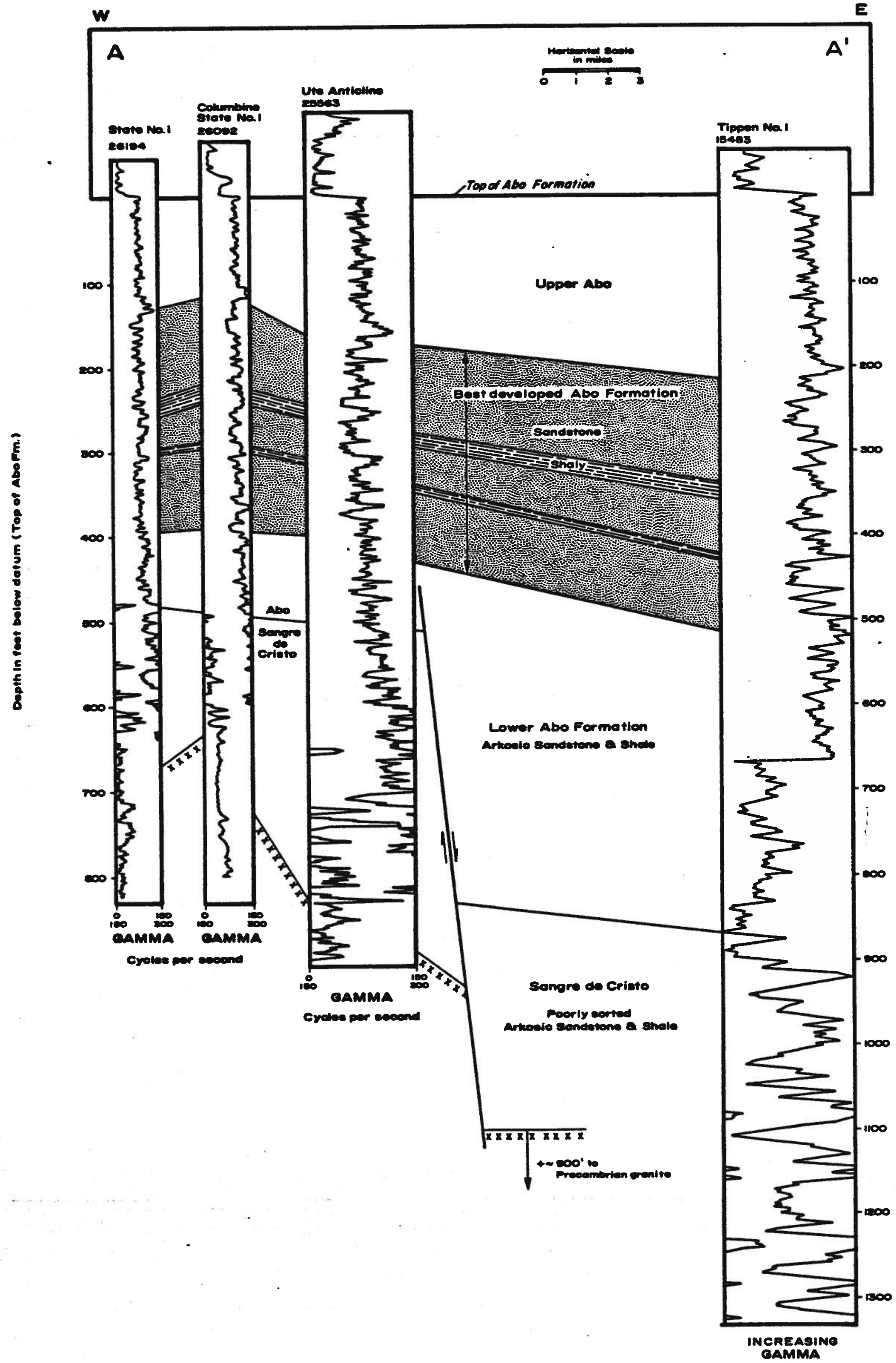

Figure 7. Cross-section A-A'.

the Sangre de Cristo Formations thicken dramatically across the fault zone that marks the edge of the Tucumcari Basin.

Cross-section B-B', shown in Figure 8, illustrates the thinning of the arkosic sediments in a northerly direction towards the Oldham nose. The middle Abo sandstone sequence is continuous to the north, although it is thinner than observed in cross-section A-A'. Below this horizon, the sands are difficult to correlate, demonstrating the interfingering characteristic of the arkosic sediments lower in the section.

Comparison of the two sections shows that the middle Abo sands form a continuous horizon throughout the Logan area. The continuity of sands within the lower Abo and Sangre de Cristo sands (or "granite wash") cannot be established using the logs. In summary, the following can be said about the regional character of the Abo sands:

1) The middle Abo sand section can be traced throughout the study area; these sands have relatively high porosity (10 to 17%) and moderate shale content (less than 30% in the Ute Anticline well).

2) Because of their stratigraphic position, the middle and upper Abo Formation sands appear to represent the last stages of arkosic sediment deposition in the basin and to have been deposited at a slower rate than were the earlier formed sediments. This is interpreted to mean that the sands are better sorted and have a lower shale-to-sand ratio. Both conditions are favorable to the establishment of a brine injection well.

