An Evaluation of the Carbon Sequestration Potential of the Cambro-Ordovician Strata of the Illinois and Michigan Basins:

Part 1:
Evaluation of Phase 2 CO_2 Injection Testing in the Deep Saline Gunter Sandstone Reservoir (Cambro-Ordovician Knox Group), Marvin Blan No. 1 Well, Hancock County, Kentucky

Part 2:
Time-lapse Three-Dimensional Vertical Seismic Profile (3D-VSP) of Sequestration Target Interval with Injected Fluids

Topical Report

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An Evaluation of the Carbon Sequestration Potential of the Cambro-Ordovician Strata of the Illinois and Michigan Basins

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ABSTRACT

Part 1 of this report focuses on results of the western Kentucky carbon storage test, and provides a basis for evaluating injection and storage of supercritical CO_2 in Cambro-Ordovician carbonate reservoirs throughout the U.S. Midcontinent. This test demonstrated that the Cambro-Ordovician Knox Group, including the Beekmantown Dolomite, Gunter Sandstone, and Copper Ridge Dolomite in stratigraphic succession from shallowest to deepest, had reservoir properties suitable for supercritical CO_2 storage in a deep saline reservoir hosted in carbonate rocks, and that strata with properties sufficient for long-term confinement of supercritical CO_2 were present in the deep subsurface. Injection testing with brine and CO_2 was completed in two phases. The first phase, a joint project by the Kentucky Geological Survey and the Western Kentucky Carbon Storage Foundation, drilled the Marvin Blan No. 1 carbon storage research well and tested the entire Knox Group section in the open borehole – including the Beekmantown Dolomite, Gunter Sandstone, and Copper Ridge Dolomite – at 1152–2255 m, below casing cemented at 1116 m. During Phase 1 injection testing, most of the 297 tonnes of supercritical CO_2 was displaced into porous and permeable sections of the lowermost Beekmantown below 1463 m and Gunter. The wellbore was then temporarily abandoned with a retrievable bridge plug in casing at 1105 m and two downhole pressure-temperature monitoring gauges below the bridge plug pending subsequent testing. Pressure and temperature data were recorded every minute for slightly more than a year, providing a unique record of subsurface reservoir conditions in the Knox. In contrast, Phase 2 testing, this study, tested a mechanically-isolated dolomitic-sandstone interval in the Gunter. Operations in the Phase 2 testing program commenced with retrieval of the bridge plug and long-term pressure gauges, followed by mechanical isolation of the Gunter by plugging the wellbore with cement below the injection zone at 1605.7 m, then cementing a section of a 14-cm casing at 1470.4–1535.6. The resultant 70.1-m test interval at 1535.6–1605.7 m included nearly all of the Gunter sandstone facies. During the Phase 2 injection, 333 tonnes of CO_2 were injected into the thick, lower sand section in the sandy member of the Gunter. Following the completion of testing, the injection zone below casing at 1116 m in the Marvin Blan No. 1 well, and wellbore below 305 m was permanently abandoned with cement plugs and the wellsite reclaimed.

The range of most-likely storage capacities found in the Knox in the Marvin Blan No. 1 is 1000 tonnes per surface hectare in the Phase 2 Gunter interval to 8685 tonnes per surface hectare if the entire Knox section were available including the fractured interval near the base of the Copper Ridge. By itself the Gunter lacks sufficient reservoir volume to be considered for CO_2 storage, although it may provide up to 18% of the reservoir volume available in the Knox. Regional extrapolation of CO_2 storage potential based on the results of a single well test can be problematic, although indirect evidence of porosity and permeability can be demonstrated in the form of active saltwater-disposal wells injecting into the Knox. The western Kentucky region suitable for CO_2 storage in the Knox is limited updip, to the east and south, by the depth at which the base of the Maquoketa shale lies above the depth required to ensure storage of CO_2 in its supercritical state and the deepest a commercial well might be drilled for CO_2 storage. The resulting prospective region has an area of approximately 15,600 km^2, beyond which it is unlikely that suitable Knox reservoirs may be developed. Faults in the subsurface, which serve as conduits for CO_2 migration and compromise sealing strata, may mitigate the area with Knox reservoirs suitable for CO_2 storage. The results of the injection tests in the Marvin Blan No. 1, however, provide a basis for evaluating supercritical CO_2 storage in Cambro-Ordovician carbonate reservoirs throughout the Midcontinent.

Reservoir seals were evaluated in the Knox and overlying strata. Within the Knox, permeabilities measured in vertical core plugs from the Beekmantown and Copper Ridge suggest that intraformational seals may problematic. Three stratigraphic intervals overlying the Knox in the Marvin Blan No. 1 well may provide seals for potential CO_2 storage reservoirs in western Kentucky: Dutchtown Limestone, Black River Group, and Maquoketa Shale. The Dutchtown and Black River had permeabilities suggest that these intervals may act as secondary sealing strata. The primary reservoir seal for the Knox, however, is the Maquoketa. Maximum seal capacity calculated from permeabilities measured in vertical core plugs from the Maquoketa exceeded the net reservoir height in the Knox by about two orders of magnitude. Rock strength measured in core plugs from the Maquoketa suggest that it is unlikely that any CO_2 migrating from the Knox would have sufficient pressure to fracture the Maquoketa.

Part 2 of this report reviews the results of vertical seismic profiling in the Marvin Blan No. 1 well to model post-injection CO_2 plume migration. Two three-dimensional vertical seismic profiles (3D-VSP's) were acquired at the Kentucky Geological Survey Marvin Blan No. 1 CO_2 sequestration research well, Hancock County, Kentucky. The initial (pre-injection) survey was performed on September 15–16, 2010. This was followed by the injection of 333 tonnes of supercritical CO_2 and then 584 m^3 of 2% KCl water (to displace the remaining CO_2 in the wellbore) on September 22, 2010. After injection, the well was shut in with a downhole pressure of 17.5 MPa at the injected reservoir depth of 1545.3 m. The second 3D-VSP was acquired on September 25–26, 2010. These two 3D-VSP's were combined to produce a time-lapse 3D-VSP data volume in an attempt to monitor and image the subsurface changes caused by the injection. Less than optimum surface access and ambient subsurface noise from a nearby active petroleum pipeline hampered quality of the data, resulting in the inability to image the CO_2 plume in the subsurface. However, some changes in the seismic response post-injection (both wavelet character and an apparent seismic "pull-down" within the injection zone) are interpreted to be a result of the injection process and imply that the technique could still be valid under different circumstances.

EVALUATION OF PHASE 2 CO_2 INJECTION TESTING IN THE DEEP SALINE GUNTER SANDSTONE RESERVOIR (CAMBRO-ORDOVICIAN KNOX GROUP), MARVIN BLAN NO. 1 WELL, HANCOCK COUNTY, KENTUCKY

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EVALUATION OF PHASE 2 CO_2 INJECTION TESTING IN THE DEEP SALINE GUNTER SANDSTONE RESERVOIR (CAMBRO-ORDOVICIAN KNOX GROUP), MARVIN BLAN NO. 1 WELL, HANCOCK COUNTY, KENTUCKY

EXECUTIVE SUMMARY

The objective of this study was to demonstrate the injection of supercritical CO_2 into the Gunter Sandstone, middle Knox Group, and provide an estimate of the supercritical CO_2 storage volume in the entire Knox. The results of the injection tests in the Kentucky Geological Survey Marvin Blan No. 1 well provide a basis for evaluating supercritical CO_2 storage in Cambro-Ordovician carbonate reservoirs throughout the Midcontinent. This topical report evaluates the reservoir properties, injectivity, and storage capacity of the Gunter, as well as the Knox as a whole. The sealing capacity of the Maquoketa Shale, the primary confining interval above the Knox, was also evaluated. These evaluations were completed using laboratory core analyses, wireline geophysical electric logs, and injection pressure data acquired during Phase 1 testing conducted in the Marvin Blan No. 1 well in 2009 by the Kentucky Geological Survey and its industry partners, and Phase 2 testing conducted in 2010 by the Kentucky Geological Survey, the subject of this study. Petrophysical and graphical presentation software and spreadsheet-based physical models were employed for interpretation of these data.

Calculating reservoir volume required to store a volume of supercritical CO_2 required data provided by wireline electric logs, analysis of whole and sidewall cores, wireline temperature and pressure surveys, and analysis of formation waters collected prior to injection tests. Phase 1 injection testing focused on the entire Knox section. A total of 297 tonnes of CO_2 were injected into the Knox section in the open wellbore below 1116 m. Phase 2 injection testing focused on the Gunter, the highest porosity and permeability section within the Knox. The Gunter section was mechanically isolated to a 70.1 m interval of the wellbore. A total of 333 tonnes of CO_2 were injected into the Gunter. As part of the test program, pre- and post-injection 3D vertical seismic profiles (VSP) surveys were conducted from vibrators at about shot 900 points and recorded with downhole geophones on tubing to model the extent of the CO_2 plume migration. This unsuccessful because of the relatively small volume of CO_2 injected. The wellbore was subsequently abandoned with cement plugs and the wellsite was reclaimed. Storage volume calculated for the Phase 2 test interval is 2194 tonnes per surface hectare. Thus, 456 hectares of surface area is required to store 1 million tonnes of supercritical CO_2 in the Phase 2 Gunter test interval. The range of most-likely storage capacities calculated in the Knox in the Marvin Blan No. 1 is 1000 tonnes per surface hectare in the Phase 2 Gunter interval to 8685 tonnes per surface hectare for the entire Knox section. Thus, by itself the Gunter lacks sufficient reservoir volume to be considered for CO_2 storage, but it may provide up to 18% of the reservoir volume available in the Knox as a whole.

Primary sealing strata tested in the Marvin Blan No. 1 is the Ordovician Maquoketa Shale. The Maquoketa is considered a primary reservoir seal for CO_2 storage in underlying reservoirs. The Maquoketa section was cored and laboratory analyses performed as part Phase 1 testing program. Analyses of this core included laboratory measurements of porosity, permeability, and mercury-injection threshold pressure. Sealing capacity of strata was determined by two methods in this study: mercury-injection capillary pressure tests, or from permeability measured in core plugs. Supercritical CO_2 seal capacity calculated for these core plugs from the Maquoketa were 1756–16,056 m. Rock mechanical measurements made on a representative sample from the

Maquoketa yielded a compressive strength of 1.75 MPa. Therefore the Maquoketa can act as an effective confining interval for supercritical CO_2 stored in the Knox.

Regional extrapolation of CO_2 storage potential based on the results of a single well test can be problematic unless corroborating evidence can be demonstrated. Core analysis from the Knox is not available from wells in the region surrounding the Marvin Blan No. 1 well although indirect evidence of porosity and permeability can be demonstrated in the form of active saltwater-disposal and gas-storage wells injecting into the Knox. Pore volume is reduced in wells east of the Marvin Blan No. 1 because of erosional truncation of the Beekmantown on the western flank of the Cincinnati Arch, whereas wells west of the Marvin Blan No. 1 have sections comparable to the Marvin Blan No. 1 but lose pore volume because of compaction at their greater depths. The preliminary regional evaluation suggests that the Knox reservoir may be found throughout much of western Kentucky. The western Kentucky region suitable for CO_2 storage in the Knox is limited updip, to the east and south, by the depth at which the base of the Maquoketa lies above the depth required to ensure storage of CO_2 in its supercritical state and the deepest a commercial well might be drilled for CO_2 storage. The resulting prospective region has an area of approximately 15,600 km^2, beyond which it is unlikely that suitable Knox reservoirs may be developed. Faults in the subsurface, which serve as conduits for CO_2 migration and compromise sealing strata, may mitigate the area with Knox reservoirs suitable for CO_2 storage. The results of the injection tests in the Marvin Blan No. 1, however, provide a basis for evaluating supercritical CO_2 storage in Cambro-Ordovician carbonate reservoirs throughout the Midcontinent.

This topical report documents the results of Subtasks 3.3–3.5 and 3.7 of the project, *An Evaluation of the Carbon Sequestration Potential of the Cambro-Ordovician Strata of the Illinois and Michigan Basins.* This project was funded by the United States Department of Energy (USDOE) through Recovery Act: Site Characterization of Promising Geologic Formations for CO_2 Storage, Number: DE-FOA-0000033, under cooperative agreement DE-FE0002068 from 08 December 2009, through 31 September 2013.

OBJECTIVES

The objective of this study was to demonstrate the injection of supercritical CO_2 into the Cambro-Ordovician Gunter Sandstone, middle Knox Group, and provide an estimate of the supercritical CO_2 storage volume in the entire Knox section encountered in the Kentucky Geological Survey Marvin Blan No. 1 well. The Marvin Blan No. 1 well was drilled by a consortium of the Kentucky Geological Survey and its industry partners and the Phase 1 testing program completed in 2009. The extensive suite of geological, geophysical, and reservoir data was acquired as part of the Phase 1 program contributed to the planning and implementation of the Phase 2 testing program, the subject of this topical report. The additional data was acquired during this program focused on the Gunter to better evaluate the CO_2 storage capacity of this widespread sandstone reservoir.

