USE OF 3D SEISMIC DATA TO OPTIMIZE SITING AND COMPLETION OF MULTIPLE HIGH VOLUME BRINE DISPOSAL WELLS

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ABSTRACT

Increasing importation of LNG and LPG into the Gulf Coast and increased production of domestic natural gas resources has resulted in the development of additional salt cavern storage capacity on the Spindletop Salt Dome located near Beaumont, Texas. A total of five storage caverns for natural gas and one brine production cavern currently are operated on the dome. Ownership or lease rights have been acquired over a majority of the remaining useable salt of this domal structure. Cavern development schedules and operational considerations has led to a co-use approach to the siting of the storage caverns but more particularly to the siting of a nine well grouping of high volume brine disposal wells located off the dome. Domal structures are intrusive bodies resulting in radial faulting around the salt stock and often associated with other regional fault trends. An extensive 3-D data suite that encompassed both the domal structure and the area of the proposed brine disposal wells was obtained and evaluated to optimize the location of the brine disposal wells with respect to potential faults which resulted in a more suitable arrangement of wells. The same data suite was also evaluated with respect to selected cavern locations on the dome. The evaluation was reviewed by the Texas permitting authorities and permits have been issued for all of the proposed disposal wells and storage caverns. A description of the wells and the geologic profile is presented along with description of the related surface facilities. Additionally, well logs of the brine wells were also correlated with the 3-D seismic data for high permeability and porosity zones. Various horizons were identified and horizontal slices through the entire disposal area were made and continuity was evaluated. Examples of the horizontal slices are included herein.

KEY WORDS: 3-D Seismic; Salt Dome; Faults; Brine Disposal; Spindletop Salt Dome; LPG Storage

INTRODUCTION

Solution-mined hydrocarbon storage caverns have been in use in Texas for more than 50 years. There are currently over 400 solution-mined caverns in Texas Gulf Coast salt domes, and over 300 of these are actively storing hydrocarbons (LPG, crude, natural gas) and/or producing brine and 34 have been plugged. Of the active domal salt hydrocarbon storage caverns, 257 are active LPG and 23 are active natural gas storage caverns with a current cumulative storage capacity of more than 450 million barrels and more than 150 Bcf respectively. No new grass-roots LPG facility development has been undertaken in Texas since 1979 [Johnson, 2008].

Both the Coastal Caverns, Inc. (CCI) LPG storage project and the AGL Gas storage project are grass-roots facilities at the Spindletop salt dome near Beaumont, Texas (see Figure 1).

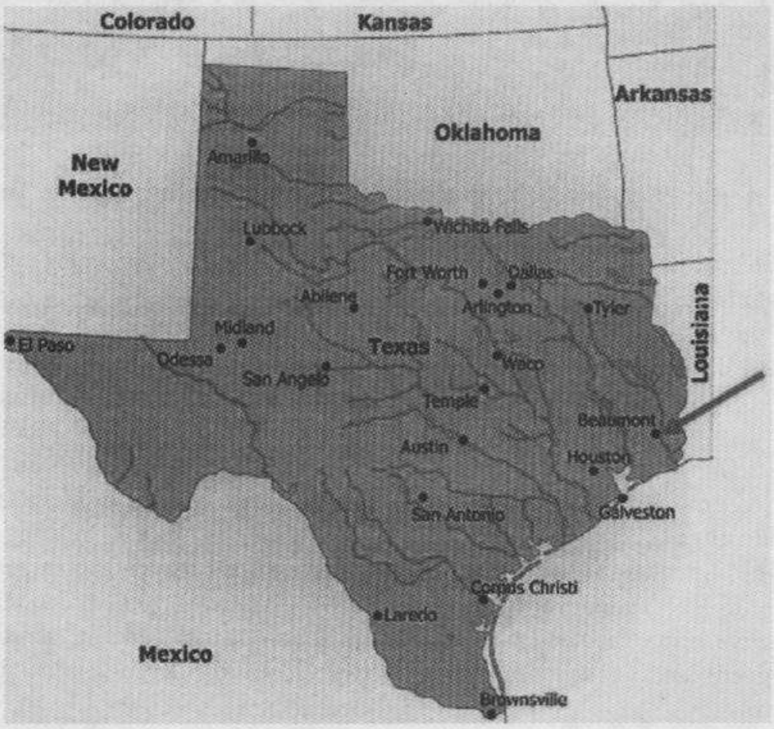

Figure 1. Location of the Spindletop Salt Dome Site in Texas.

The dome has a rich history and is considered the birthplace of the Texas oil industry with the discovery in 1901 of the first large producing oil well in the Gulf Coast area of the state. The dome enjoyed a second "boom" in the mid-1920s as drilling technology allowed for deeper wells and again in the 1960s and 1970s as a sulfur-producing structure. Nearly 10 million long tons of sulphur was mined by Texas Gulf Sulfur Inc. between about 1952 and 1976 [Ratigan et al., 2007]. The typical sulphur mining subsidence feature is apparent at the Spindletop salt dome, as shown in Figure 2.

Figure 2. Aerial Photograph of Spindletop Salt dome Showing Surface Topography

Subsidence associated with the sulphur mining and oil and natural gas extraction has been extensive over the Spindletop salt dome and has been reported to be at least 15 feet in some areas.

After the sulfur mining ceased, the dome was essentially unused until the early 1990s when two different natural gas storage projects were developed. The Spindletop salt dome is currently home to six natural gas storage caverns, one active brine production cavern, and two plugged and abandoned brine production caverns.

In 2004, CCI began to evaluate the property for a number of uses, including an LPG storage complex. CCI decided to move forward with the permitting of the property as a hydrocarbon storage facility. AGL acquired rights to about 90 acres of property adjacent to the CCI property in 2007. In 2004 AGL decided to move forward with the permitting of their property for natural gas storage. This paper discusses some of the studies undertaken and experiences encountered during the permitting of the brine disposal wells associated with the respective projects. Permits for eight caverns totaling 24 million barrels of capacity have been issued to CCI and permits for five caverns totaling nearly 30 BCF to AGL.

An atypical gas and brine cavern connectivity issue [Johnson, 2003] increased the Railroad Commission of Texas' scrutiny of new solution-mined cavern development at Spindletop. Additionally, concerns elsewhere in Texas relating to potential interference between the interests of oil and gas exploration and production and brine injection heightened the scrutiny associated with locating large-volume brine disposal wells.

The unique challenges faced by the CCI and AGL projects were addressed with state-of-the-art technology, how this technology was applied to the siting and development of brine disposal wells is the focus of this paper. Below, the Spindletop salt dome is briefly described and is followed by a brief description of the CCI and AGL facilities. The design descriptions are followed by brief descriptions of the three-dimensional seismic survey evaluations used to locate the brine disposal wells and evaluate the subsurface injection zones. The paper concludes with a short summary and conclusions section and a listing of cited references.