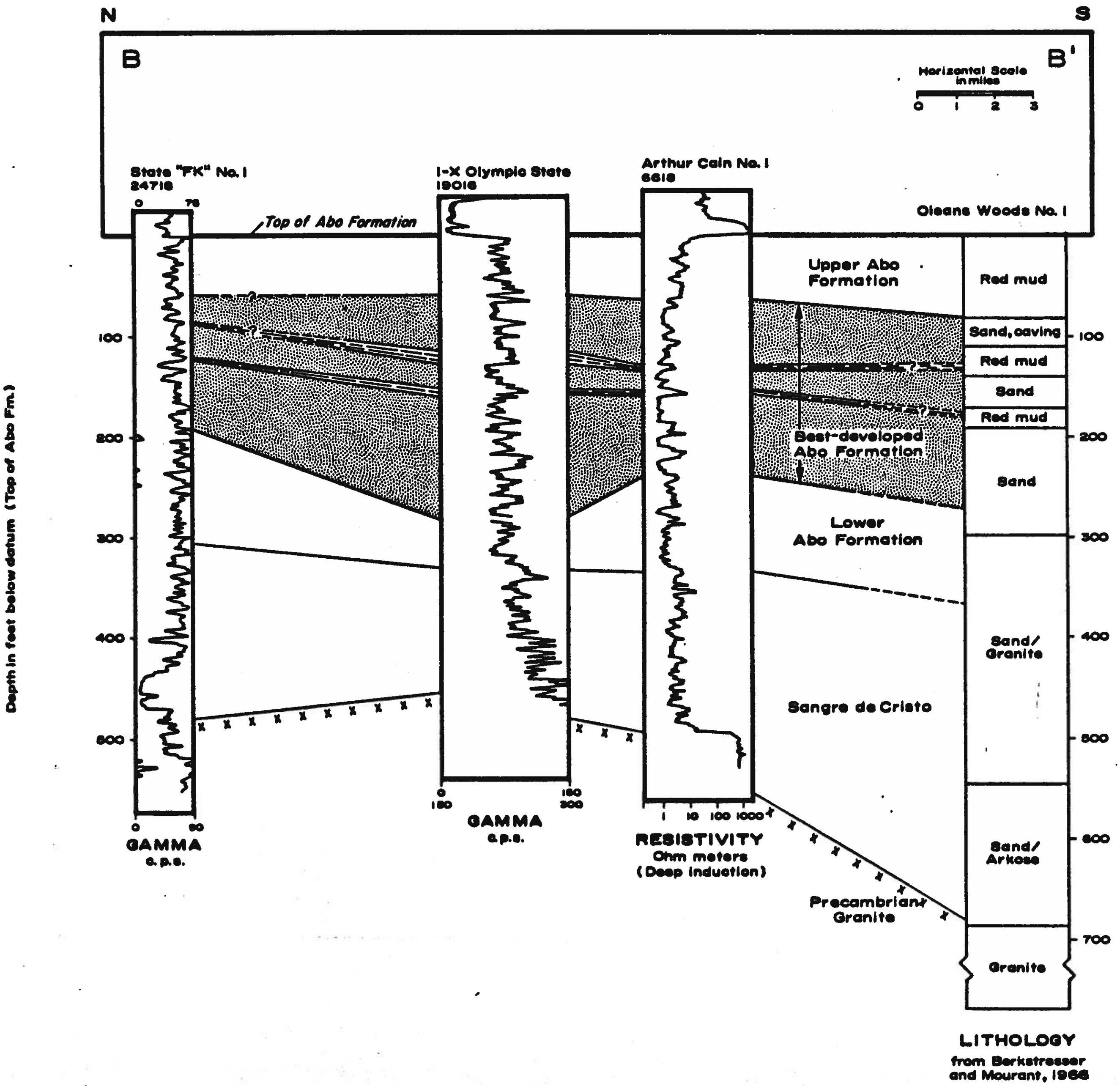

Figure 8. Cross-section B-B'.

3) Much of the sandstone found in the middle Abo at the Ute Anticline well appears to be suitable for brine disposal. An injection well completed over this entire section has the possibility of accepting large volumes of brine if the pore fluid, formation mineralogy and injected fluid compositions are compatible.

CHAPTER 3

SEISMIC SURVEY RESULTS

A Vibroseis seismic reflection survey was run near Logan to examine the subsurface structure and to augment the sparse drill-hole coverage in the area. Twenty-four fold common depth point (CDP) data were gathered using geophone groups spaced 110 feet apart. Two seismic lines were run (Figure 9) which used 990 and 440 foot in-line offsets for lines A and B, respectively. The Vibroseis signal was run over 20 to 120 Hz using a linear sweep (i.e., the Vibroseis trucks generated a signal that linearly increased in frequency). A full listing of the survey and processing specifications is included in Appendix C.

SEISMIC EXPLORATION TECHNIQUE

Seismic reflection data are a record of the reflection of seismic waves from layers in the subsurface. The reflected arrivals are recorded and displayed in terms of the time it takes for a wave to travel from the land surface to the reflector and back. An acoustic source, in this instance a truck-mounted vibrator, sends a signal into the ground that reflects from subsurface features and is recorded at the surface by a series of geophones sensitive to ground motion. Because the subsurface can be assumed to be effectively horizontal, many source/receiver combinations will correspond to the same reflection point in the subsurface (see Figure 10). For this survey, a sufficient number of geophones were laid out to provide 24 source/receiver combinations per point in the ground. These data are gathered together (stacked) after correcting for the difference in arrival times from different

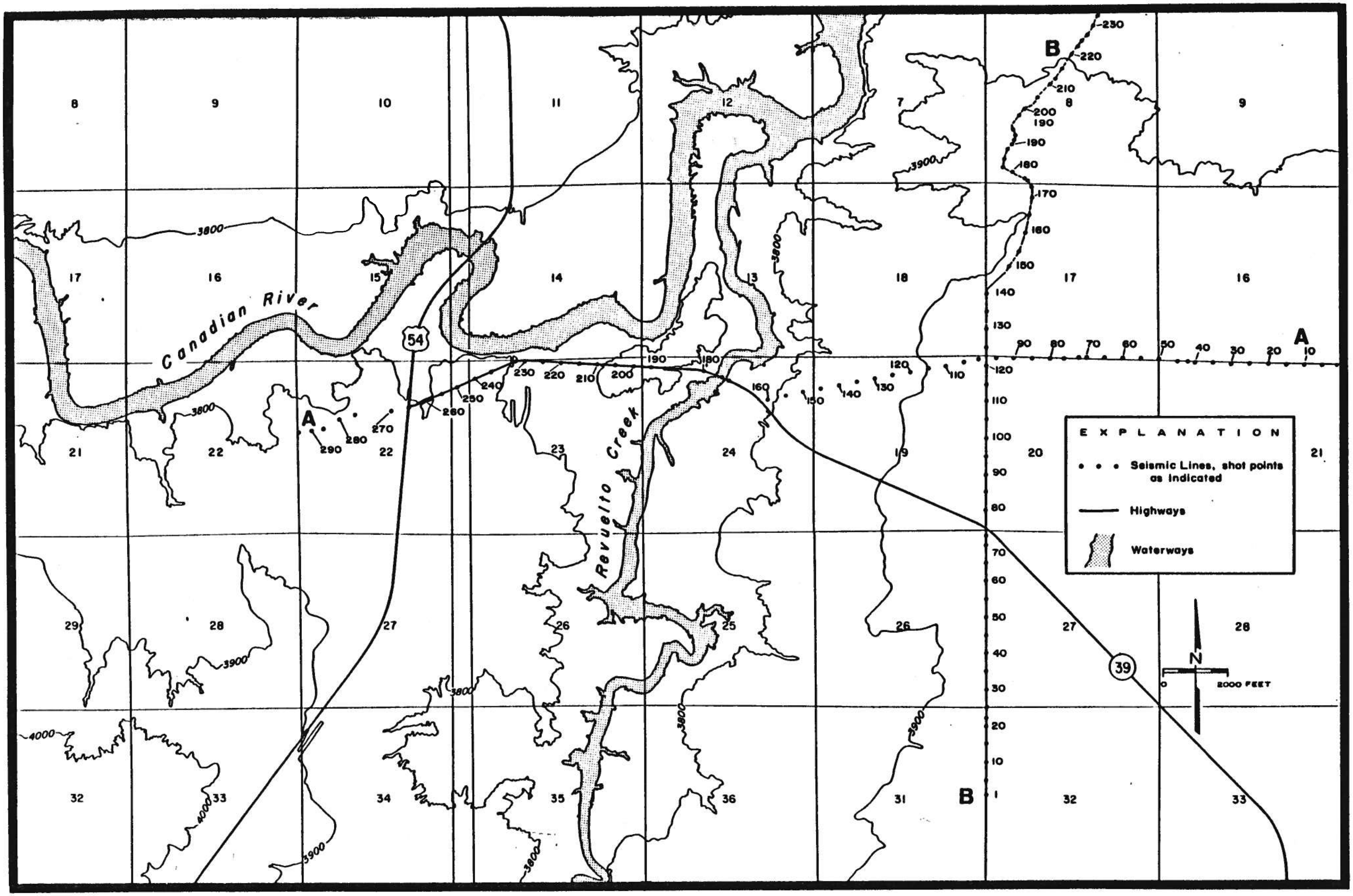

Figure 9. Location of the seismic lines.