Project tasks included:

1. **Geology and Geophysics**
   a. Interpretation of the first phase of testing in the Marvin Blan No. 1 well, Hancock County, Kentucky, to determine the zone and fluids to be injected in the second phase of testing.
   b. Collect additional data and determine petrophysical properties of the Gunter section encountered in the Marvin Blan No. 1 well including acquiring 20 rotary sidewall cores.
   c. Determine the potential reservoir volume for storage of supercritical CO_2 in the Gunter.
   d. Review the rock properties of the Maquoketa and determine its sealing capacity.

2. **Reservoir Injectivity Testing**
   a. Design a program for the mechanical isolation of the Gunter section and subsequent injection of 363 tons of supercritical CO_2.
   b. Perform the injection test, collecting pressure and temperature data.
   c. Abandon the injection zone as required by the U.S. Environmental Protection Agency and remediate the wellsite.
   d. Have pressure transient analysis performed on the Phase 1 CO_2 injection test, long term pressure record, and Phase 2 injection test.

INTRODUCTION AND BACKGROUND

The Kentucky Geological Survey's Marvin Blan No. 1 well was drilled in east-central Hancock County, Kentucky (Fig. 1), about 6.5 km southeast of the Ohio River, to demonstrate CO_2 injection in the Western Kentucky Coal Field, following the mandate and partial funding by the Kentucky state legislature in 2007. Additional funding for the Phase 1 drilling and testing was provided by industry partners through the Western Kentucky Carbon Storage Foundation (disincorporated in December 2010). The well was located on the easternmost margin of the Western Kentucky Coal Field in order to evaluate the CO_2 storage characteristics of the Knox Group, which has a broad distribution in Kentucky, at its shallowest depth. Secondary targets included the St. Peter Sandstone overlying the Knox, and the underlying Mount Simon Sandstone, although these formations proved to be absent in the well. The Phase 2 testing program, the subject of this report, was funded by the U.S. Department of Energy through a grant to the Illinois State Geological Survey

Units of Measurement

All dimensions, depths, volumes, temperatures and pressures, and other measurements made during the construction, drilling, Phase 1 and Phase 2 testing, seismic surveys, and well abandonment and wellsite remediation of the Marvin Blan No. 1 well ("measurements"), were made using U.S. Standard Units, as is customary for the U.S. petroleum industry, except as where otherwise may be noted. These measurements have been converted to the International System of Units ("S.I. Units") in the text of this report where appropriate and practical using the conversion factors of Thompson and Taylor (2008). Measurements may be parenthetically presented in the text in U.S. Standard Units where required for clarity. All figures, tables, and reports by others in Appendix 1–3, retain the units in which the measurements were originally made or recorded, whether U.S. Standard Units or S.I. Units, with conversion to S.I. Units presented in figure captions where appropriate and necessary.

Phase 1 Program (2009)

Drilling, Completion, and Geophysical Electric Logging and Coring Programs

The Marvin Blan No. 1 well commenced drilling on 24 April 2009, after 18 months of planning, drillsite due diligence and construction, and regulatory agency permitting (Bowersox et al., 2009). It reached its total depth (TD) of 2477 m in Precambrian Middle Run Sandstone on 15 June 2009, after 63 days of drilling. The top of the Knox, the Beekmantown Dolomite, was penetrated at 1152 m. Drilling through the Knox proved to be difficult: Borehole deviation greater than 5° required specialized equipment to return it to vertical and maintain a vertical borehole, and circulation was lost in a fracture at 1701 m. Surface conductor pipe was cemented at 15.9 m, 34-cm surface groundwater protection casing was cemented at 134.4 m, and 21.9 cm. casing was cemented at 1115.6 m, 36.6 m above the Knox. The wellbore was left uncased below 1116 m to facilitate testing. A total of 120.4 m of whole-diameter, 10-cm cores were cut and recovered from the well. The Devonian New Albany Shale, Ordovician Maquoketa Shale, Black River Group, and basal Dutchtown Limestone were cored to test reservoir sealing properties. The Knox Group was cored in three intervals to test reservoir characteristics and rock properties. The Precambrian Middle Run Sandstone was cored to test for any CO_2 storage potential below the Paleozoic rocks. The testing program commenced on 25 July 2009, and was successfully completed on 22 August 2009. All testing was in open hole below the casing. Following the completion of the Phase 1 injection testing, the wellbore was temporarily abandoned, with long-term memory pressure monitoring gauges left in place below a bridge plug at 1105 m, pending Phase 2 injection testing.

The Marvin Blan No.1 drilled through the characteristic Paleozoic section of western Kentucky from Early Pennsylvanian to Middle Cambrian, and reached its total depth in the Precambrian Middle Run (Fig. 2). Three electric log runs were made during the drilling of the Marvin Blan No. 1: array induction (dual induction), SP, gamma ray, and borehole caliper at 134.7 m TD to the surface; array induction, SP, gamma ray, spectral gamma ray with lithology analysis, photoelectric density and compensated neutron porosity logs, dipole sonic with mechanical rock properties analysis, and borehole caliper at 1116 m TD to casing at 134.6 m; and array induction, SP, gamma ray, photoelectric density and compensated neutron porosity logs, dipole sonic with mechanical rock properties analysis, image log and interpretation, and borehole caliper at 2477 m TD to casing at 1115.6 m. The Marvin Blan No. 1 was mud logged from the surface to its total depth at 2477 m and samples collected at 1.5 m intervals. Depths of selected tops of formations penetrated by the well, as well as those of the groundwater monitoring well drilled on the Marvin Blan No. 1 well site and the Knight Brothers No. 1 well (rounded to the nearest whole meter of depth), are listed in Table 1. The depths of formation tops recorded on log runs 2 and 3 appear to have been recorded 1.2 m (4 ft) shallower than those of run 1. Whole-diameter 10-cm cores were cut and recovered from the New Albany Shale, Maquoketa Shale, and Black River Limestone to test sealing capabilities of these intervals, and in the Beekmantown, Beekmantown–Gunter, and Copper Ridge to test reservoir properties of porous and permeable intervals, and reservoir seal properties of impermeable intervals within the Knox. A total of 120.4 m of cores were cut and recovered from the New Albany (571.5–580.6 m; 9.1 m), Maquoketa (853.4–862.9 m; 9.5 m), Black River (1016.5–1035.1 m; 18.6 m), basal Dutchtown Limestone–Beekmantown (1146.0–1183.5 m; 37.5 m), Beekmantown–Gunter (1530.4–1561.2 m; 30.8 m), Copper Ridge (1868.4–1874.2 m; 5.8 m), and Middle Run (2438.4–2447.5 m; 9.1 m). Correlation of core gamma ray log depths with openhole gamma ray log depths (electric log runs 2 and 3) are given in Table 2.

Phase 2 Program (2010)

Completion and Geophysical Electric Logging and Coring Programs

A single injection test was planned for the Phase 2 testing program. The Gunter was chosen for Phase 2 testing to evaluate this interval separately from the comingled Knox section tested during Phase 1. The higher porosity and permeability of the Gunter (below) makes it an attractive, though thin, reservoir target. These same characteristics, however, makes the Gunter a potential thief zone if comingled with the larger Knox dolomite reservoir during industrial-scale injection. During Phase 1 testing communication through strata between the wellbore below the test packer and the annulus above compromised the test results' quality. Thus for the Phase 2 program the Gunter was mechanically isolated to mitigate communication during testing. Mechanical isolation of the Gunter included plugging the wellbore with cement below the injection zone at 1605.7 m, 24.1 m stratigraphically above the base of the Gunter, then cementing a section of a 14-cm casing at 1470–1536 m, 15.8 m above the top of the Gunter. The resultant 70-m test interval at 1536–1606 m included nearly all of the Gunter sandstone facies.

Additional cased-hole electric logs were recorded during the Phase 2 testing program, and an additional 20 rotary sidewall cores were cut and recovered from the Gunter. Rotary sidewall cores were cut prior to setting plugs and cementing casing to mechanically isolate the Phase 2 injection test interval to prevent contamination of the wellbore with cement. A temperature and pressure log was recorded after initially re-entering the Marvin Blan No. 1 to determine static reservoir conditions after the well had been temporarily abandoned for a year. A second temperature was recorded after the lower section of the borehole was plugged at 1605.7 m. Two subsequent temperature logs were recorded across the Phase 2 injection test interval at 1535.6–1605.7 m, one before the injection test and one afterwards. During rotary sidewall coring, a gamma ray correlation log and core penetration log was recorded. No additional openhole logs were recorded during the Phase 2 testing program.

Stratigraphy and Structure of the Hancock County Region

The subsurface stratigraphy of penetrated in the Marvin Blan No. 1 well is summarized in Figure 2. The Marvin Blan No. 1 penetrated Pennsylvanian through Precambrian strata. In general, the stratigraphic succession above the Precambrian consists of three cratonic sequences of Sloss (1963, as modified by Noger and Drahovzal, 2005) with basal transgressive, shallow-marine to nonmarine sandstones overlain by deeper-water to basinal shales, limestones, and dolomites with rare, lenticular sandstones in the section. The Silurian through Mississippian section is dominated by carbonates, although there are several thin sandstones in the Mississippian section as well as the New Albany in the Upper Devonian. The Middle Cambrian through Upper Ordovician section is dominantly carbonates capped by the Maquoketa Shale. The thick Upper Ordovician section, including the Maquoketa Group penetrated at 832–952 m and the underlying Black River Group carbonates penetrated at 952–1111 m, is the primary reservoir seal for the deeper Knox. The St. Peter Sandstone overlies the Knox further north in the Illinois basin but was absent in the Marvin Blan No. 1. The Beekmantown Dolomite, uppermost Knox, was penetrated at 1152–1536 m; the Gunter Sandstone at 1536–1630 m; Copper Ridge Dolomite at 1630–2255 m, overlying the Eau Claire Formation. A total of 1103 m of Knox section was encountered in the well. A 57 m section of Middle Cambrian Eau Claire Formation, a major regional sealing interval where underlying Mount Simon is present, underlies the Knox and, in turn, unconformably overlies the Neoproterozoic Middle Run. At TD, the Marvin Blan No. 1 had penetrated 165 m of Middle Run unconformably below the Eau Claire at 2312–2477 m, the only Middle Run section penetrated and cored in western Kentucky.

Generalized subsurface structural contours on top of the Knox are shown in Figure 3. In western Kentucky and the Hancock County region, strata above the Knox unconformity dip homoclinally approximately 0.5° west. The Middle Ordovician cratonic sequence-bounding unconformity at the top of the Knox Group progressively truncates deeper into the Beekmantown east of Hancock County (Fig. 3). This suggests Cincinnati Arch uplift during the Early Ordovician, and development of a 0.7°/ S80°W dip in the Knox in western Kentucky (Fig. 4). Seismic data and dipmeter interpretation suggest that Eau Claire and deeper strata dip to the south in Hancock County (see, for example, Drahovzal, 2009). The surface fault nearest the Marvin Blan No. 1 is a strand of the Indian Creek Fault Zone, lying approximately 3.5 km west of the well (Figs. 3–4). The Rough Creek Graben, a major structural feature in western Kentucky, lies approximately 29 km south of the Marvin Blan No. 1. No subsurface faulted sections can be demonstrated in the Marvin Blan No. 1, although fractures with small offsets were interpreted from the imaging log.

General Characterization of the Knox Group CO_2 Storage Reservoirs

The Knox was the primary test objective in the Marvin Blan No. 1 well, where as many as five intervals with suitable reservoir properties were anticipated based on correlations with other western Kentucky deep wells. Injection into the Knox dolomites has been demonstrated in Kentucky in three EPA UIC Class I injection wells: DuPont No.1 WAD and No.2 WAD in Jefferson County, and IMCO Recycling No.1 International Metal in Butler County (U.S. Environmental Protection Agency, 2009)(Fig. 1). Elsewhere in Kentucky oil and gas are produced and gas stored in Knox reservoirs (Gooding, 1992). UIC Class I injection wells developed in the Knox Group have also been permitted in Illinois and Ohio (Fig. 1), as well as UIC Class II wells used for oilfield brine disposal and utility natural gas storage. Knox lithology is a heterogeneous section containing varying amounts of sandstone and siliciclastic detritus, chert, anhydrite, authegenic feldspars and pyrite, and fracture fillings of mixed mineralogies. Reservoir zones can be thin and widely distributed throughout the section (Harris, 2007). Dolomitization and porosity and permeability in the Knox appear to be related to several generations of diagenesis of parent limestones and early-stage dolomites by late-stage hydrothermal fluid flow (Pittenger, 2008). Karst development associated with the post-Knox unconformity is found in south-central Kentucky (Gooding, 1992), but was not evident in cores from wells further to the north in Kentucky. Epikarsts were observed in cores at the top and within the Knox, no evidence of large-scale karstification was observed in cores from the Marvin Blan No. 1.