THE SPINDLETOP SALT DOME

Both the CCI and AGL storage facilities are located atop the southern portion of the Spindletop salt dome in northeast Jefferson County, Texas. The dominant geological feature of the region is the Gulf Coast Basin. The Spindletop salt dome is situated in the Houston Embayment, a structural subdivision of the Gulf Coast Basin. Deposition occurred in the area on basement rocks and has resulted in over 40,000 feet of sedimentary deposits. This structural province is characterized by regional faulting parallel to the coast, normal faulting, and salt diapirism with its associated faulting and salt withdrawal basins.

Stratigraphically, the region consists of largely unconsolidated sands, marls, clays, and shales. The units crop out in belts that parallel the Gulf of Mexico shoreline. The thick sequence of Gulf Coast Tertiary sediments contains abundant normal faults which have little or no surface expression. Most of Jefferson County is located in the Frio (or Frio-Vicksburg) growth-fault trend. This area lies in the western part of the Hackberry Embayment within which the Hackberry deep-water member of the Frio Formation was deposited.

The Spindletop salt structure is categorized as a shallow piercement-type salt dome. As with all Gulf Coast salt structures, it is considered to have originated from the Louann salt formation. The Louann is of Triassic/Jurassic age and usually occurs at depths greater than 30,000 feet in coastal areas. Like most piercement-type salt domes, faulting is found associated with the Spindletop salt dome. The faults are both radial and circumferential extension or normal faults and are the result of tensile deformation of overlying sediments.

Ground elevations around the dome vary from 10 to 20 feet above sea level. Eighteen feet of topographic relief is associated with this dome. The shallowest occurrence of salt is about 1,200 feet below ground surface. The salt core is roughly circular in plan and about 1 mile in diameter. The caprock at Spindletop is a disk-like mass of anhydrite, gypsum, and limestone, which occurs on top of the salt but does not completely cover it. The shallowest occurrence of caprock is about 700 feet below ground surface.

Figure 3 illustrates the Spindletop salt dome structure map and the sonar surveys of existing caverns in the salt dome. This figure also illustrates the location of the CCI project, the AGL natural gas storage site, as well as the location of inferred "planes of preferred dissolution" in the salt stock of the dome. The planes have been inferred from the nature of the solution-mined cavern development in the dome from previously solution-mined caverns.

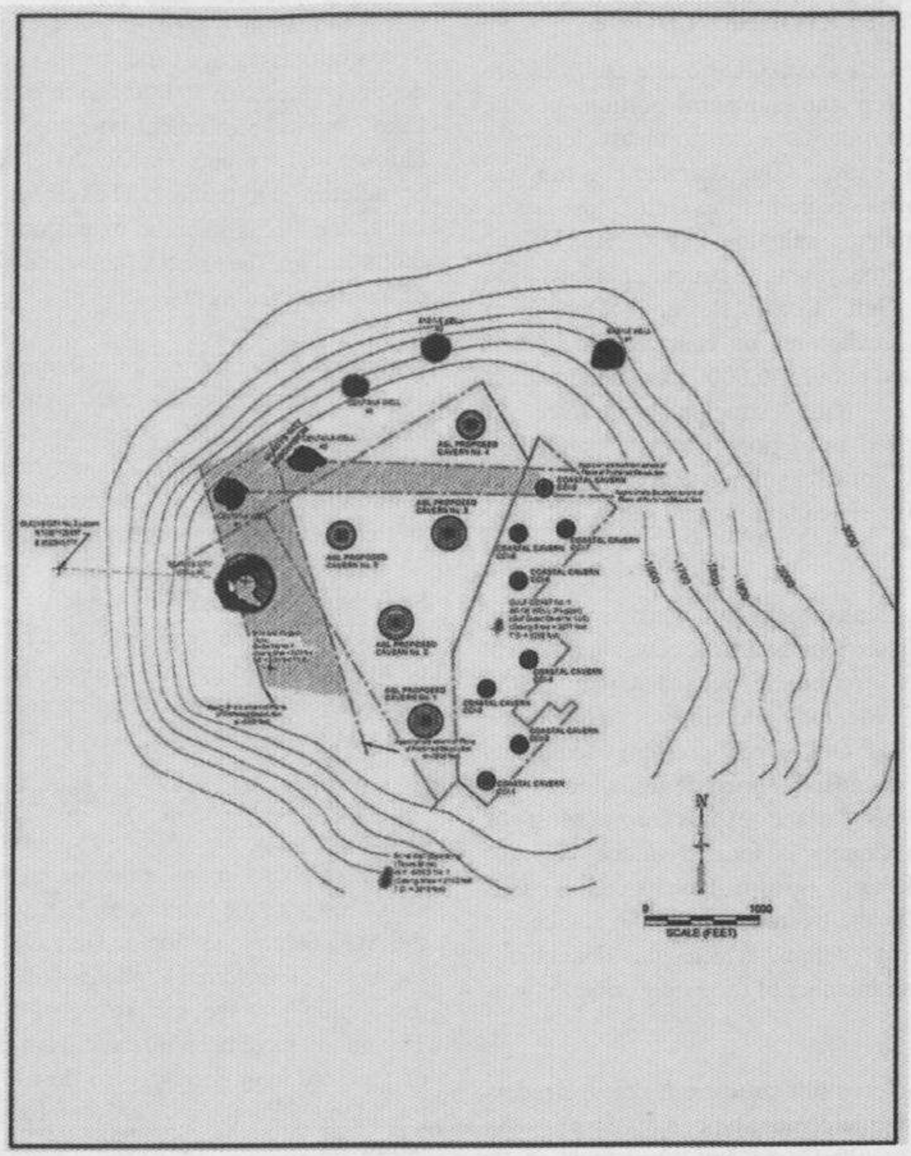

Figure 3. Illustration of Spindletop Salt Dome Structure Map, Existing Caverns, CCI Property, AGL Storage Facility Site, and Inferred Planes of Preferred Dissolution.

THE COASTAL CAVERNS FACILITY

As described earlier, the Spindletop salt dome has an interesting history and is also uniquely situated in the Texas Gulf Coast area to receive hydrocarbon products, including but not limited to, crude oil, LPG, natural gas liquids, and natural gas. The dome is situated very near a growing aggregation of pipelines, refineries, petrochemical plants, deep-water vessel access, and landfall for major offshore production pipelines. New large-volume, high-receipt and high delivery rate caverns provide the needed infrastructure to efficiently manage the various products used both by local and national facilities within the United States. The primary focus for CCI is to provide storage and deliverability options for impending large volumes of imported LPG and other products.

The CCI Facility is located on a 47-acre tract of land on the southern portion of the Spindletop salt dome. The property is trapezoidal in shape and has a limited number of very shallow oil-producing wells clustered in one portion of the property. The AGL facility is located on a 90-acre tract of land immediately north and west of and contiguous to the CCI property. The tract is roughly triangular in shape and also has a limited number of very shallow oil producing wells across the property. Both of these situations provided some challenges in the layout of the plant facilities. Initially because of the presence of both existing and planned AGL gas storage projects, CCI decided to develop an independent solution-mining plant to support its own cavern development plans. The solution-mining plant, in addition to the anticipated pumping requirements of the main product injection pumps and associated surface facilities, required the installation of a 30 MW power substation along with new power transmission lines. A subsequent review of CCI and AGL project needs has led to a cost sharing arrangement between the two respective companies for both the power substation and portions of the raw water intake and pumping structures.