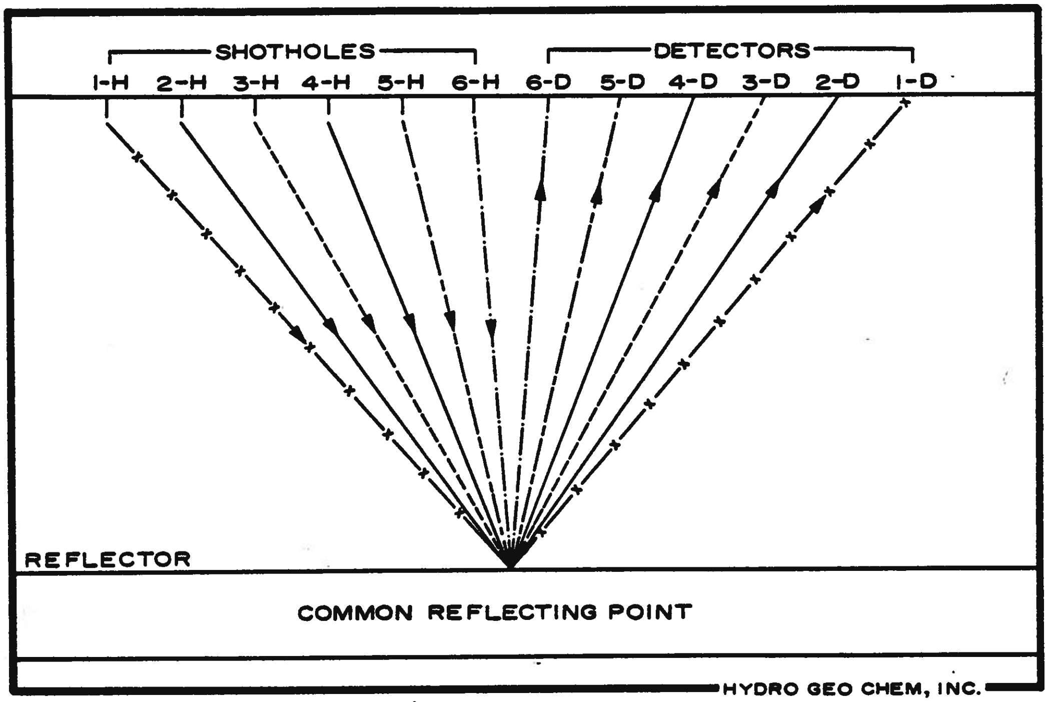

Figure 10. Schematic diagram of six-fold common depth point raypaths.

source-geophone distances. The stacked data are then digitally processed and a single wavetrain per shot point is displayed in the final seismic section.

SYNTHETIC SEISMIC TRACE

An indication of the seismic response of the area near Logan can be gained through the use of a synthetic seismic record constructed from the acoustic velocity log of the Ute Anticline Well. A synthetic trace is based upon the calculated strength and known position of reflections from the sedimentary section encountered in the well. Reflector strength is calculated for the case of a vertically incident acoustic wave. Especially strong reflections occur at the interface between "typical" sandstones and shales (with an acoustic velocity of 10,000 to 15,000 feet per second) and anhydrite or limestone (with velocities around 18,000 feet per second) because of the abrupt change in velocities.

A synthetic seismic trace is generated by combining (convolving) a waveform with the value of the acoustic impedance (the relative strength of the reflection that occurs at the interface) at each lithologic boundary determined from the acoustic velocity log. The synthetic trace determined from the Ute Anticline Well is shown in Figure 11. The left-most tracer in Figure 11 is the acoustic velocity log. Next to the log is a stick diagram of the acoustic reflection coefficients (acoustic impedance) determined from analysis of the velocity log. A 50 Hz wavelet was used to construct the synthetic trace shown on the right side of the figure. At the bottom of the trace is the waveform used in the convolution.

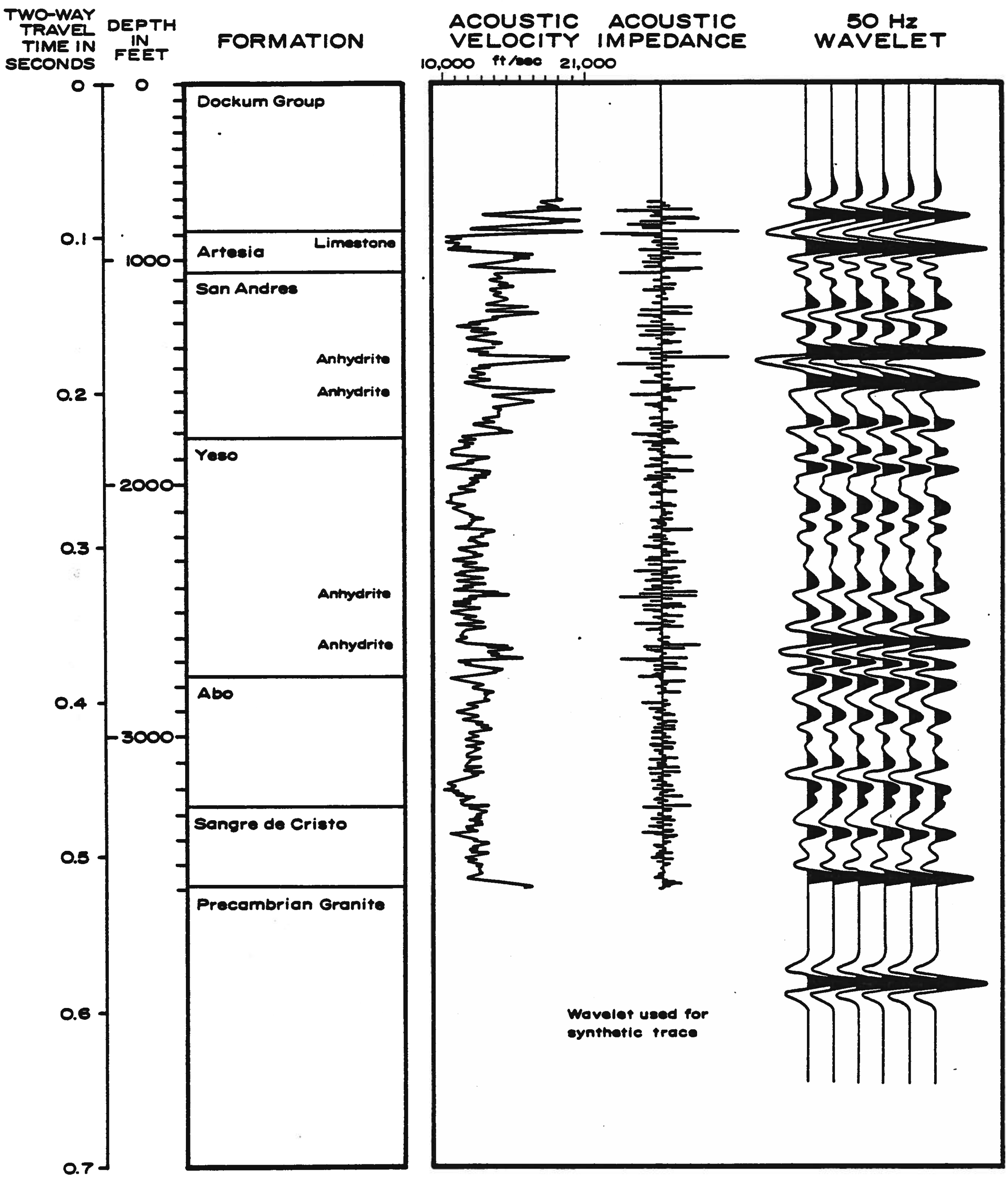

Figure 11. Ute Anticline well synthetic trace.

The strongest reflectors in the section are units of anhydrite which have an acoustic velocity of around 18,000 feet/second as measured by the acoustic velocity log. Of primary interest are the Abo and Sangre de Cristo Formations which occur below 0.38 seconds (2850 feet below land surface at the Ute Anticline Well). A seismic signature of the horizons within these formations can be seen, although there are no exceptionally strong individual reflectors in the lower sequence.