Beekmantown Dolomite

The Beekmantown was penetrated at 1152–1536 m in the Marvin Blan No.1 well, a gross interval of 399 m. A total of 52.4 m of whole-diameter 10-cm core was cut and recovered from two intervals in the Beekmantown: 31.4 m of core recovered from the top of the Beekmantown, immediately below the Middle Ordovician Knox unconformity, and 21.0 m recovered from the basal Beekmantown above the Gunter. The cored sections consist of fabric-preserving primary dolomite and fabric-destructive secondary dolomite, vug-filling saddle dolomite, vug-lining chert, chert nodules and fracture fills, including microporous chert, and nodular to disseminated pyrite. Thin quartz sandstones in the section at 1385.9–1415.8 m are similar to those found in the Roubidoux Formation of westernmost Kentucky (Schwalb, 1969) and southeast Missouri. Preserved primary sedimentary structures observed in Beekmantown cores suggest deposition in peritidal to shallow–subtidal carbonate platform environments with episodic transgression and regression. Epikarsts observed at the Knox unconformity, and within the Beekmantown, demonstrate episodic subaerial exposure and weathering during and post-deposition. No structures indicative of the karsting comparable to that developed in south-central Kentucky (Gooding, 1993) were observed in the Beekmantown cores. Salinity of a formation water sample recovered from the uppermost Beekmantown in the Marvin Blan No. 1 well falls along the general trend of increasing water salinity with depth for Knox reservoirs in Kentucky (Takacs et al., 2009). Analysis of a water sample recovered from the top of the Beekmantown at 1158–1165 m yielded 56,776 ppm of total dissolved solids (TDS), almost entirely NaCl, with 3,070 ppm Ca, 739 ppm Mg, 1,573 ppm SO_4, and minor to trace amounts of other ions.

Gunter Sandstone

The Gunter was penetrated at 1536–1630 m, a 78.3-m thick section. The Gunter can be divided into two informal members (Fig. 5): an upper sandy member at 1536–1595 m, and a lower dolomitic member at 1595 m to the top of the Copper Ridge at 1630 m. Whole-diameter 10-cm core recovered from the uppermost 9.8 m of the Gunter, and 20 rotary sidewall cores cut prior to Phase 2 testing, showed a mixed lithology of interbedded sandstones composed of fine-grained, well rounded quartz sand with a dolomite matrix, and thin dolomite interbeds. Planar bedding and crossbeds were observed in whole core from the sand beds, indicative of beach to nearshore deposition. Sandstones were characterized by intergranular porosity and vuggy porosity from dissolution of the dolomite matrix. Dolomite interbeds were characterized by vuggy porosity largely developed in fabric-destructive dolomites with solution-enhanced fractures and pervasive styolites, and in fabric-preserved stromatolites. Interpretation of the compensated neutron porosity and photoelectric density logs suggests a net 36.3 m of sand is present in the Gunter in 27 distinct 0.3- to 4.3-m thick sand bodies. About 75% of the sand was found in the upper sandy member. Analysis of a formation-water sample recovered from the upper Gunter at 1561–1568 m yielded 97,192 ppm of TDS, nearly all NaCl, with 5,440 ppm Ca, 1,250 ppm Mg, 2,950 ppm SO_4, and minor to trace amounts of other ions.

Copper Ridge Dolomite

The Copper Ridge was penetrated at 1630–2255 m, a gross interval of 625 m. It overlies the thin, 57-m thick section of Eau Claire Formation encountered in the Marvin Blan No. 1 (Fig. 4). A 5.8 m whole-diameter 10-cm core was recovered from the middle Copper Ridge at 1868.4–1874.2 m. Sedimentary structures observed in the core included solution collapse breccias with coarsely crystalline anhydrite nodules filling vugs lined with saddle dolomite, a preserved layer of ooid dolograinstone, microbial mats, stromatolites, edgewise conglomerate, fabric-preserved burrows, and dolomitized fabrics characteristic of sabkha environments. Interpretation of the imaging log suggests that the porosity system in the Copper Ridge consists of intercrystalline matrix porosity enhanced by vugs and open fractures. Borehole rugosity in intervals at 2172–2253 m suggests intense fracturing in the basal of the Copper Ridge. An attempt to collect a formation water sample from the Copper Ridge was unsuccessful.

EXPERIMENTAL PROCEDURES

Objectives and General Methodology for Reservoir Analysis

Interpretation of Wireline Geophysical Electric Logging Data

The wireline geophysical electric logging program for the Marvin Blan No. 1 well is discussed above. Individual descriptions of the logs ("logs") recorded in the Marvin Blan No. 1 well are found in Weatherford (2006). Wireline rotary sidewall cores were cut and recovered from 20 depths in the wellbore to augment the whole core data from the uppermost Gunter acquired during the Phase 1 well testing program. Routine core analysis was performed by a commercial laboratory (Appendix 1). Data recorded by the logs was used to calculate porosity and permeability in the Knox, evaluate the natural fractures encountered in the wellbore, and determine the sealing capacity of strata overlying the Knox. These data were normalized to data from the core analysis to calibrate analytical models. Methods employed in the analysis of the wireline electric log data are discussed below. PETRA well data management and analysis software was used to create subsurface cross sections from the log data as well as structural contour maps. Analysis of log data was performed with PETRA, Quattro Pro X4 and Excel 2010 spreadsheet software, and DeltaGraph 5 graphic presentation software.

Objectives and General Methodology for Supercritical CO_2 Injection Testing

Supercritical CO_2 injection testing was focused on the Gunter, the section within the Knox with the highest permeability and porosity. The Gunter was mechanically isolated from the underlying Copper Ridge by cement plugs, and isolated from the overlying Beekmantown by a segment of casing cemented in the wellbore. Heated liquid CO_2 was pumped into the wellbore, becoming supercritical CO_2 in the wellbore at a depth of about 884 m because heat and pressure in the wellbore exceeded the CO_2 critical point. Temperature and pressure surveys were recorded in the wellbore before and after CO_2 injection to determine its placement and distribution in the Gunter. Pressure in the wellbore was recorded throughout the test. Pressure transient analysis was employed to determine in situ reservoir characteristics and response to CO_2 injection. Wellbore diagrams, daily operations reports, and pressure transient analysis report are in Appendix 2.

RESULTS AND DISCUSSION

Evaluation of Porosity and Permeability in the Knox

The Knox porosity system is a complex of (1) primary dolomite intercrystalline porosity and relic primary porosity associated with stromatolites, (2) vugs, fractures and solution-enhanced fractures, (3) siliceous fabrics of microporous chert and moldic and interparticle pores associated with silicified peloidal grainstones, and (4) intergranular porosity in sandstone facies, primarily in the Gunter, enhanced by dissolution of the dolomite matrix (Figs. 8A-D, 9A). Horizontal porosity and permeability were measured under ambient conditions in 34 horizontal core plugs selected from whole cores acquired during the Phase 1 evaluation program to represent the range of lithologies in the Knox, and in the 20 rotary sidewall cores from the Gunter as part of this evaluation (Fig 8). Porosity ranged from 0.3% in the densest dolomite intervals in the Beekmantown to 23.3% in the Gunter sandstone, and permeability ranged from 0.0003–580 md (Fig. 8). Porosity and permeability measured in core plugs and sidewall cores from the Phase 2 test interval range from 0.7–7.2% porosity and 0.0003–1.17 md permeability in dolomite samples to 1.1–23.3% porosity and 0.17–1570 md permeability in sandstone samples.

Correlation of horizontal porosity and permeability was excellent (Fig. 9A–B). Vertical porosity and permeability were measured under ambient conditions in 12 core plugs adjacent to horizontal core plug locations (Fig. 10): seven in the Beekmantown, two in the Gunter, and one in the Copper Ridge. All but one of the Beekmantown core plugs were from intervals with vugs visible in photographs, although not pervasively vuggy. Vertical porosity ranged from 0.8% in a dense Copper Ridge dolomite to 10.6% in a Gunter sandstone, and vertical permeability ranged 0.0009–15.0 md (Fig. 10). Vertical porosity and permeability are poorly correlated (Fig. 11), although horizontal porosity and vertical porosity are well correlated (Fig. 12A) as are horizontal permeability and vertical permeability (Fig. 12B), suggesting that although vugs may be large, and vuggy intervals having higher porosity than non-vuggy intervals, vugs are poorly connected and thus have disproportionally lower permeability. Although natural fractures in the Knox may enhance its CO_2 storage capacity, the contribution to the total porosity system cannot be quantified.

Modeling Porosity from the Compensated Density/Photoelectric Log

Evaluation of porosity from electric logs recorded through the Knox required careful attention to borehole rugosity through the Beekmantown and basal Copper Ridge sections, as well as the sand–dolomite interbeds in the Gunter. In this study porosity in the Knox was calculated from the compensated density/photoelectric (density/PE) log. Dolomite matrix density was determined as the highest recorded density value for non-porous dolomite of 2.84 g/cm^3, the value typically measured in dolomite samples (Gearhart-Owen Industries, Inc., 1976). Gunter grain density was determined from crossplots of density and PE logs compared to grain density calculated from x-ray diffraction analysis (XRD) of a core plug, assuming a non-porous sandstone with a dolomite matrix. Gunter sandstone grain density was determined to be 2.69 g/cm^3. Measured formation fluid density used to calculate porosity was 1.05 g/cm^3 for water of 97,000 ppm NaCl at 100°F (Gearhart-Owen Industries, Inc., 1976). Porosity (in percent) was then calculated from the density log:

$$\varphi_d = ([\rho_{ma} - \rho_b] / [\rho_{ma} - \rho_f]) * 100 \qquad (1)$$

where φ_d is the porosity calculated from the density log, ρ_{ma} is the formation grain density appropriate for the lithology under analysis, ρ_b is the formation bulk density recorded by the density log, and ρ_f is the formation water density.

Porosity calculated from the density log and porosity measured in core plugs and sidewall cores is shown in Figure 13. Porosity is bimodal, with a peak at 4.5% and smaller peak at 13.5% interpreted as vuggy porosity. Compaction reduces porosity in the Knox section by about 6.2% per kilometer of burial (Fig. 14). There is a good correlation between porosity measured in core plugs and sidewall cores and porosity calculated from the density log (Fig. 15), although with considerable scatter of values. Calculated mean porosity of the Knox section is 6.5% where rugose wellbore intervals greater than 27 cm in diameter (approximately 6.3 cm larger than the drill bit diameter) are included (Fig. 13), and 6.4% if rugose intervals are excluded from the mean. Excluding the rugose wellbore intervals, mean porosity of the Beekmantown is 6.4% , the Gunter is 9.0%, and the Copper Ridge is 6.2%. Borehole rugosity in the basal Copper Ridge interval from 2172–2255 m (high apparent porosity sections immediately above the Eau Claire in Fig. 13) suggests intense fracturing. This 83-m interval was evaluated using a 27 cm. borehole caliper cutoff to differentiate unfractured sections with a borehole diameter less than 27 cm from fractured sections with a rugose borehole greater than 10.5 inches in diameter. Net unfractured sections total 56 m of the interval, and net fractured sections total 27 m. Mean porosity of unfractured sections is 6.6% with the porosity of balance of the interval being unknown.

Modeling Permeability in the Knox

An industry-standard 7%-porosity cutoff (Medina et al., 2011) was used to evaluate the subsurface CO_2 storage volume in the Phase 1 and Phase 2 test intervals. Mean Knox reservoir porosity at the 7%-porosity cutoff was 9.6%, and net reservoir height was 386 m. Mean porosity in the Phase 1 effective test interval at 1152–1753 m was 9.6% (Fig. 13), and the net reservoir height for the interval is 241 m. Mean porosity in the Gunter Phase 2 test interval at 1536–1606 m at a 7%-porosity cutoff is 11.0%, with a net reservoir height of 50.3 m (Fig. 16). Mean air permeability for the CO_2 storage reservoir was calculated from the permeability/porosity regression in Figure 9A:

$$k_{calc} = 0.00092 * e^{0.80 * \varphi} \tag{2}$$

where k_{calc} is air permeability in md and φ is the mean net percent porosity for the reservoir interval calculated from the density log ($R^2 = 0.68$, $p < 0.0001$). Mean air permeability calculated for the Phase 1 test interval was 2.0 md. Realistically, this permeability value is too low to explain the pressure record from the injection test (Appendix 2). Mean air permeability was calculated for the Phase 2 test interval from the permeability/porosity regression in Figure 25B:

$$k_{calc} = 0.0017 * e^{0.83 * \varphi} \tag{3}$$

where k_{calc} is air permeability in md and φ is the mean net percent porosity for the reservoir interval calculated from the density log ($R^2 = 0.73$, $p < 0.0001$). A mean air permeability of 15.7 md was calculated for the Phase 2 test interval.