The size of the CCI tract of property located over the salt structure is not sufficient to support the installation of brine storage ponds necessary to operate the liquid hydrocarbon caverns. To accommodate the need for brine storage capacity and the need for brine disposal wells, CCI acquired an additional large tract of property located off the domal structure and far enough away so as not to be overly impacted by near-dome upturned formations. The tract is sufficient to provide additional brine storage capacity and was also considered suitable for the siting of the CCI brine disposal wells. The location of this tract in relation to the cavern storage location is shown on Figure 4. This figure also shows the location of the five AGL brine disposal wells.

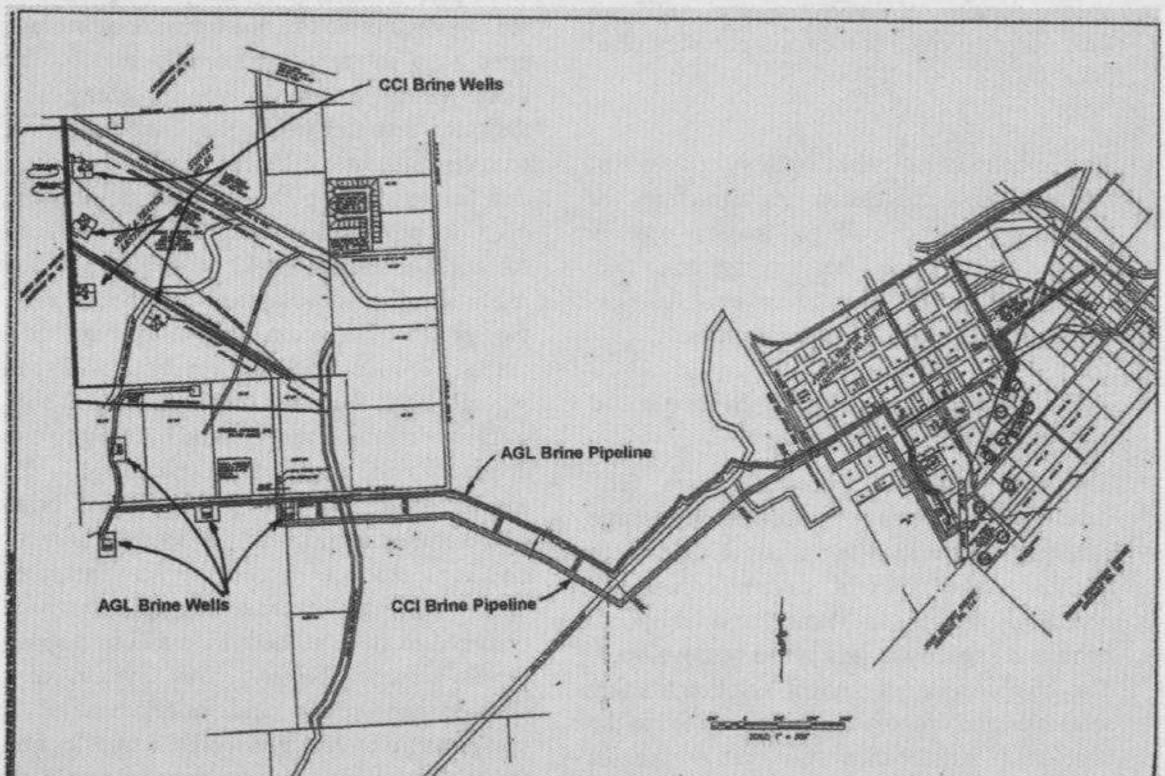

Figure 4. Location of CCI & AGL Brine Disposal Sites.

THE AGL FACILITY

The AGL Resources, Inc. (AGL) Facility is located on an approximate 90-acre tract of land contiguous to and immediately north and west of the CCI tract. This is illustrated in Figure 3. The tract is roughly triangular in shape. As with the CCI property, this tract also has a series of very shallow oil producing wells across the property. These wells trace their history back to the earliest oil exploration over the salt dome, although most of the wells have been drilled within the last 30 years or so. The wells have had no impact on the facility development other than their proximity to proposed surface infrastructure construction.

Like the CCI project, the AGL Facility will produce a large volume of brine from leaching of the gas storage caverns. Each cavern will have a nominal initial capacity of 8.2 million barrels or approximately 6 Bcf of working gas and 3.1 Bcf of pad or cushion gas. AGL also initially decided to develop an independent solution-mining plant to provide the anticipated higher mining rates and closer control of the mining schedule. The plant consists of a bank of eight pumps, each rated at a nominal 1000 gpm output. Four of the pumps are dedicated to freshwater injection during solution mining and the remainder are brine injection pumps. Whereas the CCI facility has their brine injection pumps located on the remote off-dome property, AGL has their pumps located at the main pumping plant site.

The remainder of the facility consists of natural gas compression infrastructure for receipt and injection of gas into the storage caverns, gas line header system, line connections to the storage caverns and gas transmission lines to off-site locations.

BRINE DISPOSAL WELL SITING and COMPLETION

The CCI and AGL projects when fully developed will result in thirteen new large caverns being drilled and solution mined. In addition, other current cavern owners or operators on the salt dome have additional permitted capacity that is yet to be developed. The combination of known solution mining schedules and proposed mining rates led to the conclusion that the interest of both companies could be best served by cooperating in the construction of common infrastructure elements where possible and jointly reevaluating an available 3-D seismic data base that covered not only the Spindletop salt dome but also extended out to the several hundreds of acres of property on which the brine disposal wells of both companies were proposed to be located.

The infrastructure requirements for both companies shared certain common points but varied in functionality in other areas. For instance, the need for power was common to both projects as well as the need to obtain large volumes of freshwater for high rate solution mining. In these two particular areas, it was beneficial to develop a cost sharing agreement for the construction of these facilities and some connecting pipelines. In other area, such as the solution mining plant and the brine pipelines to the brine disposal wells, the requirements are different and thus these facilities were constructed independently by each company.

The operation of a LPG facility requires the storage of large volumes of brine and the ability of moving large brine volumes from storage to the caverns and displaced brine from product injection back into storage. At the Spindletop facility, the initial brine storage pond (and future ponds) are located on the more remote, off-dome property along with the brine disposal wells. Since the functional requirements are different than AGL, CCI decided to develop its own solution-mining plant to provide assurances that a plant of sufficient capacity would be available when required. The development of the caverns, the product injection capability, and the outbound product delivery pipelines will span several years; thus, it is highly likely that both solution mining and product receipt and delivery will occur simultaneously. To accommodate both the production of brine from solution mining and the need for brine to displace product from the caverns, an integrated brine management system was designed to store needed brine and to dispose of any excess brine. This system also allowed the design and installation of a low-pressure bi-directional HDPE transfer line for brine. A booster pump system located on the remote property is used for brine injection.