A characteristic seismic wavelet pattern is derived from the acoustic velocity log, which can be used in comparison to the recorded seismic data. With this pattern, formation tops can be better located and the acoustic resolution of individual rock strata in the subsurface can be examined. The Ute Well trace shows that the top of the Artesia Formation and the anhydrite layer at the base of the Yeso Formation should be especially easy to locate in the seismic sections.

ANALYSIS OF THE SEISMIC DATA

Two lines of seismic reflection data, comprising approximately seven miles of full 24-fold subsurface coverage (eleven line-miles on the surface) were collected for the Bureau of Reclamation. Interpretation of the data is designed to 1) examine the continuity and thickness of the arkosic sandstone in the subsurface, and 2) identify faulting and structural complexities.

Two types of processed data are presented in this report. The first, which is the most accurate portrayal of subsurface reflectors, is a migrated version of the time of arrivals of seismic waves. A 24-fold CDP gather was used and the stacking velocities for various source/receiver combinations were determined at one mile intervals. Additional correction to the data was performed by migrating the data. Migration is a processing procedure which accounts for the effect of dipping reflectors. The CDP technique assumes that the reflectors are effectively horizontal, but where significant dips are encountered, reflectors shown in a standard time section will be mislocated. This proved to be the case for structures found deep in the Precambrian basement rock. The migration processing greatly improved the resolution of reflectors and fault locations in both sections. The second type of processed data was depth converted sections. Such processing is not normally performed for the interpretation of seismic data because of the difficulty in accurately determining the lateral and vertical velocity variations found in the subsurface. However, for the purposes of this study, the depth sections are sufficiently accurate to describe the structure and lateral continuity of potential disposal reservoir sands.

During acquisition of the seismic data, several factors affected the resolution and accuracy of the survey. In the field, the highest possible input frequencies were used (swept up to 120 Hz) to obtain maximum resolution. Some parts of the lines were skipped because of cultural problems such as the bridge over Revuelto Creek and the nearby location of windmills resulting in some loss of near-surface seismic coverage. Resolution was also lost on the northern end of line B (see Figure 9) because the survey line was not straight and processing did not adequately correct for the deviations, especially between shotpoints 125 and 170. Overall, however, the data collected along line B are better than along line A because the offset (the distance between the input signal and the closest geophone) was reduced from 990 to 440 feet after line A was run. This adjustment, based upon the experience gained from the first line, served to increase the signal to noise ratio of the traces in the upper section because the additional near traces contain larger amplitude information than data obtained from distant locations.

Migrated and depth sections for both lines are enclosed as Plates 1 through 4. These plates should be examined simultaneously to see all the features of the data. A reduced version of the depth converted dip section (line B) has also been included as Figure 12 (for the reader's convenience to illustrate the gross morphology of the basin). It should be noted that the depth sections have been set to a surface datum approximately 600 feet above the land surface.

Both the migrated and depth converted sections can be used to examine the structure and stratigraphy of the subsurface. Because the migrated data, (Plates 1 and 2) most accurately show the deep faulting and the overall geologic structure, we have used them as the basis for our structural analysis. The stratigraphic horizons are shown fairly well by the sub-horizontal reflectors, but the formation tops have not been drawn on the section to avoid obscuring the features of the sections. The depth sections, (Plates 3 and 4) have been interpreted to show the formation tops because they best illustrate the relative depths and thicknesses of the stratigraphic section. These sections, as displayed, contain data shallower than shown by the migrated lines and hence do

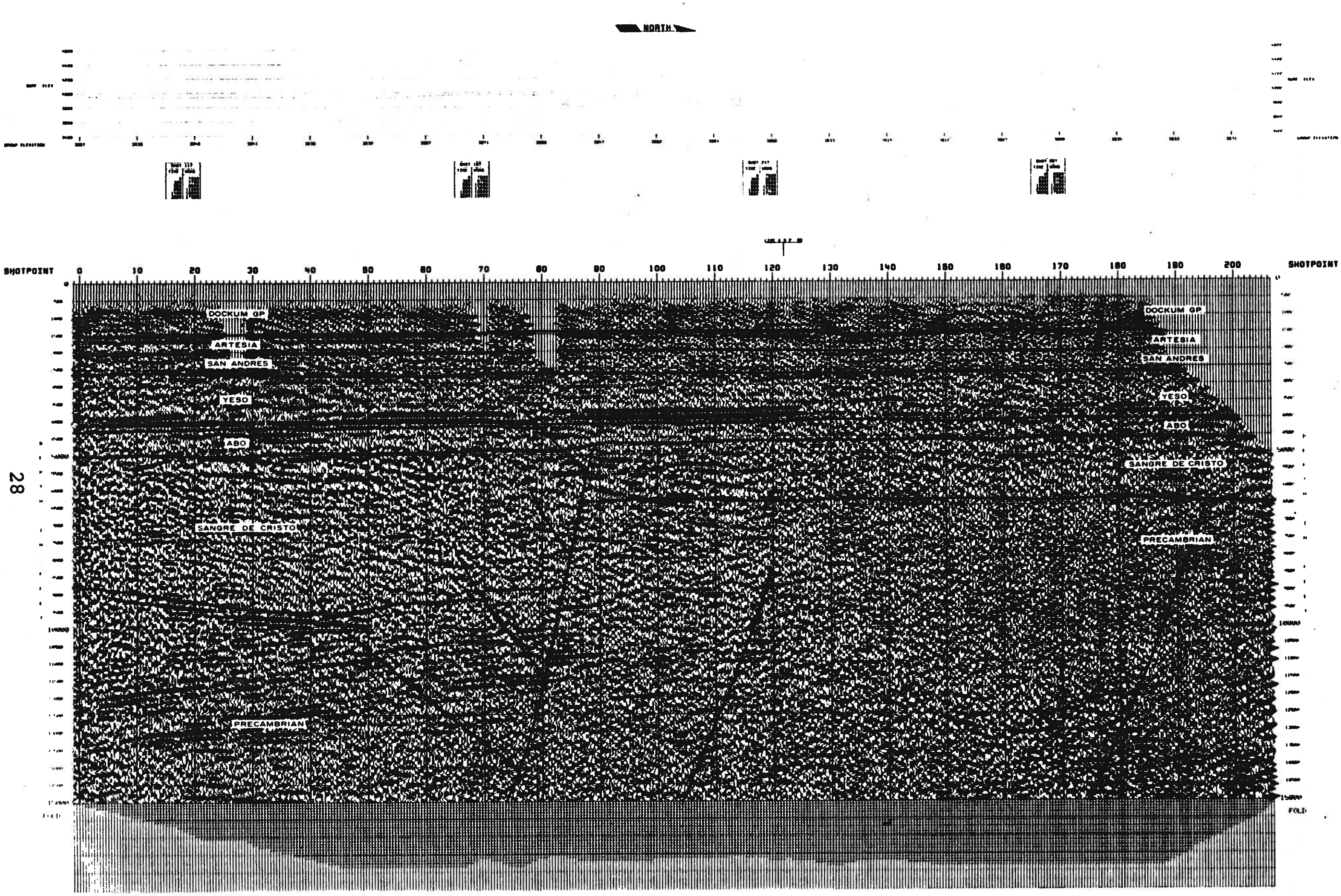

Figure 12. Reduction of survey line B depth section.