In contrast to permeability modeled by correlation to porosity, permeability of the Phase 1 and Phase 2 test intervals were calculated from pressure transient analysis (Appendix 2C). Permeability of the Phase 1 injection test interval was calculated by a homogeneous model with constant skin and no boundaries and a complex reservoir, two-porosity system model with perpendicular boundaries. In both models post-injection pressure falloff was best matched with a test interval permeability of 9.3 md. A second complex reservoir assuming a two-porosity system with a 60° angle between boundaries yielded a test-interval permeability of 14 md (Appendix 2C). All three models match the pressure-falloff record, thus the permeability of the Phase 1 test interval is probably lies in the range of 9.3–14 md. Permeability in the Gunter Phase 2 injection test interval was calculated from the post-injection pressure falloff by a homogeneous model with constant skin and no boundaries and a complex reservoir, two-porosity system model without boundaries. In both models the calculated permeability of the test interval was 12.5 md (Appendix 2C).

Contributions to Total Porosity by the Knox Fracture System

Fractures can contribute significantly to reservoir porosity, but contribute little to total reservoir flow capacity (Warren and Root, 1963). Understanding the origin and timing of fractures, however, is necessary to reliably predict fracture attributes and there effects on fluid flow in a reservoir (Gale and Gomez, 2007). Several generations of fractures were observed in Knox cores from the Marvin Blan No. 1 during the Phase 1 evaluation (Fig. 17A–D). These included near-vertical mineralized fractures ranging from a few inches to several feet long cross-cut by later mineralized fractures (Fig. 17A), near-vertical solution-enhanced fractures (Fig. 17B), mineralized primary solution-collapse fractures breccias (Fig. 17C), and late-generation open and partially-mineralized fractures (Fig. 17D). Well-developed system of 105 open and partially-open fractures contributing to total Knox reservoir porosity were identified and their structural attitudes interpreted from the image log. Few open fractures were identified in the

Beekmantown (16 fractures) and Gunter (12 fractures) compared to those identified in the Copper Ridge (77 fractures). Although mineralized fractures were observed in the cores, no mineralized fractures were interpreted in the Knox from the image log. In the Beekmantown–Gunter section, fractures were found in the upper and lower Beekmantown and in the Gunter (Fig. 18A), with no fractures identified in the middle Beekmantown (Fig. 18B-C).

Mean dip of Beekmantown–Gunter fractures is 69°/ S26°W (Fig. 18A). Fractures dip to the south in the Beekmantown above 1,524 m, and occur in intervals of conjugate north–south dipping fractures in the basal Beekmantown to the base of the Copper Ridge (Fig. 18B-C). Most of the fractures identified in the Copper Ridge (61 fractures) were found in the lower 396 m of section, below 1859 m (Fig. 18B-C). Copper Ridge fractures generally occur in three orientations: conjugate fracture sets dipping 68°/ N20°E and 69°/ S11° W, and a minor conjugate set dipping 68°/ N12°W (Fig. 18A). Open Knox fractures appear to be late-stage shear conjugates oriented to the contemporary regional horizontal stress field. The regional stress field in the southern Illinois basin in western Kentucky, southwest Indiana, and southeast Illinois is oriented approximately east–west (Sbar and Sykes, 1973; Zoback and Zoback, 1980, 1981; Crampin, 1987; Nelson and Bauer, 1987; Heidbach et al., 2008). In southern Indiana, coal mine stress faults trend N85°W (Ault et al., 1985) and cleats in the Danville Coal trend N80°E (Solano-Acosta et al., 2007), both paralleling the contemporary regional stress field.

Laubach et al. (2004) questioned whether open fractures were necessarily aligned with maximum horizontal stress, and suggested that open fractures may also be relicts of past stress field. Although the open fractures in the Knox are aligned with the contemporary stress field, the mineralized fractures may not be. Orientations of the mineralized fractures observed in Knox cores from the Marvin Blan No. 1 are not available, however orientations of mineralized fractures were interpreted from the image log in the underlying Middle Run section. Mineralized fractures have a mean trend of N55°W, with conjugate sets oriented N24°W and N74°E. Nearly all mineralized fractures in the Middle Run dip 54°–58° to the southwest. Continental convergence along the Mississippian Alleghenian front caused fracturing oriented along a northwest principal stress axis in Mississippian and older Midcontinent strata (Engelder and Geiser, 1980; Engelder, 1987; Craddock and van der Plujim, 1989; van der Plujim and Craddock, 1996; Lacombe, 2010). Orientation of mineralized fractures in the Middle Run thus suggest an Alleghenian origin, and further suggests that mineralized Knox are likely also to be Alleghenian.

Knox Reservoir Pressure and Temperature in the Marvin Blan No. 1 Well

Evaluation of Subsurface Temperature and Pressure on Supercritical CO_2 Storage

Effective subsurface storage of CO_2 in deep saline reservoirs requires that reservoirs have sufficient pressure and temperature to ensure CO_2 remains in a supercritical state. Thus the reservoir must have a pressure greater than 11.7 MPa and temperature greater than 31.1 °C, the critical point of CO_2 (Freund et al., 2005). Where either the pressure or temperature in the storage reservoir falls below these values, CO_2 will not remain in a supercritical state, but exist in a two-phase gaseous/liquid state (Freund et al., 2005). Therefore the reservoir depth required to store supercritical CO_2 will be the deeper of the critical-point value for pressure or temperature. Kentucky petroleum reservoirs are typically normally pressured, with pressure increasing with depth at the hydrostatic gradient of 9.8 kPa/m, to slightly underpressured. Thus a reservoir at hydrostatic pressure will need to be deeper than 754 m to store CO_2 in a supercritical state. The average geothermal gradient in the subsurface of western Kentucky is 22 °C per kilometer of depth, however, suggesting a minimum depth to store supercritical CO_2 in western Kentucky of about 860 m to reach the 31.1 °C critical temperature.

Long-term Pressure/Temperature Record from the Marvin Blan No. 1 Well

A long-term pressure gauge was recovered from the Marvin Blan No. 1 and static temperature and pressure log was recorded in the Marvin Blan No. 1 after it had been shut-in for a year, before any subsequent work in the well during the Phase 2 evaluation. During this period the wellbore was open from the casing shoe at 1116 m to its filled depth at 2376 m. The Knox reservoir was found to be underpressured. At the top of the Knox at 1152 m the reservoir pressure was 11.1 MPa (pressure gradient of 9.6 kPa/m). Static fluid level in the wellbore after re-entry stood at 32 m. The expected pressure at 1152 m was 11.7 MPa in a reservoir with 60,000 ppm TDS fluid (pressure gradient of 10.2 kPa/m). Average geothermal gradient in the Marvin Blan No. 1 calculated from the temperature log was 20 °C per kilometer of depth in the section of the wellbore above 914 m. A pressure of 7.4 MPa was recorded at 776 m and a temperature of 31.1 °C at a depth of 890 m. Reservoir temperature and pressure in the Knox at the Phase 1 average reservoir depth of 1452 m was 39.3 °C and 14.1 MPa, and 40.7 °C and 15.4 MPa at the average Phase 2 reservoir depth of 1571 m. Pressure transient analysis was conducted using the pressure records from the Phase 1 CO_2 injection test combined with this subsequent post-CO_2 injection long-term pressure falloff record (Appendix 2C) to determine reservoir properties of the Knox.

Calculation of Knox Reservoir Storage Volume

Calculating reservoir volume required to store a volume of supercritical CO_2 requires five data: porosity, reservoir height, temperature, pressure, and formation water salinity. These data were acquired by wireline electric logs, analysis of whole cores and sidewall cores, wireline temperature and pressure surveys, and analysis of formation waters prior to injection tests. Porosity was calculated from the density log after testing the quality of its record through crossplots and comparison to whole core and sidewall core analysis. Porosity calculated from the density log showed good correlation with porosity measured in the cores (Fig. 13, 15–16). Scatter in the core porosity values (Fig. 15) reflects the choice of whole core plugs and sidewall core samples to measure specific reservoir properties of the Knox from an otherwise heterogeneous lithologic sequence. Two formation water samples were collected from the Marvin Blan No. 1: one from the Gunter, and the second at the top of the Beekmantown near the unconformity with overlying middle Ordovician strata.

Supercritical CO_2 Storage Volume in Knox Reservoirs

The Phase 1 effective test interval at 1152–1753 m had a mean porosity of 9.6% at a 7%-porosity cutoff, mean permeability of 2.0 md, and net reservoir height of 241 m (Fig. 13). Effective reservoir pore volume for this interval is about 38,100 m^3 per hectare of surface. The Phase 2 test interval at 1535.6–1605.7 m, included in the Phase 1 test interval, had a mean porosity of 11.0% at the 7%-porosity cutoff, mean permeability of 15.7 md, and a net reservoir height of 50.3 m. Phase 2 reservoir pore volume is about 9100 m^3 per hectare of surface, contributing 23.9% of the total Knox pore volume tested during the Phase 1 program. Reservoir temperature and pressure in the Knox at the Phase 1 average reservoir depth of 1452 m was 39.3° C and 14.1 MPa, and 40.7 °C and 15.4 MPa at the average Phase 2 reservoir depth of 1571 m. For this evaluation, reservoir water salinity is assumed to be 100,000 ppm NaCl, approximately the salinity of water recovered from the Gunter. Density of CO_2 under average reservoir conditions (DeSimone, 2002) for the Phase 1 testing is 760 kg/m^3, and 790 kg/ m^3 under Phase 2 reservoir conditions.

CO_2 storage volume in the Knox was calculated using efficiencies for dolomite and clastic reservoirs from U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory (2010), weighted for the relative contributions of the dolomite sections and Gunter sandstone to the total reservoir volume. The P_{50} (most likely) efficiency factor for the Knox, is 19.3%, with a range of 14.0% (P_{10}) to 25.5% (P_{90}). Efficiency factors for clastic reservoirs are 7.4% (P_{10}) to 24.0% (P_{90}), with a most likely efficiency factor of 14.0% (U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, 2010). Thus, calculated storage volume in Phase 1 test interval, including the Gunter, ranges from about 5330 m^3 per surface hectare (P_{10}) to 9710 m^3 per surface hectare (P_{90}), with a most likely volume of 7350 m^3 per hectare of the surface. By itself, storage volume in the Gunter Phase 2 test interval ranges from about 670 m^3 per surface hectare (P_{10}) to 2180 m^3 per surface hectare (P_{90}), with a most likely volume of 1270 m^3 per hectare of the surface. Supercritical CO_2 storage volume, then, is about 3940–7185 tonnes per surface hectare in the Phase 1 Knox section encountered in the Marvin Blan No. 1 well, with a most-likely storage volume of 5440 tonnes per surface hectare. With the higher density of supercritical CO_2 at Phase 2 reservoir conditions in the Gunter, estimated storage volume is 530–1720 tonnes per surface hectare, with a most-likely storage volume of 1000 tonnes per surface hectare. In the most-likely case, the Gunter contributes 18% of the total storage volume in the Knox. Thus, the most likely area required to store 1 million tonnes of supercritical CO_2 in a Knox section comparable to the Phase 1 test interval is 184 hectares (455 acres), and 1000 hectares (2470 acres, or about 4 mi^2) for a Gunter section comparable to the Phase 2 test section.

Separate most-likely cases were developed for supercritical CO_2 storage capacity in the Beekmantown and Copper Ridge sections encountered in the Marvin Blan No. 1 well. Mean porosity of the Beekmantown at the 7%-porosity cutoff is 9.3% and net reservoir height is 137 m, thus the reservoir pore volume is about 20,730 m^3 per surface hectare. At an average reservoir depth of 1352 m, the formation temperature in the Beekmantown is 38.3 °C and pressure is 13.1 MPa. Supercritical CO_2 density under these conditions (DeSimone, 2002) is about 740 kg/m^3. The most likely storage efficiency in dolomite reservoirs is 21% (U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, 2010), thus the most-likely supercritical CO_2 storage capacity of the Beekmantown is about 3220 tonnes per surface hectare, and about 310 surface hectares (766 acres) would be required to store 1 million tonnes of CO_2. The Copper Ridge, excluding fractured intervals near its base, has a mean porosity of 9.4% and a net reservoir height of 181 m. Reservoir volume is 27,875 m^3 per surface hectare. At an average reservoir depth of 1942 m in the Copper Ridge, formation temperature is 44.4 °C and pressure is 19.3 MPa. Supercritical CO_2 density under these reservoir conditions (DeSimone, 2002) is about 800 kg/m^3. Most-likely supercritical CO_2 storage capacity in the Copper Ridge dolomite section is about 4680 tonnes per surface hectare, thus about 215 surface hectares (530 acres) would be required to store 1 million tonnes of supercritical CO_2.