In contrast, the AGL solution mining system is designed as a once through system of injecting freshwater and immediate disposal of return brine. Storage and reuse of brine is not required in gas storage operations. Thus all of the pumping capacity is located at one site and the brine disposal pipeline is a much higher pressure steel line.

Both the CCI and AGL projects expect to rely on up to four to five brine disposal wells respectively functioning at a maximum injection rates of up to 1,200 gallons per minute (gpm). Disposal will be either in the Frio, the Heterostegina (HET), and/or the Miocene Formations. The Frio, which is the deepest of the three injection zones, is one of the major clastic progradational units of the Texas Gulf Coast. The middle Frio, which is predominantly shale, is overlain by the more sand-rich upper Frio. The upper Frio is approximately 700 feet thick and is composed of several 40- to 50-foot, well-defined sands, divided by interbedded shales. Overlying the Frio is the Anahuac Formation. The uppermost limestone unit within the Anahuac is known as the HET Lime. The Miocene strata is approximately 2,900 feet thick around the dome and thins toward the dome. The upper Miocene sediments are about 2,200 feet thick and consist of thick, blocky sands separated by intervals of shale. The disposal well injection interval for each well will be selected after drilling and logging each well.

Recognizing the challenge associated with the large volume of brine disposal, CCI undertook a study to accurately map the location of fault blocks on the western and southern sides of the Spindletop salt dome to select brine disposal well sites with suitable disposal performance. CCI engaged Hill Geophysical (Shreveport, Louisiana) to reprocess an existing three-dimensional seismic dataset and map the faulting (with emphasis on the west side of the salt dome) in the Frio, HET, and Miocene Formations for CCI to strategically locate their disposal wells.

The 3-D seismic data base covered an area in excess 50 square miles. The salt dome structure is located approximately in the center of the data suite. The first effort was to review the quality of the data base and make whatever adjustments were necessary with respect to shot point and receiver locations. Figure 5 is attached which depicts the data base area and shows one horizon and the location of the salt dome in the approximate center of the data base.

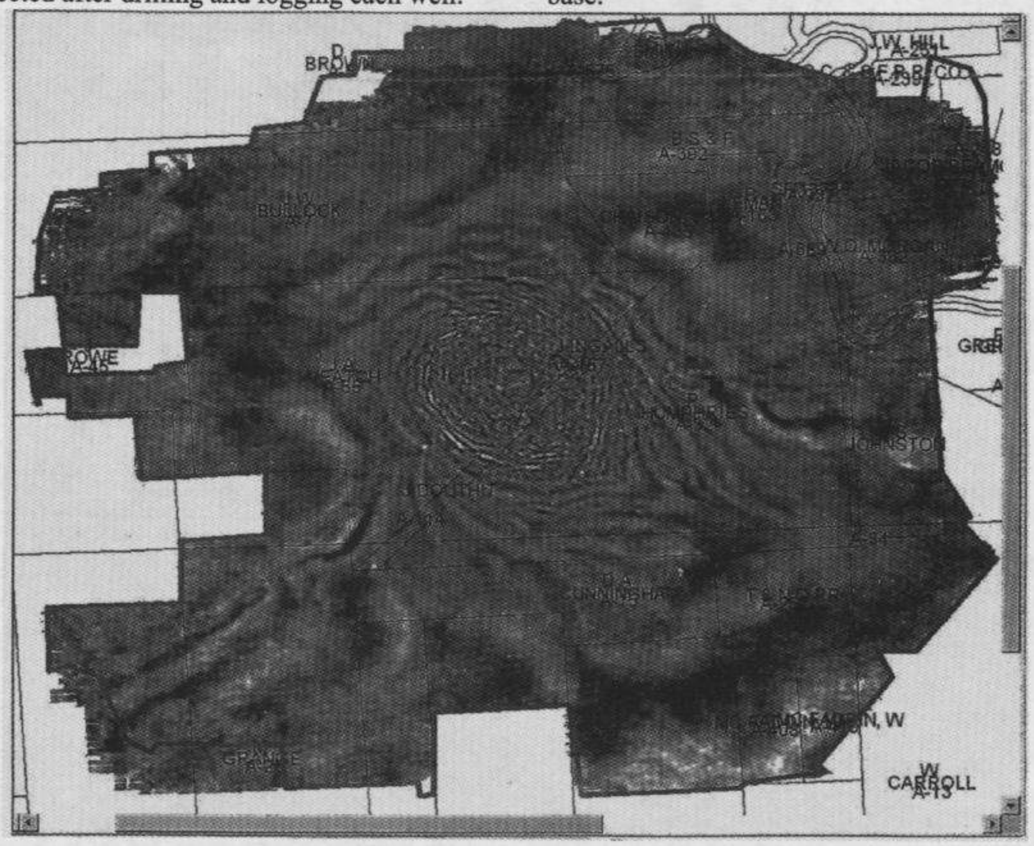

Figure 5. General Coverage Area of 3-D Seismic Program

A mapping strategy was developed by the geophysical consultant. The strategy included first purchasing a land base for Jefferson County, Texas. Several existing well logs from previously drilled oil/gas exploration wells were purchased and Texas Railroad Commission maps were reviewed to determine published depths to the top of salt on the Spindletop dome. One of the deep well logs from near the proposed brine well locations was digitized and turned into a synthetic seismogram. The time/depth information from the synthetic seismogram was used to calculate the various depth maps developed. Based on an understanding of the regional geologic setting and the potential for high volume disposal rates, three different subsurface horizons were mapped to evaluate whether and to what extent major faults might exist around and away from the salt dome and there relative locations. Figures 6 through 8 are attached which depict these three horizons. The three horizons include the top of the Miocene Formation, the Heterostegina (HET) limestone and the base of the Frio Formation. These zones are described in more detail below.