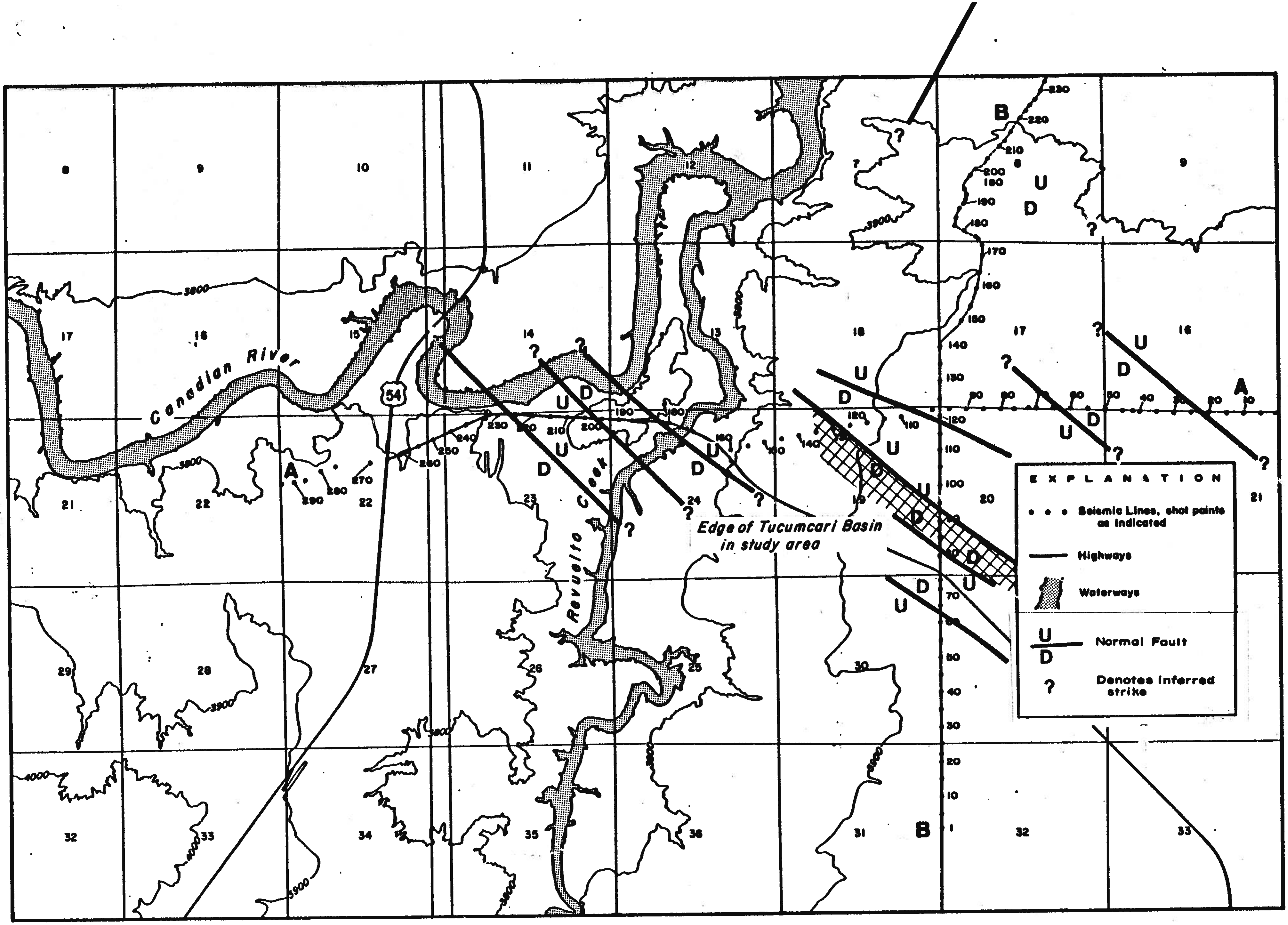

Figure 13. Faults inferred from the seismic data

area penetrated carbonates. The deep structures that can be seen below the Sangre de Cristo sediments may be carbonates, or they may also be layered volcanics or diabasic sills. The interval seismic velocities for either type of rock are similar and the seismic data may appear alike in either case. Because the nature of the igneous basement in this region is largely unknown, either case is plausible.

The importance of structurally characterizing the study area is two-fold. First, faults in the subsurface may lead to upward leakage of brine disposed at depth. Knowledge of the location of the northwest-trending faults helps avoid such problems and serves to guide the location of future exploration and drilling programs. Second, the stratigraphy of the arkosic sediments is dependent upon the structural evolution of the basin. The middle and upper Abo Formation sands are the least structurally influenced of all the arkosic sediments and also appear to be the most continuous.

Local Stratigraphy

The depth-converted seismic sections for lines A and B, Figure 12 and Plates 3 and 4, have been interpreted to show the location of the contacts between the stratigraphic units. The anhydrite at the base of the Yeso Formation is a strong reflector, which is predicted from the synthetic seismic trace discussed previously. This anhydrite, which is interbedded with thick shales and mudstones, forms a caprock to the potential disposal zones in the underlying Abo Formation.

Sandstones in the upper and middle parts of the Abo Formation are relatively continuous across the area and are considered to be potential disposal reservoirs. These sandstones occur throughout an interval about 500 feet thick. The sedimentary reflectors underlying this interval are more irregular and discontinuous and show the lenticular nature of the arkosic sedimentary bodies.

The potential disposal zone lies immediately below the lower Yeso Formation reflector at 3800 to 4000 feet below land surface as shown in the seismic depth section. The upper and middle Abo Formation sands are the most continuous of the potential disposal reservoir sands. Below the upper 500 feet of the Abo Formation, the sedimentary reflectors are more irregular and discontinuous. This is a result of the lenticular nature of arkosic sediments. Above the Abo, the low permeability shales and mudstones of the lower Yeso Formation are thick and continuous. This caprock to the potential disposal sands can be observed in the section immediately above the strong anhydrite reflector in the Yeso.

Potential disposal sands may also occur in the deeper sandstones of the Sangre de Cristo Formation which underlies the Abo Formation. Because of the irregularity of the sands, a single unit that could serve as an "ideal" disposal horizon may not be present. Planning the drilling of the disposal well for completion in zones within the lower sand section, or even completing the well over the entire lower section may be advisable. The costs of drilling and completion of a single or multi-well injection system will ultimately dictate the type of well completion.

Summary

An injection well completed within the Abo and Sangre de Cristo Formations can be located within the Tucumcari Basin, thus ensuring that a thick sequence of sandstones are available as an injection horizon. The seismic data show the upper arkosic sandstone section within the Abo Formation is laterally continuous and has minor structural complications across both seismic sections. A caprock consisting of the lower Yeso isolates the lower strata from the one of active dissolution located within the overlying Permian evaporites.

The dominant northwest-trending fracture system and northeast-trending folds mapped during previous work suggest that minor regional stresses existed through Triassic times. The bulk of the tectonic activity as reflected by the sedimentary record occurred prior to the deposition of the Abo Formation sediments. Sediments deposited during the early formation of the basin are arkosic, highly irregular, and discontinuous. Because the fault system was active during deposition, much of the lower section is prone to faulting. Locally, the faults appear to trend northwest.

Additional seismic coverage is recommended to define more specifically the position of fault traces and the nature of the potential disposal horizons, in view of the cost of installing an injection system as compared with the cost of seismic surveys. The primary target for drilling should be the middle Abo Formation sandstones with a secondary target the sands within the lower Abo and Sangre de Cristo Formations.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

Placement of a brine injection well near Logan is dependent upon the ability of sandstones in the subsurface to accept large volumes of brine. The location is also contingent upon piping and delivery costs. From the results of this study, we conclude that a thick and continuous section of arkosic sandstone exists below the Yeso Formation which can be used as an injection reservoir. The lower Yeso contains a thick and continuous section of shale and mudstone that can act as a barrier to upward movement of waste brine.

Subsurface faults can be identified from the seismic data. These faults appear to trend WNW, subparallel to the edge of the Tucumcari basin. Because of uncertainty regarding the extent of faulting, we recommend that additional reflection surveys be run to detail the subsurface structure and stratigraphy if a large scale brine injection project is planned. A grid of approximately 30 miles of additional seismic coverage is shown in Figure 14.