A most-likely case assuming the entire Knox section encountered in the Marvin Blan No. 1 well, excluding the fractured Copper Ridge section, was available for supercritical CO_2 storage cannot be made by simply adding the individual cases for the Beekmantown, Gunter, and Copper Ridge because of the difference in the supercritical CO_2 density at the average reservoir conditions of temperature and pressure in the Knox section as a whole. Pore volume is additive, however, thus the total Knox reservoir pore volume is 55,955 m^3 per surface hectare. At an average reservoir depth of 1703 m, temperature is 42.2 °C and pressure is 16.8 MPa, and the density of supercritical CO_2 (DeSimone, 2002) is 780 kg/m^3. Weighted P_{50} storage efficiency, in this case where the Gunter contributes about 16% of the total storage volume, is 19.9%. Thus, if the entire Knox section encountered in the Marvin Blan No. 1 well is considered, excluding fractured sections near the base of the Copper Ridge, supercritical CO_2 storage capacity would be about 8685 tonnes per surface hectare and the surface area required to store 1 million tonnes of supercritical CO_2 thus reduced to about 115 hectares (284 acres).

Determination of Reservoir Sealing Capacity

Deriving Sealing Capacity from Threshold Entry Pressure and Permeability

Sealing capacity of strata overlying the Knox was calculated from laboratory core analyses acquired during the Phase 1 testing program (Appendix 1B–1F). Primary sealing strata tested in the Marvin Blan No. 1 include the Ordovician Black River carbonates and Maquoketa shales, and their stratigraphic equivalents overlying the Knox and its stratigraphic equivalents (Harris, 2007; see Swezey, 2009, for details of the correlations). The Devonian New Albany (Fig. 2) may act as a secondary seal for CO_2 storage in deeper saline reservoirs (Finley, 2005; U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, 2007, 2008, 2010), but was not evaluated in this study because of its shallow depth in Hancock County. Thick, impermeable intervals within the Knox may also act as reservoir seals, although there is an increased risk for leakage from the natural fracture system in the Knox (Finley, 2005; this study).

Sealing capacity of strata was determined by two methods in this study: mercury-injection capillary pressure tests (Dewhurst et al., 2002; Gibson-Poole, 2009)(Fig. 19), or from permeability measured in core plugs (Thomas, 1967; Li et al., 2005)(Fig. 20A–B). Either of these methods can accurately identify the point where the threshold pressure of the seal is reached and the reservoir seal rock has failed (Dewhurst et al., 2002; Gibson-Poole, 2009). Mercury-injection capillary injection tests were made on four horizontal core plugs from the Beekmantown and one from the Gunter, all with prior permeability and porosity measurements (Fig. 19) . Threshold pressure relative to N_2 or air is determined from mercury-injection capillary pressure where there is a large gradient increase in incremental pore volume of the capillary pressure curve (Dewhurst et al., 2002)(Fig. 19). Threshold pressures determined from mercury-injection capillary pressure tests range from 6.5–200.4 Mpa.

Threshold pressure to N_2 or air is calculated from permeability measured in core plugs by the relationship established from 57 measurements from the literature (Fig. 20A):

$$P_T N_2 = (e^{3.02} * k_{seal}^{-0.434}) \quad (4)$$

where P_T is the threshold pressure in psi in reference to N_2 or air, and k_{seal} is permeability in millidarcies ($R^2 = 0.96$, $p < 0.0001$). Because the pressure unit of these measurements are in relationship to air or N_2, threshold pressures must be converted to the equivalent of a pressure in relationship to supercritical CO_2 (Dewhurst et al., 2002). Mean pressure given in relationship to supercritical CO_2 is 42.7% of that measured in relationship to air or N_2 (Fig. 20B), thus

$$P_T = (0.427 * (e^{3.02} * k^{-0.434})) \quad (5)$$

where P_{TSCO2} is the threshold pressure to supercritical CO_2 in psi. The supercritical CO_2 threshold pressure for the Phase 1 test interval was calculated to be 15.2 psi (0.105 MPa), and 6.2 psi (0.43 MPa) for the Phase 2 test interval.

The maximum column of supercritical CO_2 that the strata can support (sealing capacity) is calculated by equation 5 (adapted from Smith,1966, equation 9, for supercritical CO_2):

$$h_{SCO2} \max = ((P_{dB} - P_{dR}) / ([\rho_f - \rho_{SCO2}] * 0.433)) * 0.3048 \quad (6)$$

where h_{SCO2} max is the maximum vertical column of supercritical CO_2 in meters that can be sealed, P_{dB} is the supercritical CO_2 threshold pressure of the seal in psi, P_{dR} is the supercritical CO_2 threshold pressure in the storage reservoir in psi, ρ_f is the Knox reservoir water density of 1.05 g/cm^3, ρ_{SCO2} is the density of the supercritical CO_2 of 0.80 g/cm^3 under conditions of temperature and pressure at the average Phase 1 reservoir depth of 1452 m, and 0.78 g/cm^3 at the average Phase 2 reservoir depth of 1571 m (Freund et al., 2005), and 0.433 is the gravitational constant. Therefore, for this evaluation, P_{dR} is assumed to be zero. Substituting equation 5 for P_{dB} and P_{dR} to place threshold pressures in terms of permeability, equation 6 can be re-written as:

$$h_{SCO2} \text{ max} = (0.427 * ([e^{3.02} * k_{seal}^{-0.434}] - [e^{3.02} * k_{res}^{-0.434}] / [\{\rho_f - \rho_{SCO2}\} * 0.433])) * 0.3048 \qquad (7)$$

where h_{SCO2} max is the sealing capacity in meters, k_{seal} is the permeability of the sealing strata in millidarcies and k_{res} is the permeability of the reservoir interval in millidarcies. Equation 7 was solved for h_{SCO2}max at a range of k_{seal} values over several orders of magnitude (Fig. 21), and k_{res} and ρ_f and ρ_{SCO2} values of the Phase 1 and Phase 2 test reservoirs. At $k_{seal} < 0.001$ md, h_{SCO2} max values for the Phase 1 and Phase 2 tests are approximately equal (Fig. 21), thus for subsequent analyses and discussion Phase 1 values of k_{seal}, k_{res} (2.0 md, above), and h_{SCO2} max were assumed (Fig. 22).

Knox Group, Basal Dutchtown Limestone, and Black River Group

Dense dolomite sections in the Knox may provide effective seals against the vertical migration of supercritical CO_2 from storage intervals. Vertical core plugs chosen as representative of intraformational reservoir seals within the Knox had porosity of 1.3–9.8% and permeability to air of 0.0009–0.063 md (Appendix 1). Supercritical CO_2 seal capacity calculated by equation 7 range from 12 m in a sample from the Beekmantown to 500 m for a sample from the Copper Ridge (Fig. 22). Six vertical core plugs from the Beekmantown at 1155.7–1180.8 m had calculated supercritical CO_2 seal capacities of 12–439 m (39–1440 ft). The overlying basal Dutchtown Limestone was cored at 1146 m to the top of the Knox at 1152 m. This section largely consisted of gray dolomitized algal thrombolites with scattered very thin sands. A vertical core plug from the basal Dutchtown dolomitic section at 1025.1 m was analyzed to determine reservoir sealing properties. Porosity was 3.9% and permeability to air was 0.0011 md, yielding a supercritical CO_2 seal capacity of 457 m (1498 ft)(Fig. 9, 22).

The Black River provides a primary reservoir seal for the St. Peter and deeper reservoirs in Kentucky (Harris, 2007). It was penetrated at 952–1066 m in the Marvin Blan No. 1, overlain by a thick Maquoketa shale section, and cored at 1016.6–1034.8 m. Lithology in this core was gray limestone that parted along bioturbated, crinkly bedding planes. XRD analysis of one sample showed it to consist of 97% calcite, 2% quartz, and 1% clays. Triaxial compressive rock-strength and ultrasonic velocity tests were made on two plugs from the Black River (Appendix 1). Compressive strength averaged 52.1 Mpa. The entire Black River section shows borehole rugosity on the caliper log, however, suggesting pervasive fracture development. A vertical core plug from the Black River at 1025.1 m was analyzed for its reservoir sealing properties (Fig. 9). Its porosity was 0.4% and permeability was 0.0009 md. Supercritical CO_2 seal capacity calculated for this core plug was 500 m (1,640 ft)(Fig. 22).

Maquoketa Shale

The Late Ordovician Maquoketa shale, the lower interval of the Maquoketa Formation, is a low-permeability groundwater-confining unit throughout the Midwest (Young, 1992a, 1992b), and is considered a primary reservoir seal for CO_2 storage in underlying reservoirs (Finley, 2005; U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, 2007, 2008, 2010). The Marvin Blan No.1 penetrated the subsurface Sebree Trough, a Midcontinent paleogeographic feature of the middle to upper Ordovician section (Kolata et al., 2001; McLaughlin et al., 2004; Ettensohn, 2003), at a location where the Trenton was absent and a thick section of Maquoketa was present. It penetrated 103 m of shale in the Maquoketa at 849.5–952.5 m, in contrast to the 65-m thick section overlying the Trenton Group penetrated in the Braden No. 1 well, 26 km to the southeast.

The Maquoketa shale section was cored in the Marvin Blan No. 1 at 853.4–862.9 m. Analyses of this core included descriptions and facies interpretation, laboratory analyses, thin section photomicrographs, and CT scan photographs (Appendix 1B–1F). Two facies were described in the core: a dark gray, calcareous, silty fissile shale with carbonate-rich concretionary layers 2.5–12.7 cm thick, and a dark gray, slightly calcareous, silty, fissile shale. CT scans show natural fractures, partings from core recovery and transport to the lab, calcareous layers, and organic-rich intervals. Laboratory analyses performed on 11 vertical plugs from the Maquoketa, taken at approximately 1-meter intervals from the top to the base of the core, included routine crushed-core analysis (porosity, permeability, and bulk density analyses for very low-permeability rocks), XRD, and total organic carbon (TOC). XRD analysis showed most plugs to be mudstone or clayey mudstone with 25–75% clays. Dominant minerals are illite-chlorite, calcite, and quartz. TOC measured in the Maquoketa plugs was low, averaging 0.57%, and no sample exceeded 1 percent TOC (Fig. 23A–B). Permeability of the 11 vertical core plugs ranged from $3.29 x 10^{-7}$ md to $5.28 x 10^{-5}$ md, and porosity ranged from 3.7–7.0%. Supercritical CO_2 seal capacity calculated for these core plugs ranged were 1756–16,056 m (5,760–52,676 ft)(Fig. 22). Rock mechanical measurements were made on two separate core plugs. Triaxial compressive strength testing of a representative sample from the Maquoketa yielded a compressive strength of 119.0 MPa.

Testing Supercritical CO_2 Injection in the Knox

Injection testing was completed in two phases: Phase 1 (summer 2009) tested the entire Knox 1100 m-section in the open borehole at 1152–2255 m below casing at 1116 m, whereas Phase 2 (summer 2010) tested a mechanically isolated a 70 m-section of the Gunter at 1535.6–1605.7 m. During Phase 1 testing, several intervals in the Knox were identified as potential CO_2 storage reservoirs by injection tests with fresh water mixed Bio-31™ KCl substitute, followed by the injection of supercritical CO_2. After CO_2 injection, additional water was injected prior to temporary well abandonment. Total brine injected during the two phases of testing was 3612 m^3 (22,719 barrels)(bbl), and 626 tonnes of supercritical CO_2 (632.1 m^3 or 3976 bbl of liquid CO_2). The wellbore was then temporarily abandoned with a retrievable bridge plug in casing at 1105 m between Phase 1 and Phase 2 testing with two downhole pressure-temperature monitoring gauges were set in place below the bridge plug. Pressure and temperature data were recorded every minute for slightly more than a year, providing a unique record of subsurface reservoir conditions in the Knox. Operations in the Phase 2 testing program commenced with retrieval of the bridge plug and long-term pressure gauges, followed by mechanical isolation of the Gunter for injection testing. Following the completion of testing, the injection zone below casing at 1116 m in the Marvin Blan No. 1 well was permanently abandoned with cement plugs and the wellsite reclaimed.