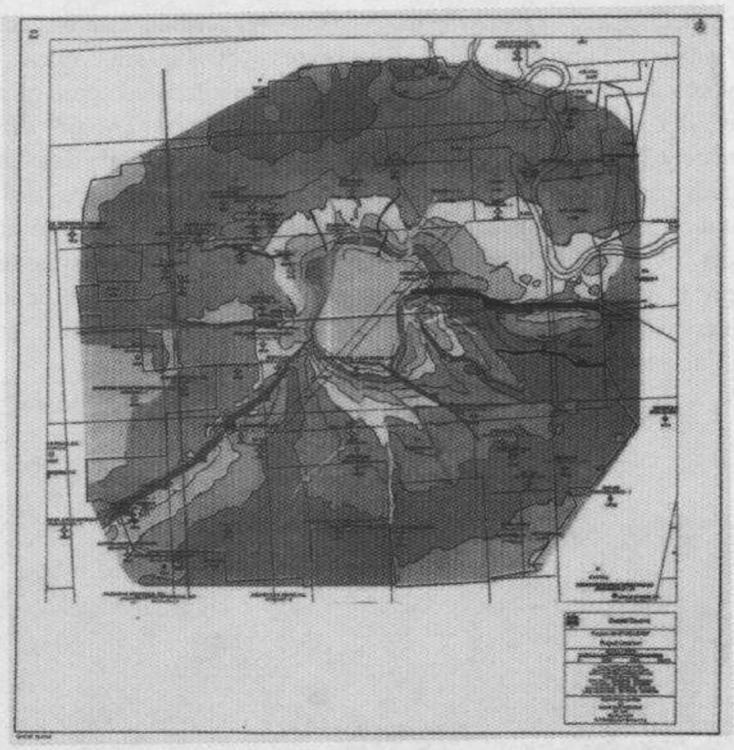

Figure 6. Top of Miocene Horizon

Figure 7. Top of HET Horizon

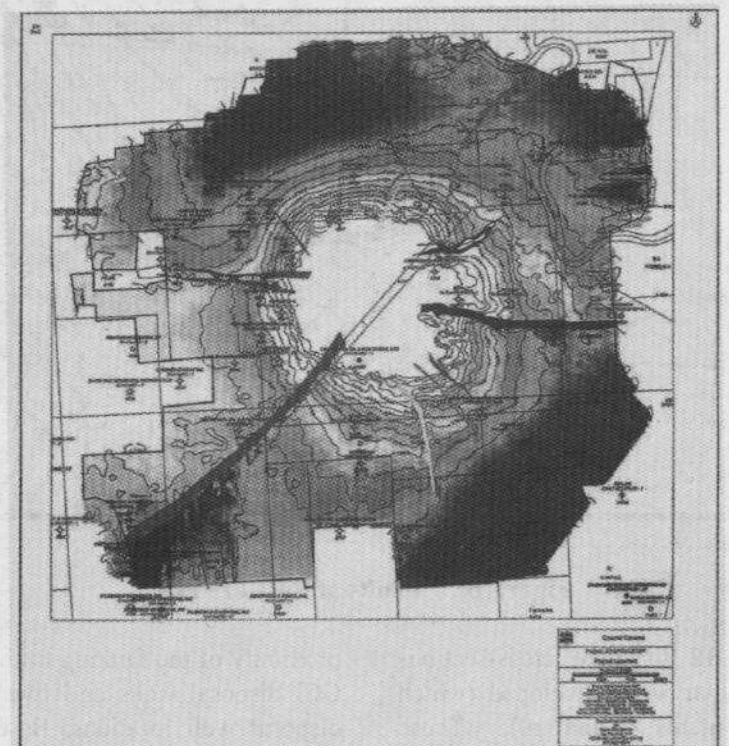

Figure 8. Base of Frio Horizon

Figures 9 and 10 illustrate in plan view the faulting at the top of the Miocene and the base of the Frio (the two preferred formations for disposal).

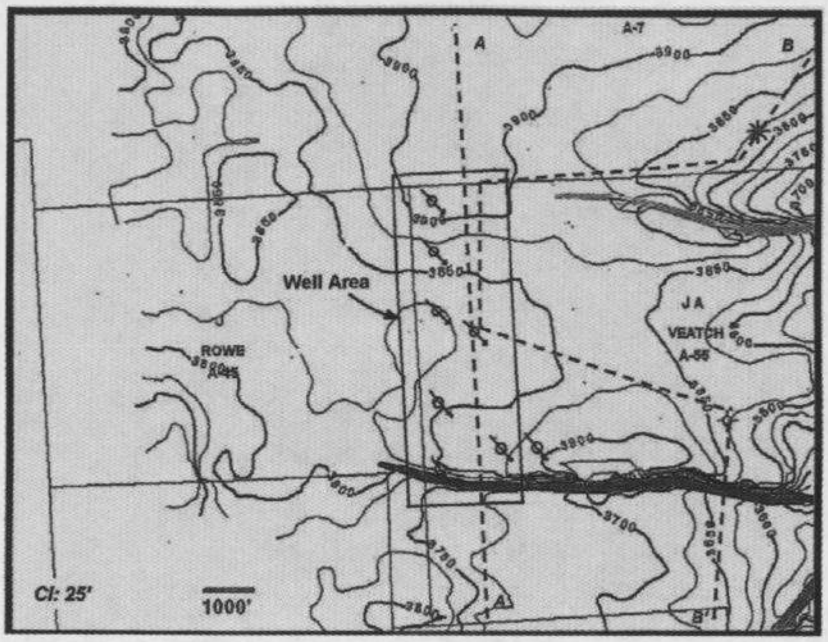

Figure 9. Faults on Top of Miocene

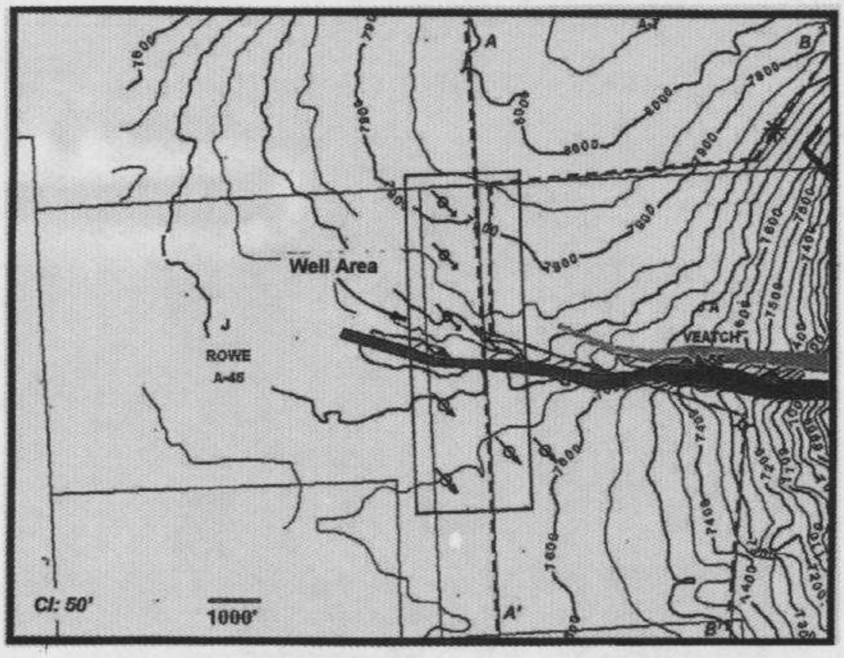

Figure 10. Faults at Base of Frio

Figures 11 and 12 illustrate cross-sections A-A' and B-B' that were developed (which are shown in Figures 9 and 10). These figures which were based on the initial reprocessing of the 3-D data illustrate the proximity of the faulting to the four permitted CCI disposal wells and five AGL permitted disposal well locations. Based on the maps and cross-sections referred to above, the AGL wells were not relocated.