The establishment of an injection well system within the basin should be feasible. The most appropriate for disposal sands appear to be in the middle of the Abo Formation at a depth of 3800 to 4500 feet below land surface. However, suitable horizons within the Sangre de Cristo formation may also exist. Based upon the present data, a preliminary recommendation can be made to place injection wells within the sedimentary basin south and west of the seismic line intersection (see location, Figure 14). The area shown in Figure 14 lies within the thickest and least structurally complicated section of arkosic sandstone.

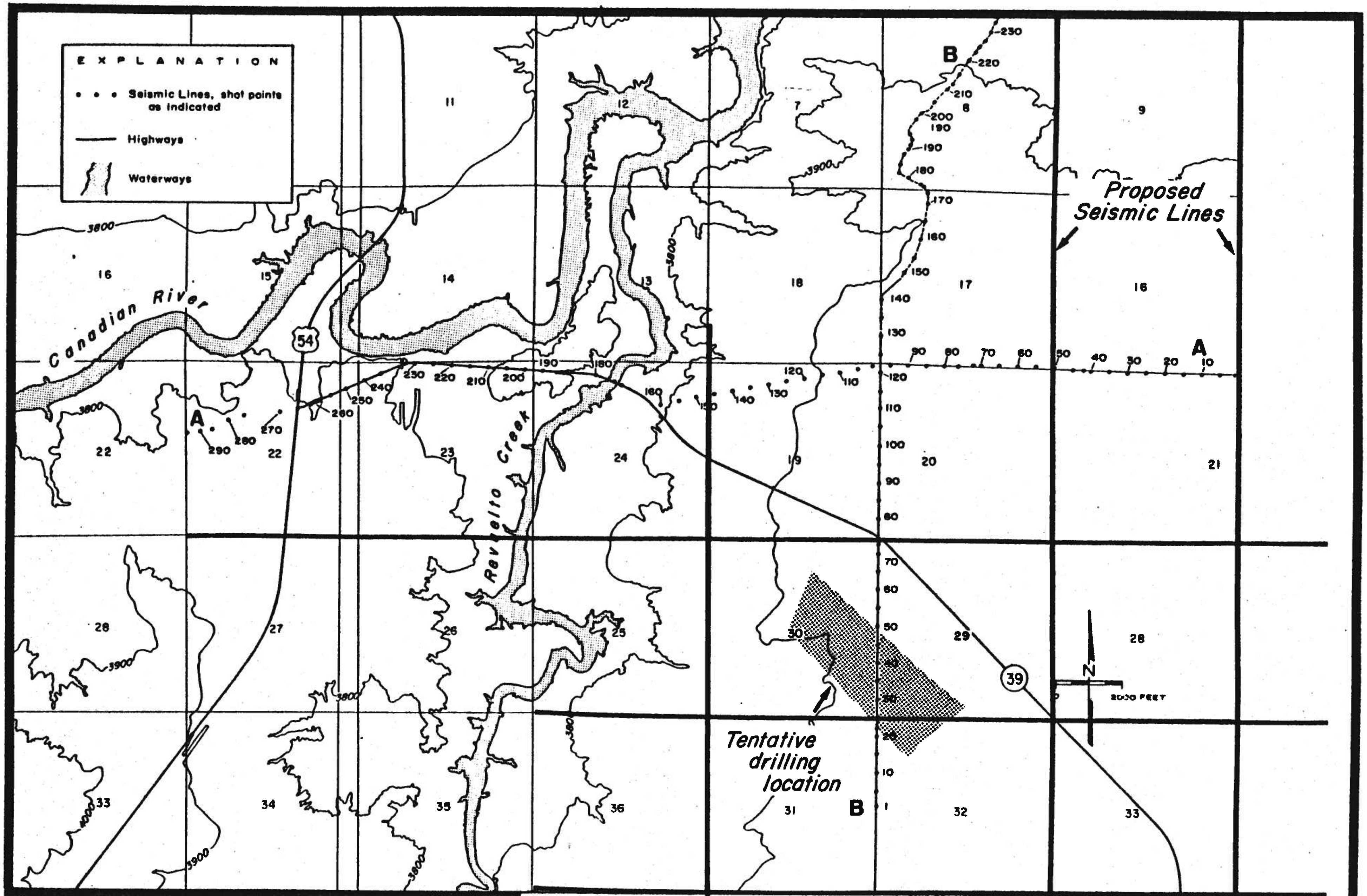

Figure 14. Recommended additional seismic coverage and tentative drilling locations.

No data are available on the hydraulic properties of the sandstones in the proposed injection horizon. An estimate of the permeability required to sustain a given injection pressure can be made, however, using the semi-logarithmic approximation to the Theis equation (Lohman, 1979) which describes flow in an infinite, confined aquifer:

$$\frac{s}{Q} = \frac{1}{4\pi K b \varepsilon}\left[-0.58 - \ln\left(\frac{r_w^2 S_s}{4Kt}\right)\right] \qquad (1)$$

where s/Q is the change in fluid head in the well bore per unit injection rate (ft/ft^3-day)

K is the average hydraulic conductivity of the water-bearing units (ft/day)

b is the cumulative thickness of the water-bearing units (feet)

t is time (days)

r_w is the effective radius of the well (feet)

ε is the well efficiency (dimensionless)

and S_s is the specific storage of the water-bearing units (feet^{-1})

Figure 15 is a plot of s/Q after 1 and 10 years injection versus hydraulic conductivity constructed by assuming a cumulative sandstone thickness of 200 feet, a specific storage of 1×10^{-5} ft^{-1}, a well diameter of 9 5/8 inches, and a well efficiency of 85 percent. The specific capacity curve for injection periods greater than 10 years is almost identical to that for 1 year.

Figure 15 can be used to estimate the injection head required to sustain a given injection rate if the hydraulic conductivity of the sands is known or can