Phase 1 Testing (2009)

Phase 1 testing commenced with a step rate test to determine the fracture gradient in the Knox, then a baseline temperature survey followed by the recovery of two formation water samples from the Knox. The fracture gradient test was performed at 2188–2272 m and yield a fracture gradient of 20.4 kPa/m. Water samples were recovered from the Gunter at 1561–1568 m and the uppermost Beekmantown at 1158–1165 m. Initial tests, injecting water mixed with Bio-31™ KCl substitute into short intervals using straddle packers on tubing, had mixed results. Two tests of the upper Copper Ridge were attempted at 1681–1765 m and 1656–1746 m. Both tests failed shortly after the pumping began at a 0.32 m^3/min (2 BPM) rate because of communication around the packers through the strata. Better injection tests were obtained by injecting into the open wellbore below a single packer. Injection rates up to 2.2 m^3/min (14 BPM) were achieved, with wellhead pressures of 2.0–3.8 MPa. The Beekmantown, interbedded Gunter, and uppermost section of the underlying Copper Ridge were identified as the principal reservoirs in the well. Temperature logs showed 70 percent of the injected brine went into the Beekmantown-Gunter interval. Injection of a 0.85 kg/l borax tracer solution and monitoring with pulsed neutron and spinner logs confirmed these results. A total of 2934 m^3 (18,454 bbl) of brine and borax solution was injected during this testing phase. Following injection tests with water, a total of 293 tonnes of CO_2 (280.6 m^3 of liquidCO_2) heated to about 40 °C were injected at the pumping equipment maximum rate of 4.1 BPM. Wellhead pressure was 6.5 Mpa, with bottom-hole pressure of 12.1 Mpa. A post-injection temperature survey showed most of the injected CO_2 was displaced into the lowermost Beekmantown and the Gunter below 1463 m, with the deepest injection point for CO_2 at about 1753 m, 122 m below the top of the Copper Ridge (Fig. 13). This would suggest that only the upper Knox section is prospective for CO_2 storage. Following completion of CO_2 injection, a small volume of water was injected to displace CO_2 out of the wellbore, and the well was temporarily abandoned.

Phase 2 Testing (2010)

Wellbore diagrams, daily operations reports, and pressure transient analysis reports for the Phase 2 testing program are in Appendix 2. Phase 2 injection testing, this study, focused on the Gunter, the highest porosity and permeability section within the Knox, in a mechanically isolated interval of the wellbore at 1534.6–1605.6 m (Fig. 16). This interval was mechanically isolated to ensure a good packer seal during injection testing and thus mitigate wellbore pressure communication issues encountered during Phase 1 testing. Isolation was accomplished by setting a cement plug at 1605.6–1609.1 m, and cementing 14-cm casing in the open wellbore at 1469.4–1535.6 m. The injection program was similar to the Phase 1 injection program, with water being injected before and after CO_2 injection. Prior to CO_2 injection, 93.7 m^3 (589 bbl) of 2% KCl water were injected during a step-rate test. A total of 333 tonnes of CO_2 (351.5 m^3 of liquid CO_2) heated to about 40 °C were injected at a rate of 0.4 m^3/min (2.5 BPM) with a surface pressure of 6.4 MPa and a bottom hole pressure of 17.5 MPa at 1545.3 m. Final injection pressures at the conclusion of the CO_2 injection were 6.1 MPa at the surface and a bottom hole pressure of 17.5 MPa. Following CO_2 injection, 584 m^3 (3,676 bbl) of 2% KCl water was injected to displace CO_2 in the Gunter. Pressure falloff was monitored for 12 hrs after the completion of water injection, then a differential temperature log was recorded across the injection interval to verify CO_2 placement (Fig. 16). Most CO_2 was displaced into the thick, lower sand section in the sandy member of the Gunter (Fig. 16). The wellbore was subsequently abandoned with cement plugs at 1535–1608 m, 1060–1202 m, and 305–366 m and the wellsite was reclaimed.

Discussion

The range of storage capacities found in the Knox in the Marvin Blan No. 1 is 2194 tonnes/hectare in the Phase 2 Gunter interval to 14,849 tonnes/hectare for the entire Knox section. This discussion will largely focus on the Phase 1 storage capacity of 9711 tonnes/hectare of surface area. By itself the Gunter lacks sufficient reservoir volume to be considered for CO_2 storage, although it may provide up to 15% of the total reservoir volume available in the Knox. Although the thicker section of Copper Ridge makes it the largest contributor to overall Knox storage capacity, providing slightly less than half of the potential supercritical CO_2 storage volume, its low net reservoir height versus gross interval thickness of 0.29 suggests that potential reservoir intervals will be widely distributed within the section (Fig. 13). Porosity distribution in the Beekmantown is much like the Copper Ridge (net-to-gross ratio 0.34; Fig. 13). The Gunter, by comparison, has a net-to-gross ratio of 0.74 reflective of porous sands occurring in a relatively thin section (Fig. 16). Phase 1 and Phase 2 injection tests demonstrated that most supercritical CO_2 was displaced into porous and permeable sections of the lowermost Beekmantown below 1463 m (Fig. 13) and Gunter (Fig. 13, 16). This would suggest that only the upper Knox section is prospective for CO_2 storage. The Phase 1 CO_2 injection test design was not optimal, however, although it was expedient for cost-control purposes. Injecting CO_2 through a single tubing string into the openhole below a packer set above the top of the Knox limited the maximum depth of CO_2 injectate placement because of the relative density contrast of supercritical CO_2 (~800 kg/m^3) versus water (~1.05 kg/m^3) in the wellbore. Optimizing injection into the Knox in an industrial project will require careful engineering to achieve and balance supercritical CO_2 distribution throughout the reservoir.

Subsurface storage of supercritical phase of CO_2 in a deep saline reservoir is determined by two physical parameters: reservoir temperature and reservoir pressure. In the Marvin Blan No. 1 well, the minimum pressure of 7.4 MPa required to store CO_2 in its supercritical state was found at a depth of 776 m. The depth at which the formation temperature reached the minimum of 31.1 °C that is required to maintain CO_2 in its supercritical phase was not reached until a depth of 890 m. Thus, despite having sufficient pressure to store supercritical CO_2 at 776 m, the formation temperature dictates that the storage reservoir must be 122 m deeper. This is important because the minimum depth required to store supercritical CO_2 in the deep subsurface is the minimum depth for the base of the primary reservoir seal. That is, the base primary reservoir seal cannot be shallower than the minimum depth required ensure that any injected CO_2 remains in a supercritical phase. When diffusion of trapped CO_2 into the primary seal is considered (Park et al., 2011), the minimum for the base of the seal may be as much as an additional 50.3 m deeper, or conservatively, at 945 m.

Adequacy of Western Kentucky Sealing Strata to Ensure Long-term CO_2 Storage

Effective reservoir seals should be less than 10^{-6} md permeability (Deming, 1994; Bennion et al., 2000), although this value depends on the height of the reservoir fluid column being trapped by the seal. Within the Knox, permeabilities measured in vertical core plugs from the Beekmantown and Copper Ridge suggest that intraformational seals are capable of supporting supercritical CO_2 columns of about 418–521 m in the Knox reservoir (Fig. 22). Whether these intraformational seals may be effective is problematic, however. During Phase 1 testing, attempts to test injection intervals within the Knox using straddle packers to isolate test intervals proved ineffective because of rapid pressure communication through the isolated intervals to the wellbore annulus. Thus, the seal for CO_2 storage in the Knox has to be in overlying strata. Three stratigraphic intervals overlying the Knox in the Marvin Blan No. 1 well may provide seals for potential CO_2 storage reservoirs in western Kentucky: Dutchtown, Black River, and Maquoketa. The Dutchtown and Black River had permeabilities of approximately 10^{-3} md, suggesting that these intervals may act as secondary sealing strata. Permeability of the first of these secondary seals above the Knox, the Dutchtown, was 1.1×10^{-3} md, will support a 478-m supercritical CO_2 column (Fig. 22). The overlying Black River had rock strength of 766.3 MPa measured in a core plug, permeability of 9.0×10^{-4} md, and will support a 521-m supercritical CO_2 column. Within the 159-m thick Black River section, however, 59 m of the borehole is more than 25% larger than the diameter of the bit used to drill the wellbore as measured by the borehole caliper log, and 5.5 m of the borehole that is more than 50% larger than the bit. This raises the concern of fracturing within the section that could compromise its sealing integrity although there is likely sufficient unfractured strata in the section to act as a secondary seal.

The primary reservoir seal for the Knox is the Maquoketa. The Marvin Blan No.1 penetrated the subsurface Sebree Trough, a Midcontinent paleogeographic feature of the middle to upper Ordovician section (Kolata et al., 2001; McLaughlin et al., 2004; Ettensohn, 2003), at a location where the Trenton is absent, and a thick section of Maquoketa is present. The thick Maquoketa shale section filling the Sebree Trough plunges southwest across western Kentucky from northwest Breckinridge County into Tennessee south of Trigg County (Kolata et al., 2001). It would be a thick seal for deeper CO_2 storage reservoirs under the central area of the Western Kentucky Coal Field including Ohio, McLean, Hopkins, and Muhlenberg counties. Maximum seal capacity calculated from permeabilities measured in vertical core plugs from the Maquoketa was 1701–16,160 m (Fig. 22), far more than the net reservoir height of 241 m in the Knox. Any fluid injected into the subsurface will have injection pressure limited to some fraction of the 20.4 kPa/m (23.5 MPa at the top of the Knox) fracture gradient. Rock strength of 119.0 MPa was measured in core plugs from the Maquoketa, suggesting that it is unlikely that any CO_2 migrating from the Knox would have sufficient pressure to fracture the Maquoketa. Therefore the requirements for an effective reservoir seal for CO_2 storage in western Kentucky are well exceeded by the Maquoketa.

Regional Potential for CO_2 Storage in the Knox

Regional extrapolation based on the results of a single well test can be problematic unless corroborating evidence can be demonstrated. For evaluating the regional potential for CO_2 storage in Kentucky Knox reservoirs, evidence is sparse but not lacking. Core analysis is not available from any of the wells penetrating the Knox in the region surrounding the Marvin Blan No. 1 well. Indirect evidence of porosity and permeability can be demonstrated in the form of active saltwater-disposal and gas-storage wells injecting into the Knox, however. There is only one active EPA UIC Class I injection well in Kentucky, the IMCO Recycling International Metal No. 1 well in Butler County, and two abandoned UIC Class I wells, the DuPont wells WAD No. 1 and WAD No. 2 in Jefferson County (Fig. 1, 24). All three wells were completed for injection into the Knox. Elsewhere in the Midwest, two UIC Class I wells completed in the Knox are active in east-central Illinois, and one in northeastern Ohio (Fig. 1). The Knox is also used extensively for oilfield saltwater disposal and utility natural gas storage. For example, there are 63 saltwater disposal wells and 44 gas storage wells in Kentucky completed in the Knox (Fig. 24). About 95% of the saltwater disposal wells are located in Adair and adjacent counties, 129 km southeast of the Marvin Blan No. 1 well, and all but two of the gas storage wells are in Louisville Gas and Electric's gas storage field in Oldham County, 129 km northeast of the Marvin Blan No. 1. Outside of Kentucky, there are six active saltwater disposal wells completed in the Knox in Harrison County, Indiana, about 65 km northeast of the Marvin Blan No. 1 well, and throughout southern Indiana there are an additional nine active saltwater disposal wells and seven active gas storage wells completed in the Knox (Indiana Geological Survey, 2010). The distribution of active saltwater and gas storage wells in Kentucky and southern Indiana suggests porous and permeable Knox is present in Kentucky west of the Cincinnati Arch.

A preliminary, conservative evaluation of prospective Knox reservoirs in western Kentucky was completed for those wells penetrating the Copper Ridge (Fig. 25) and having a density log for calculating porosity. Nine wells, extending from the WAD No. 1 well on the west flank of the Cincinnati Arch to the Jimmy Bell No. 1 in the north-central Rough Creek Graben, were selected for further evaluation; of these, six penetrated the entire Knox section. It was not possible, however, to evaluate porosity in heavily fractured Knox sections where the density log was affected by borehole rugosity and recorded anomalously-low formation bulk density. Pore volume is reduced in wells east of the Marvin Blan No. 1 (Fig. 25) because of erosional truncation of the Beekmantown on the western flank of the Cincinnati Arch thinning the section. Wells west of the Marvin Blan No. 1 (Fig. 25) have Beekmantown sections comparable to the Marvin Blan No. 1, but lose pore volume in the Copper Ridge because of compaction at their greater depths (Fig. 4).