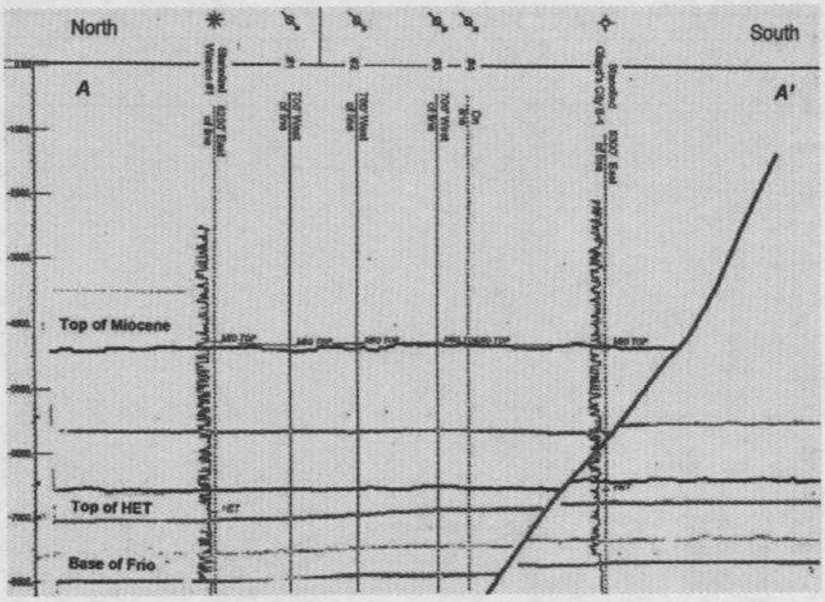

Figure 11. Cross-section A-A'

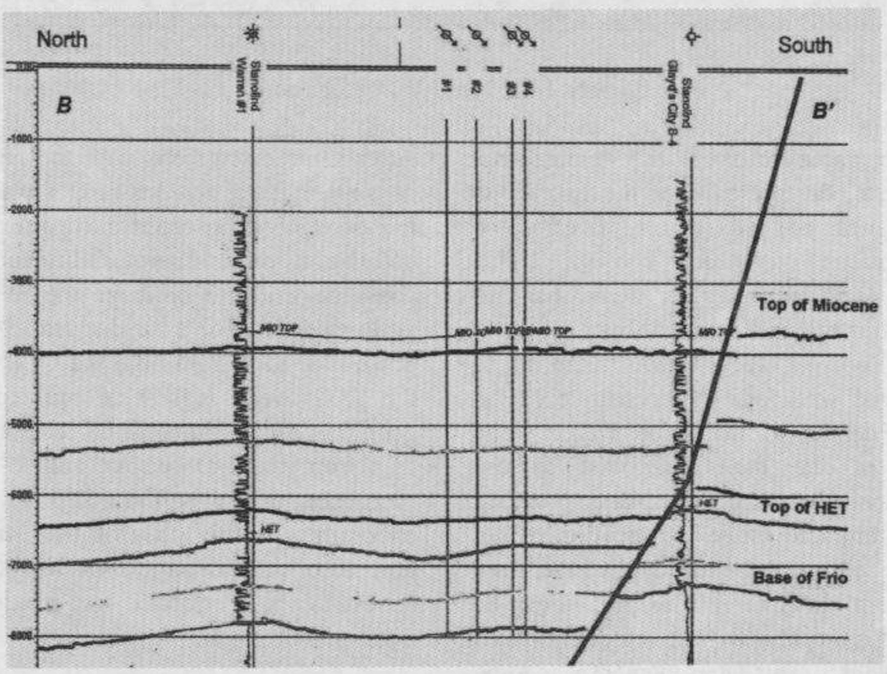

Figure 12. Cross-section B-B'

CCI decided to relocate three of the wells to more advantageous locations. Figure 13 is attached which illustrates the final locations of the wells for both companies.

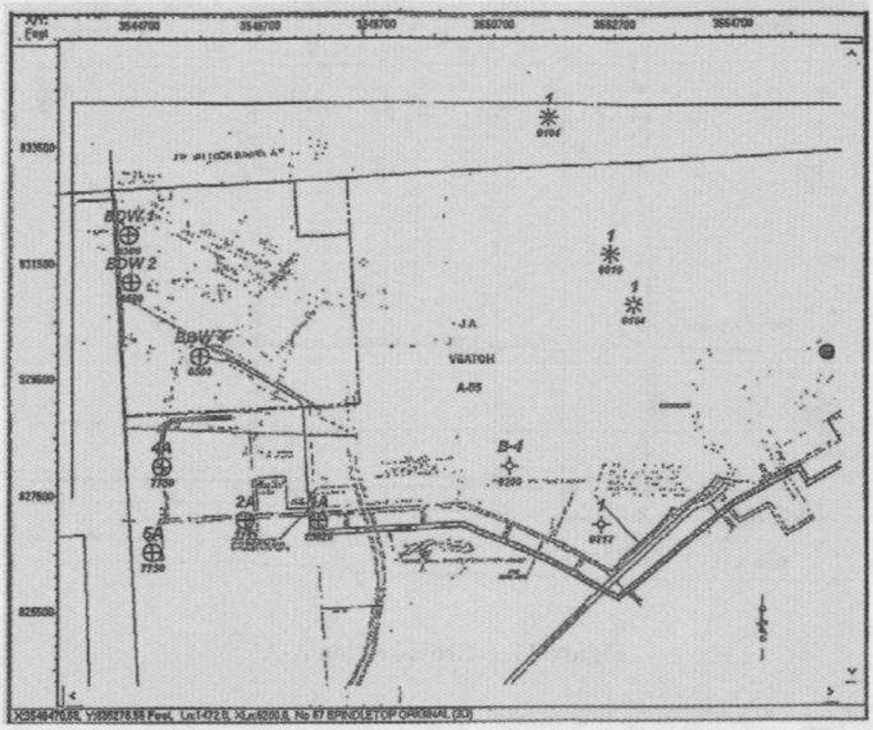

Figure 13. Final Well Locations

Before the evaluation of the three-dimensional seismic data, the presence of the two faults within or near the CCI and AGL off-dome well locations were not known. This particular area around the dome has no existing production of oil or gas resources, and there are only a very limited number of conventional well logs that penetrate to the proposed depths of the brine wells. The presence of the faults, as well as the displacement along the fault plane, provided the opportunity to move the location of the CCI wells so that in essence, the CCI wells are farther from the fault planes and could be hydraulically separated from other proposed disposal wells. This latter element was to be accomplished by careful selection of sand units within the same formation and selection of the formation in which to complete the well.

Subsequent to the reprocessing of the 3-D data base, three of the CCI wells were drilled to the base of the Miocene Formation. Four of the AGL wells were also drilled all to the base of the upper Frio Formation and all of the AGL wells were perforated in the Frio. All of the wells have been logged and include SP, Gamma-Gamma and Resistivity logs.

After some discussions with the geophysical consultant, it was felt that further evaluation of the seismic data could be performed and correlations of both permeability and porosity could be made to optimize the zones to be perforated for the brine disposal. All of the down-hole logs from both the CCI wells and the AGL wells logs were provided to the geophysical consultant for correlation with the data from the 3-D seismic and to make an estimation of the permeability and porosity distribution within the various strata. The purpose of this estimation was to optimize the zones to be perforated to maximize the injection rates in the various wells.