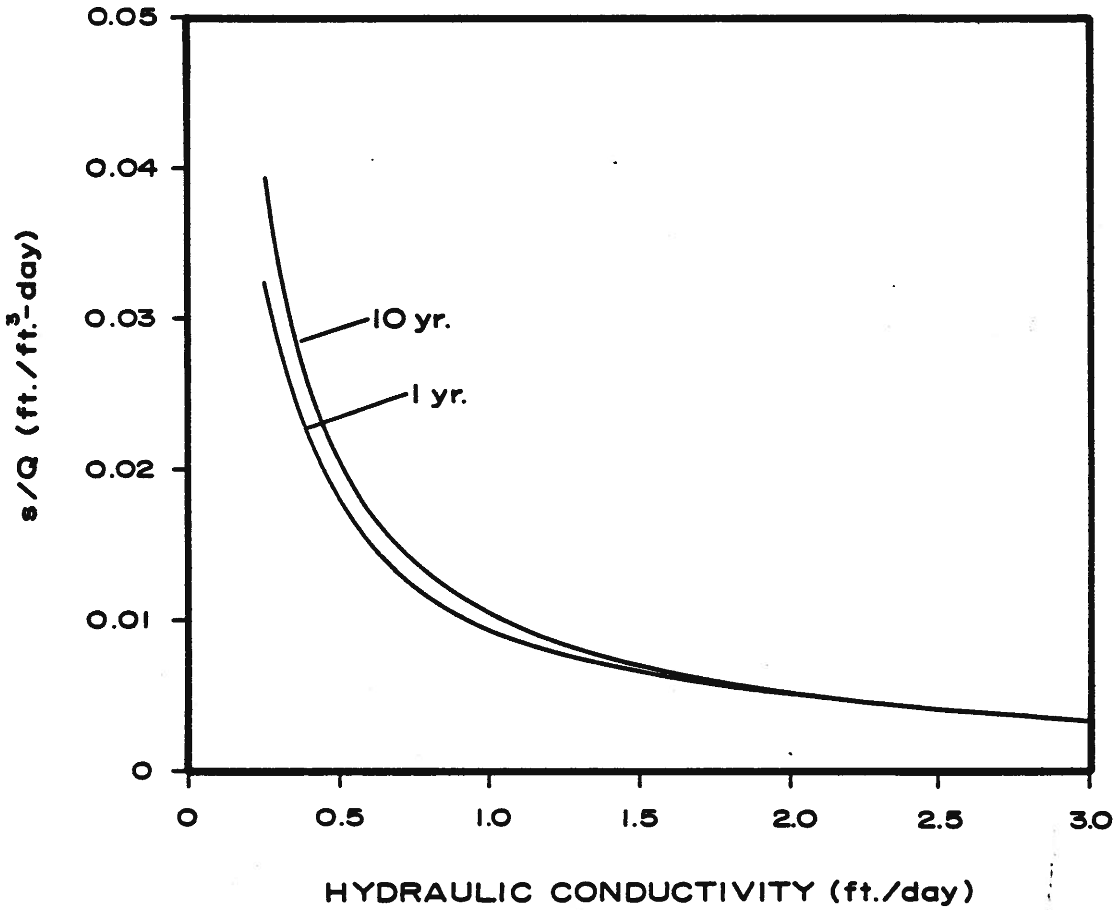

Figure 15. Potential injection rates as a function of injection pressure, hydraulic conductivity, and time.

be estimated. For example, assuming a hydraulic conductivity of 2 ft/day, Figure 15 indicates that the s/Q will be approximately 5.5×10^{-3} ft/ft^3-day after 10 years of injection. At an injection rate of 450 gpm (8.7×10^4 ft^3/day), the injection head would be about 475 ft above the static formation head.

Emplacement of brine in the subsurface may lead to a series of geologically related problems. One major consideration is the compatibility of the injected water with the injection reservoir rock and pore fluids. Reactions may occur that lead to the precipitation of minerals in the pore space of the rock. Clay minerals within the rock may also swell. We recommend that core be taken and the formation fluids be carefully sampled. After determination of the chemistry of the disposal zone, an examination of the potential geochemical changes that may occur at depth will be possible. Among the tests that should be run to detail the physical and chemical properties of the injection horizon(s) are x-ray diffraction (XRD) analysis of clay minerals, porosity and permeability tests of the core, water chemistry of the formation fluids, a complete suite of geophysical well logs, and a series of drill-stem tests to examine the in-situ permeability and formation fluid pressure within the rock.

Water-rock interactions can be examined for this system through the use of water chemistry equilibrium models such as the program PHREEQE, available through the U.S. Geological Survey (Parkhurst and others, 1980). The fluids that are in equilibrium with the injection horizon mineralogy at a specified temperature and pressure should be modeled to determine the potential for precipitation of any mineral species, particularly if the formation waters are near saturation with respect to gypsum or calcite. A range of fluids can be examined to determine the sensitivity of the disposal zone to possible injection fluids. Geochemical modeling of the interaction of the pore and injection fluids is recommended because of the possibility of the precipitation of minerals within either the injection horizon or well causing the disposal well to be plugged.

Other considerations to the successful completion of an injection well are the procedures to be followed during the drilling of the well. Because the well is to be designed for injection, the drilling fluid should be maintained with a low amount of filtrate to minimize invasion of solids into the formation. In addition, the drilling mud can be made with potassium chloride (KCl) or potassium hydroxide (KOH) (see Sydansk, 1984) to inhibit hydration of clay minerals within the injection horizon. The monovalent potassium ions react with the clay minerals to prevent structural swelling by the substitution of larger divalent ions. Casing the well to the bottom of the Yeso Formation is advisable to avoid the dissolution of the overlying evaporites. If the middle of the Abo Formation proves to be a suitable horizon, perforated casing or screen could be set over the entire interval.

Another problem often associated with injection wells, is the occurrence of low-level induced seismic activity. Until the injection well system is designed, however, there is no way to predict this risk. Even after design, differentiation between seismic activity produced by the filling of Ute Reservoir and that produced by deep-well injection may not be possible. Minor seismic activity is often associated with both injection wells and man-made reservoirs. Because it is anticipated that Ute Reservoir will be filling with water over the next few years, a determination that any seismic activity is caused by the injection process will be difficult. The low background level of seismic activity found in the tectonically quiet Panhandle region might add to the confusion because any event that occcurs in the Logan area would be suspect.

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APPENDIX A
SUMMARY OF DEEP-WELL LOCATIONS

Table A-1: Log Availability from Exploration Wells in New Mexico

Map No.	Location	Well Name	Operator	New Mexico Well ID No.	Availabile Logs
1	9.36.12	Chapman No 1	C.T. Shook	-	Drillers (no 2951)
2	10.31.23	N. Pueblo No 1	Shell Oil	14513	Acoustic, Gamma Caliper
3	10.31.25	N. Pueblo No 2	Shell Oil	14616	Neutron-porosity Gamma, Caliper
4	11.36. 7	Endee No 1	L.B. Newby	-	Drillers (no 855)
5	12.28.14	Hoover R. No 1	Miami Pet. Co.	15849	SP, Induction
6	12.29.13	Chapell No 1	Puretex Oil Co.	19324	Induction, Neutron-Porosity, Gamma, Caliper
7	12.29.18	Hoover R. No 1	Miami Pet. Co.	15850	Gamma, Laterolog
8	12.30. 7	Chapell No 2	Puretex Oil Co.	14890	Neutron-porosity, Gamma, Caliper
9	12.32.11	Ute Anticline 1	National Oil Co.	25563	Dual-Laterolog, Gamma, Acoustic, Neutron
10	12.32.11	Kimes No 1	O.L. Ledgerwood	15851	Neutron, Gamma
11	12.32.11	Ulmer No 1	S.T. Silverstein	6249	Drillers (no 6249)
12	12.32.35	Tippen No 1	N.G. Penrose	15483	Gamma, Neutron, Drillers (no 6876)
13	13.29. 3	No 1 Ranch	Marland	-	Drillers,
14	13.31.24	State No 1	Nucorp Energy	26194	Dual-Laterolog, Micro-Laterolog, Gamma
15	13.31.25	Dripping Spgs 1	Standard Pet. Co.	-	Drillers (no 858)
16	13.32.32	Columbine St. 1	National Oil Co.	26092	Gamma, Acoustic
17	13.33.15	USBR DH-3	U.S. Bureau Rec.	-	Drillers, Gamma
18	13.34. 9	Olean No 1 Woods	Olean Pet. Co.	-	Drillers
19	13.35. 2	N.M. Eng. DH-10	New Mex. St. Eng.	-	Drillers
20	14.32.16	State No 1	Sunray Mid-Cont.	2565	Mud-Log, Gamma, Neutron
21	14.33.21	Underwood No 1	Cornett	1000	Drillers
22	15.33.10	Arthur Cain No 1	J.A. Talley	6618	SP, Laterolog, Dual-Induction
23	15.33.17	Federal 1-17	Paul Haskins	21644	Gamma, Neutron
24	15.33.21	Conley Cain No 1	Conley Assoc.	21643	Neutron-Porosity, Gamma, Caliper, Density
25	15.33.22	Arthur Cain No 2	Edmonds, Peters	6619	Gamma, Caliper, Interval-Acoustic
26	15.34.28	State No 1	Powers Wire	23774	Gamma-Gamma Gamma, Caliper
27	16.33.27	1-X Olympic St.	Astro-Tex	19016	Caliper, Neutron-Porosity, Density, Gamma
28	16.36.36	State "CP" No 1	Humble Oil	13957	Gamma, Gamma-Gamma, SP, Laterolog, Dual-Laterolog