Defining the western extent of the prospective Knox CO_2 storage reservoir is both geologically and economically problematic: Is sufficient reservoir present, and does it lie at a depth where it can be economically exploited? The preliminary regional evaluation suggests that the Knox reservoir may be found throughout much of western Kentucky. The western Kentucky region suitable for CO_2 storage in the Knox is limited updip, to the east and south, by the point at which the base of the Maquoketa lies above the depth required to ensure storage of CO_2 in its supercritical state, a depth of approximately 945 m below the surface. The top of the Knox is approximately 198 m below the base of the Maquoketa in the Marvin Blan No. 1 well, at a subsea elevation of -959 m (-3,145 ft) (Fig. 25). The updip limit of the prospective region for CO_2 storage is then limited to where the Knox is below about -960 m (-3,150 ft) subsea elevation (Fig. 3). The associated issue is developing a well that is both deep enough to penetrate sufficient reservoir strata, but not so deep that the cost of drilling, completion, and operating the well is prohibitive. For this evaluation, the base of the prospective Knox reservoir is assumed to be 152 m below the effective base of the Phase 1 injection test interval, a prospective stratigraphic interval that is about 762 m thick, and the deepest a commercial well will be drilled for CO_2 storage in the Knox is about 2745 m. With an average surface elevation of 152 m in western Kentucky, the downdip limit of the prospective area will be where the top of the Knox is at a subsea elevation of -1829 m (-6,000 ft) (Fig. 25). The resulting prospective region outlined in Figure 25 has an area of approximately 15,600 km^2, and provides estimated limits beyond which it is unlikely that suitable Knox reservoirs may be developed. Mitigating this estimate is the uncertainty of faults in the subsurface, which may have the potential for CO_2 migration from the storage reservoirs and compromise sealing strata. Therefore, evaluation of faults in the prospective area will be necessary to determine whether they may act as seals for CO_2 storage or as leakage conduits, and their impact on overlying reservoir sealing intervals.

Implications for Carbon Storage in Midcontinent Carbonate Reservoirs

The results of the injection tests in the Marvin Blan No. 1 provide a basis for evaluating supercritical CO_2 storage in Cambro-Ordovician carbonate reservoirs throughout the Midcontinent. About half of the Midcontinent of the U.S. is underlain by a Cambro-Ordovician carbonate section (Fig. 26). These correlative Cambro-Ordovician strata are the Knox Group of the Illinois, Black Warrior, and Appalachian Basins, the Arbuckle Formation in Kansas and Oklahoma, and the Ellenburger Formation in Texas and southeastern New Mexico. These strata have been developed throughout the Midcontinent for oil and gas production, gas storage, and waste fluid injection. Successful CO_2 injection in the Knox in the KGS Marvin Blan No. 1 well demonstrated that deep saline reservoirs in these carbonate strata may also effectively store CO_2. Thus large sections of the Midcontinent may be suitable for geosequestration where reservoirs and sealing intervals are sufficiently deep to ensure storage of supercritical-phase CO_2.

CONCLUSIONS

The western Kentucky carbon storage tests accomplished all project goals: demonstrated that the Knox had reservoir properties suitable for storage of supercritical CO_2 in a deep saline reservoir hosted in carbonate rocks, and demonstrated the presence of strata with properties sufficient for long-term confinement of any stored supercritical CO_2 in the deep subsurface. Initial evaluation of the Knox in the Marvin Blan No. 1 and other wells drilled into the Knox suggest that large areas of western Kentucky may have reservoirs with CO_2 storage potential. Estimated CO_2 storage capacity in the Knox section in the Marvin Blan No. 1 well is about 9700 tonnes of supercritical CO_2 per surface hectare of reservoir. Therefore, a CO_2 storage well comparable to the Marvin Blan No. 1 would require approximately 103 surface hectares to store 1 million tonnes of CO_2. Further evaluation of the Knox and its correlative strata is required to determine its ultimate CO_2 storage capacity in the Midcontinent underlain by Cambro-Ordovician carbonate rocks.

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GRAPHICAL MATERIALS

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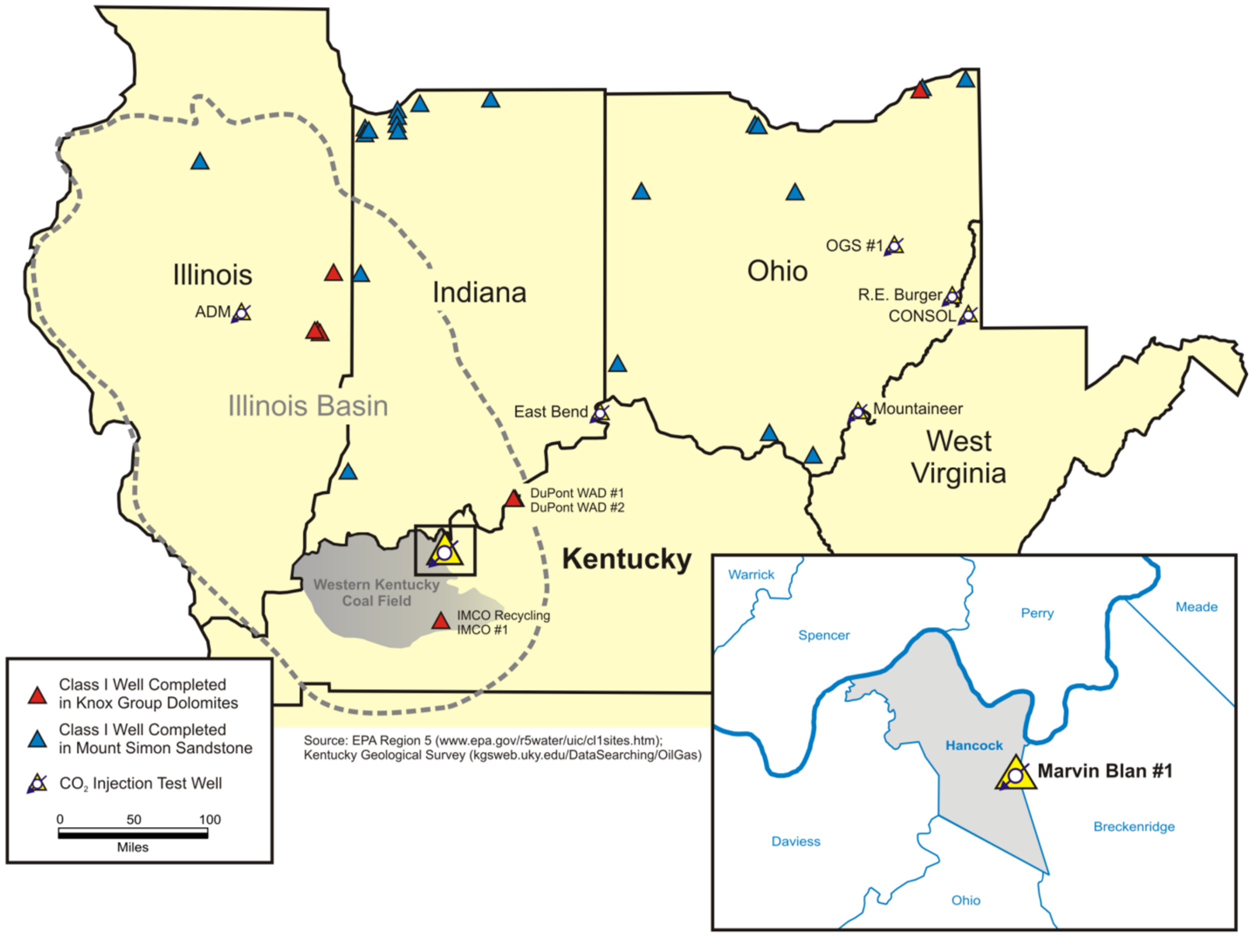

Figure 1. Location of the Marvin Blan No. 1 well, east-central Hancock County, Kentucky (yellow triangle). The Marvin Blan No. 1 lies on the eastern margin of the Western Kentucky Coal Field, southern Illinois Basin.

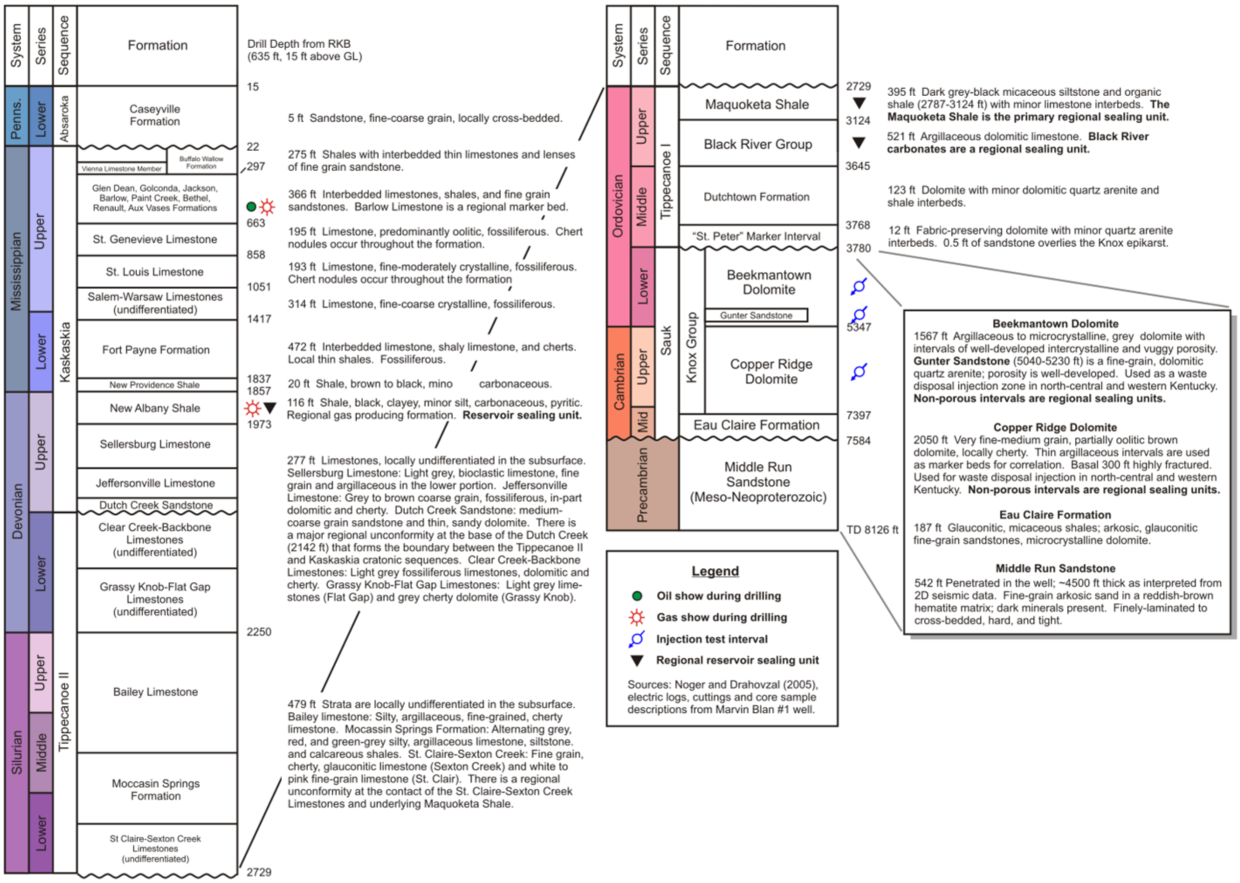

Figure 2. Generalized stratigraphy of the Marvin Blan No. 1 (adapted from Swezey, 2009). Regional reservoir sealing intervals (inverted black triangles) were cored in the Upper Devonian New Albany Shale and Upper Ordovician Maquoketa Shale and Black River Group. Intraformational seals were cored in the Upper Cambrian to Lower Ordovician Knox Group. Potential reservoir intervals were cored and tested in the Knox in the Beekmantown Dolomite, Gunter Sandstone, and Copper Ridge Dolomite. Oil and gas shows were encountered during drilling in the Upper Mississippian Aux Vases Formation and gas shows in the New Albany.