Figure 14 illustrates the initial correlation of just the CCI the well logs to the other seismic information previously developed and the down-hole well logs along with the estimated distribution of permeable/porous zones with depth. This first correlation indicated that permeability and porosity estimates based on the 3-D data fit well with a more normal evaluation of just down-hole logs. It also provides some insight to possible changes in values resulting from the depositional history of the area.

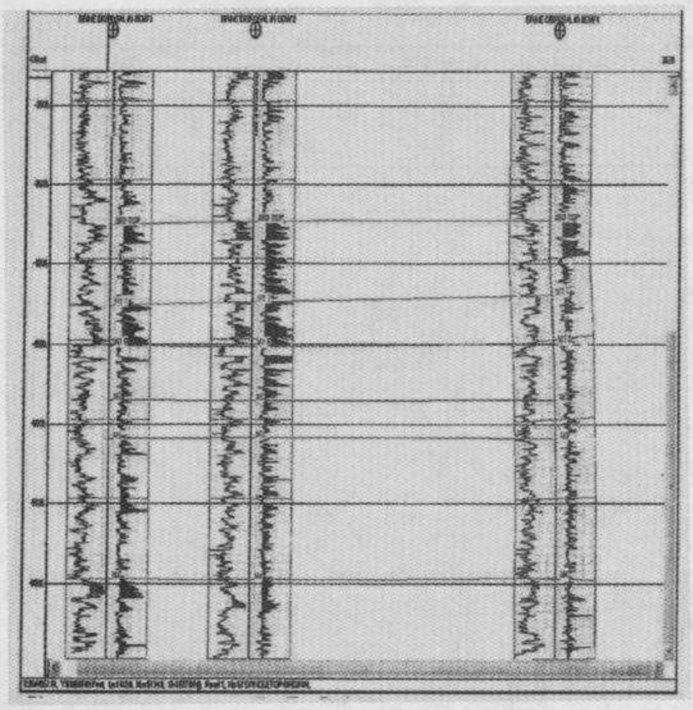

Figure 14. Permeability/Porosity Cross-Section

To test this observation, a horizontal plane at the top of the Miocene was developed which is shown on Figure 15. This figure shows that the high permeable and porous areas are widely distributed across the tract and in the general area.

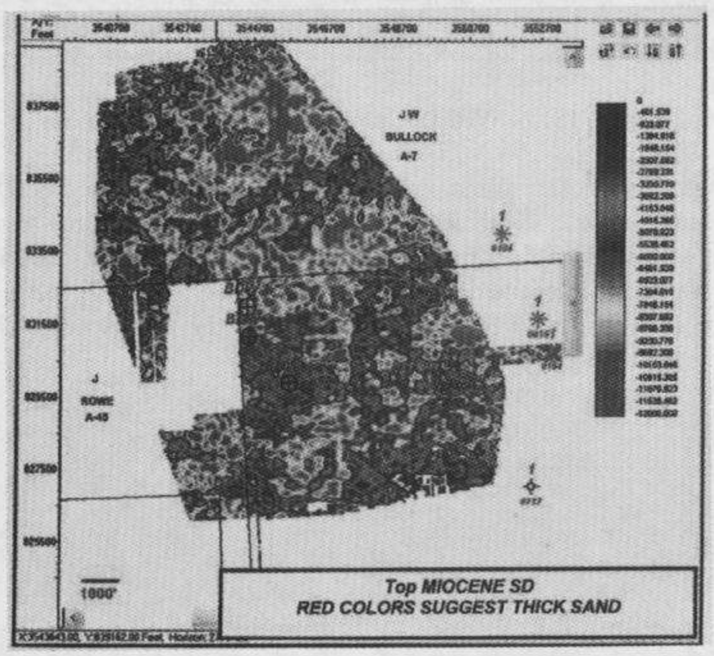

Figure 15. Spatial Distribution of Sand in Miocene

Since the first evaluation provided useful information on the permeability distribution in the Miocene, it was decided to include an evaluation of the deeper Frio wells drilled by AGL. Figure 16 shows the cross-section orientation with the wells. The same type of correlation was performed with the AGL logs as was done with the CCI wells.

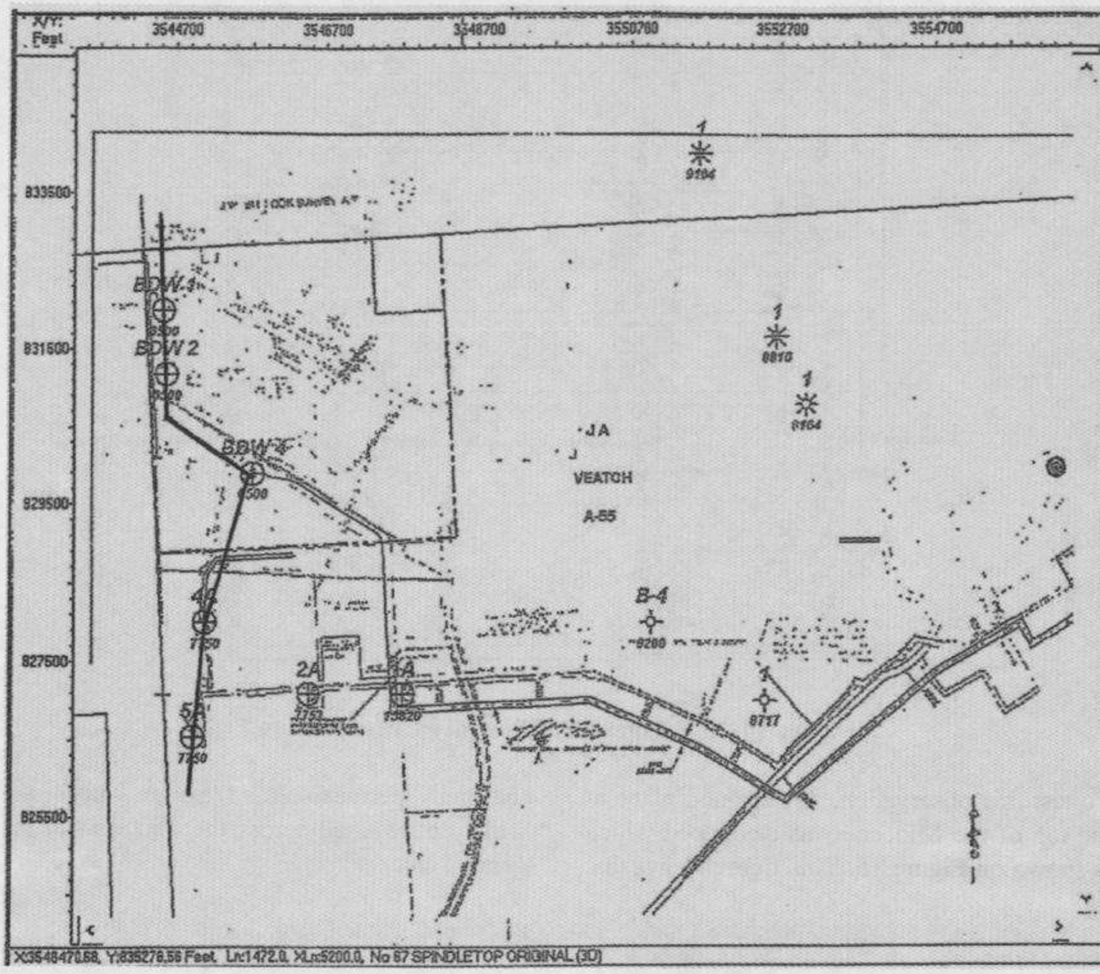

Figure 16. Well Locations and Cross-section Line

Figure 17 illustrates the vertical distribution of permeability and porosity with depth for the CCI wells and the AGL wells. This correlation includes both the shallower Miocene deposits, the predominately shale Anahuac Formation and the Upper Frio Formation. In addition to these cross sections, a plan view map was also developed depicting the estimated lateral extent of the permeable sands at the base of the Frio. This map also indicated a wide distribution of highly permeable sands very suitable for high volume injection of brine waters.