Table A-1: Continued

Map No.	Location	Well Name	Operator	New Mexico Well ID No.	Availabile Logs
29	17.32.24	State "FK" No 1	Amoco Oil	24178	Gamma, Neutron
30	17.36.28	State "CO" No 1	Humble Oil	14899	Gamma, Gamma-Gamma SP, Laterolog, Dual-Laterolog
31	18.32.14	"CM" State No 1	Humble Oil	14900	Gamma, Acoustic SP, Laterolog, Dual-Laterolog
32	18.34.31	"CK" State No 1	Humble Oil	14901	Gamma, Acoustic, Caliper
33	18.36.36	BDCDGU1836361K	Amoco Oil	23259	Gamma
34	19.34.16	State "EL" 1	Amoco Oil	24126	Gamma, Caliper, Bulk-Density

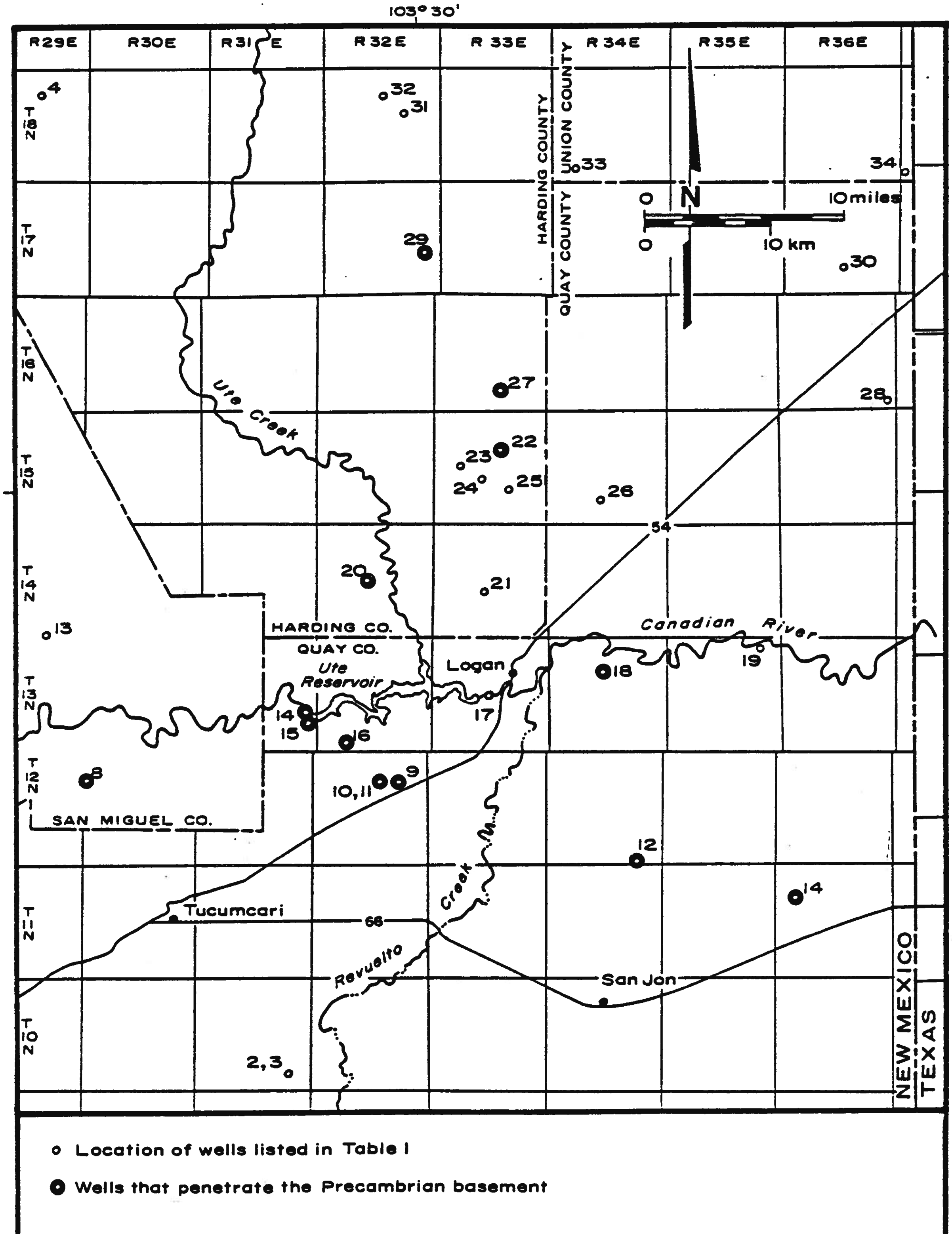

Figure A-1. Location of deep-well data in the study area.

APPENDIX B

The geophysical well log measurements for the seventeen sandstone intervals identified in Figure 4 are listed in Table B-1. These values were used to construct the neutron porosity-bulk density cross-plot of Figure 5.

Table B-1: Well Log Measurements in the Ute Anticline Well

Zone	Neutron Porosity, percent	Bulk Density g/cm^3	Interval Transit Time μ sec/ft	Thickness feet
1	14.4	2.42	83	8
2	14.0	2.33	88	13
3	15.5	2.32	83	8
4	15.3	2.34	83	12
5	15.0	2.36	84	15
6	14.5	2.30	86	14
7A	14.0	2.41	87	10
7B	12.5	2.33	92	14
8	15.8	2.35	84	13
9	15.0	2.33	84	3
10	12.0	2.43	105	18
11	12.0	2.43	95	7
12	13.6	2.32	86	10
13	14.0	2.38	84	10
14	13.5	2.32	86	8
15	12.5	2.41	83	8
16	14.9	2.20	95	10
17	13.0	2.35	88	11

APPENDIX C
PARAMETERS USED IN GATHERING AND PROCESSING SEISMIC DATA

Two types of processed data are presented in this study. The processing of the data was done by Norpac Processing Company of Englewood, Colorado and the computer programs used to digitally process the data are their proprietary routines. The processing procedure for the migrated data followed this sequence:

1. Demultiplex to 32 bit floating point data
2. Trace edit
3. True amplitude recovery
   - spherical divergence and exponentiation 3 dB/sec
4. Spiking deconvolution
5. Common depth point gather
6. Datum statics
   - reference datum at 4500 ft MSL
   - datum velocity 6000 ft/sec
   - refractor velocity 3500 ft/sec
7. Velocity analysis
8. Automatic residual statics
9. Velocity analysis
10. Automatic residual Statics
11. Normal moveout corrections
12. First break suppression
13. Common depth point stack
14. Digital filter
    - 10/16-48/58 Hz
15. Trace equalization
16. Wave equation migration

The depth conversion processing stream was quite similar except that no trace equalization or migration was done and the depth conversion was run after digital filtering.

During acquisition of the data the sample rate was set at 2 milliseconds and recording was done by a Texas Instruments DFSV- FT1 recording truck. The signal was recorded for 3.0 seconds with a 60 Hz notch filter the only field filter applied. A linear 20 - 120 Hz Vibroseis sweep was done with three vibrators in operation. Line A was set with a 990 foot single offset while line B used a 440 foot spread. Group intervals were set at 110 feet and the shotpoint intervals were 220 feet for both lines. A linear geophone group was used for all arrays.