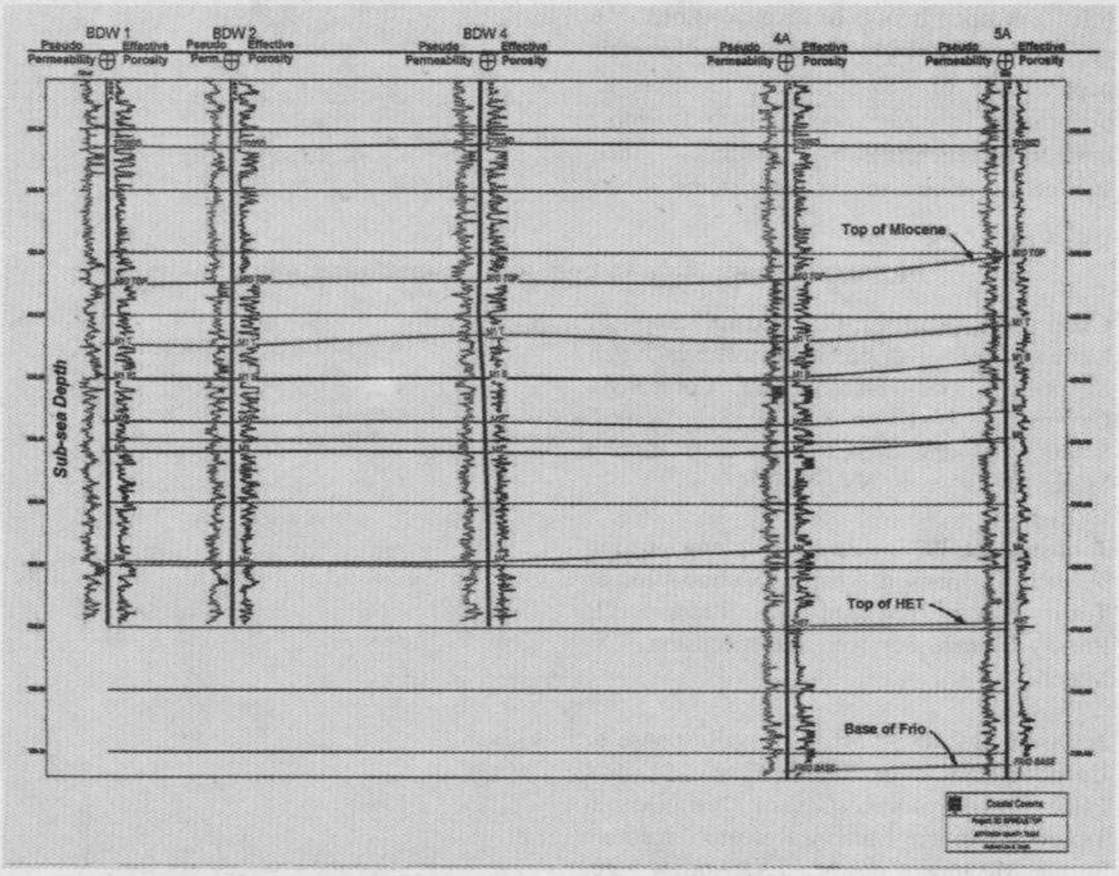

Figure 17. CCI and AGL Permeability/Porosity Cross-section

SUMMARY AND CONCLUSIONS

The Spindletop salt dome is a historically rich site from an oil and gas production perspective. In the late-1980s and early-1990s, this changed with the development of two natural gas storage projects. Before these projects, four different brine production caverns were developed, of which two were ultimately closed. A majority of the remaining property underlain by salt is currently being developed for storage of hydrocarbons. Collectively, these projects will dominate the use of the Spindletop salt dome for the foreseeable future.

The coincidental timing of these projects has led to a mutual cooperation effort between the various project owners so that the various tracts can be optimized for storage use. The two major technical issues and results described above demonstrate that innovative approaches to common issues between operators can lead to a cost-efficient solution for all parties and provide comprehensive information to aid the regulators during the permitting process. In particular, the evaluation of a large 3-D data base has provided the means to determine whether geological structural features, such as faults or salt domes, exist in near proximity to proposed injection wells and to evaluate the impact of such features. In addition, these same data can also be interpreted to assist in the selection of more suitable injection intervals within a single well or a suite of wells. To be able to do so minimizes the chance of over pressuring common zones between wells and to optimize the lateral distances between wells.

Although not used in the initial selection process for the storage cavern locations, a similar evaluation of the 3-D data was able to verify that the locations selected were not in a known fault zone. Limited use of high resolution 3-D seismic techniques have been previously used by the principal author and offer an opportunity to expand upon the general methodology discussed within this paper. Use of 3-D seismic data offers an opportunity for caverns operators to develop a more comprehensive understanding of their storage and brine management systems.

REFERENCES

Chabannes, C., J. G. Durup, and P. Lanham, 1999. "Geomechanical Evaluation of Sabine Gas Transmission Company's Cavern No. 2 at Spindle Top Salt Dome," Solution Mining Research Institute Spring Meeting, Las Vegas, NV, April 11–14.

Johnson, D., 2008. Personal communication between D. Johnson, Railroad Commission of Texas, Austin, TX, and J. L. Ratigan, PB Energy Storage Services, Inc., Houston, TX, March.

Johnson, D., 2003. "Regulatory Response to Unanticipated Geo-Mechanical Events Effecting Gas Storage Cavern Operations in Texas," Solution Mining Research Institute Spring Meeting, Houston, TX, April 27–30, pp. 205–217.

Ratigan, J. L., D. B. Singleton, and W. K. Behrens, 2007. "A Comprehensive Evaluation of Ground Motion Associated With Frasch Sulphur Mining in a Gulf Coast Salt Dome," Solution Mining Research Institute Spring Meeting, Basel, Switzerland, April 29–May 2, pp. 49–67.

Hill, K., 2007. "Jefferson County, Texas, 3-D Spindletop," Hill Geophysical Consulting, December, 2007.

Hill, K., 2009. "Coastal Caverns, Spindletop Dome Area, Brine disposal Wells BDW 1, BDW 2, and BDW 4 Porosity and Permeability Analysis For Saltwater Injection," Hill Geophysical Consulting, January, 2009