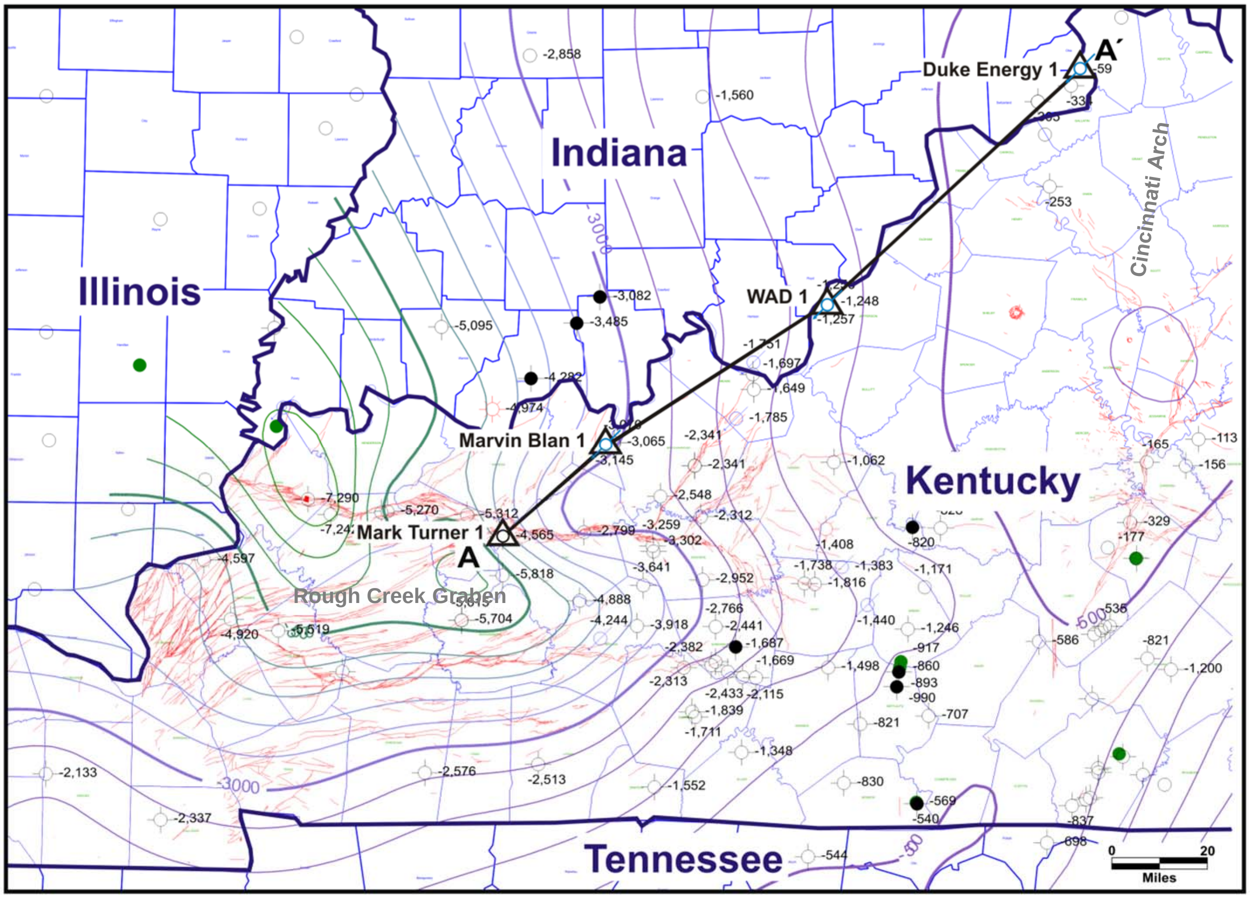

Figure 3. Generalized structural contours on top of they Knox Group from the Cincinnati Arch to southwest Illinois Basin. Surface faults are mapped in red. Subsea elevation of the top of the Knox is posted to the right of the well symbols. The top of the Knox is an unconformity developed during at the base of the Middle Ordovician section. The Knox dips about 0.75º west, whereas strata above the Knox unconformity dip about 0.5º west.

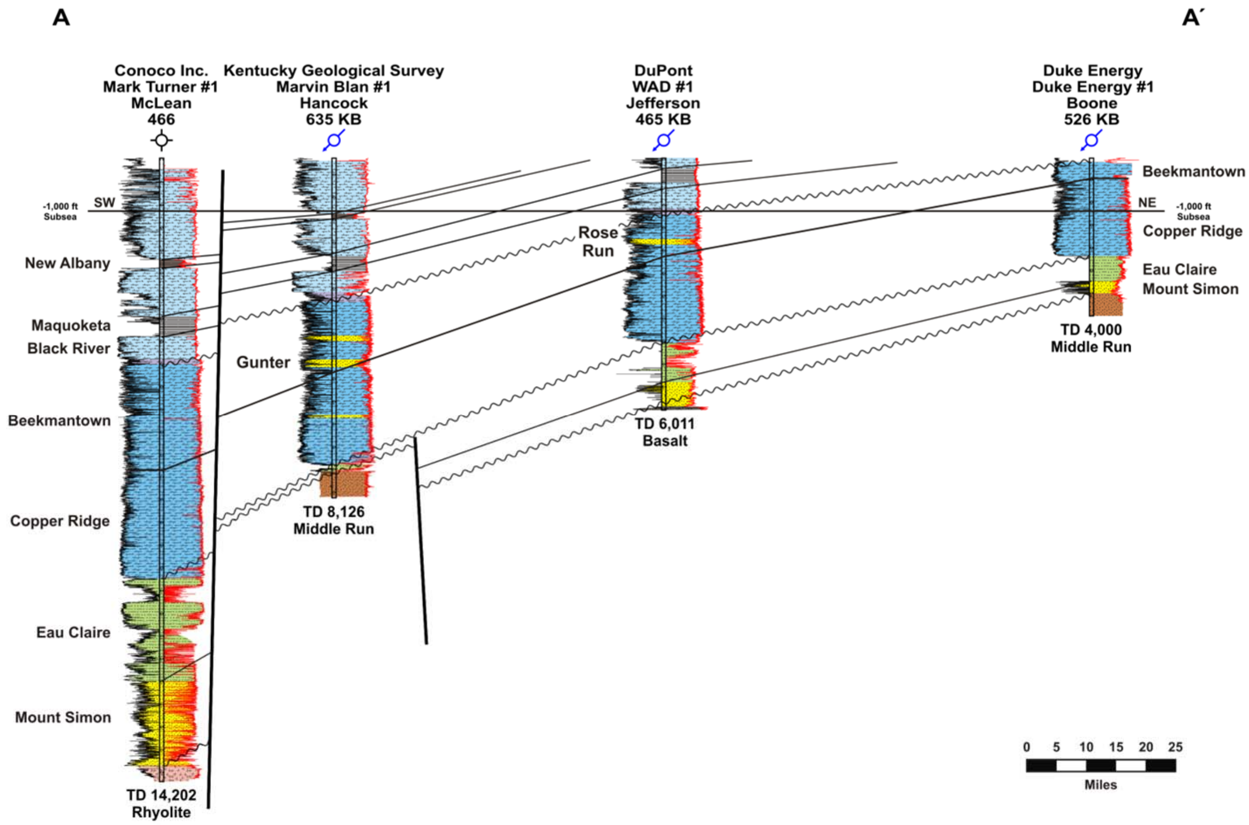

Figure 4. Generalized subsurface cross section A-A' from the Mark Turner No. 1 well in the Rough Creek Graben, to the Duke Energy No. 1 on the Cincinnati Arch. The unconformity on top of the Knox truncates progressively older strata to the east, suggesting pre-Middle Ordovician initiation of the Cincinnati Arch uplift. The Marvin Blan No. 1 was drilled on a horst, thus the Mount Simon is absent and the Eau Claire Formation is very thin compared to the other wells on the cross section.

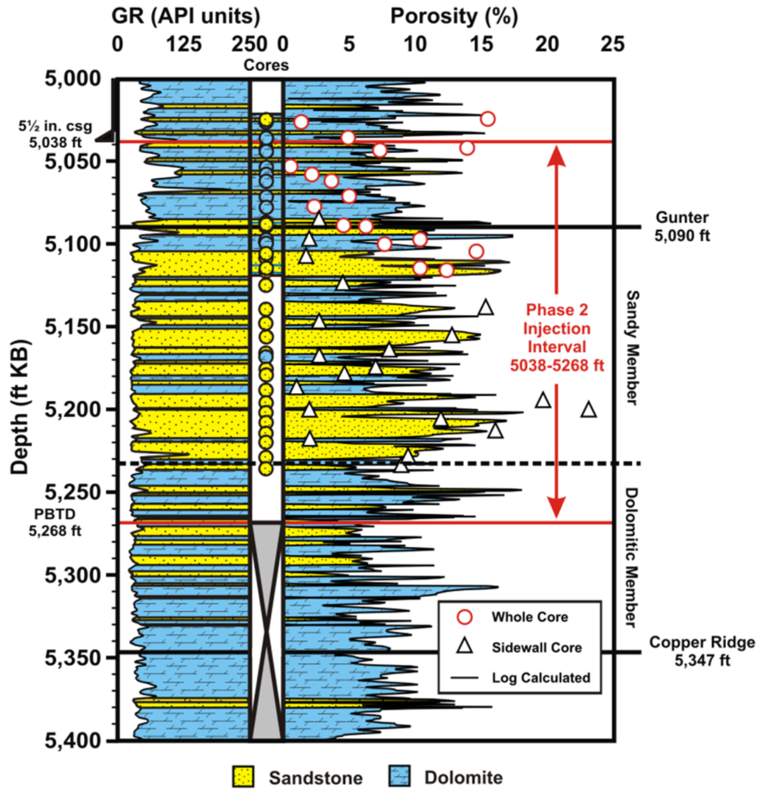

Figure 5. Stratigraphy of the Gunter Sandstone section in the Marvin Blan No. 1. The Gunter is informally divided in to an upper sandy member and lower dolomitic member. The porosity curve was calculated from the density log, differentiating for sandstone and dolomite facies.. Locations of whole core plugs and sidewall cores analyzed for their reservoir properties are annotated, and porosity measured in the samples is posted. The Phase 2 injection test interval focused on the sandstone facies of the Gunter.

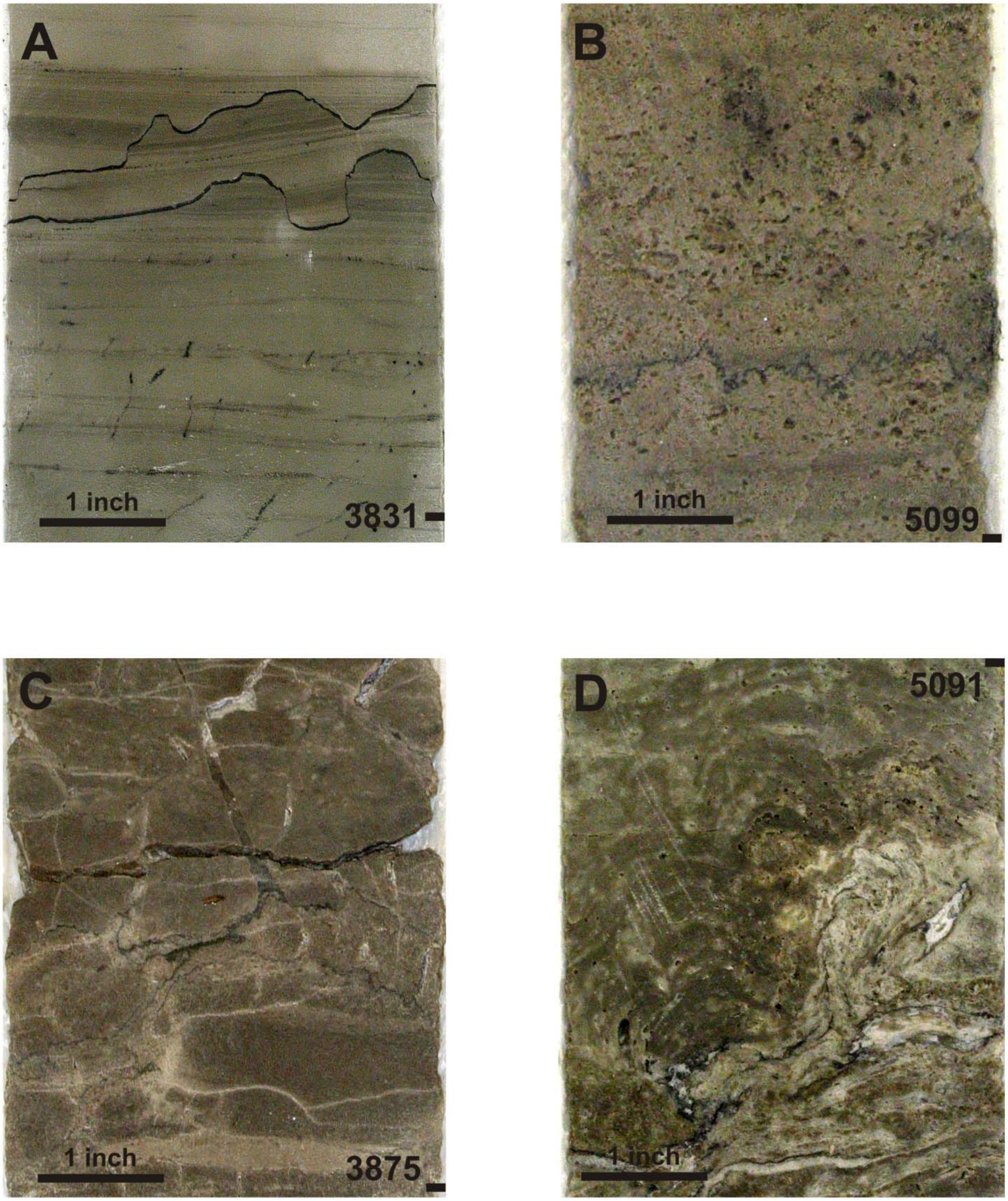

Figure 6. Sedimentological features and dolomite fabrics observed in cores from the Beekmantown (A and C) and Gunter (B and D). Core depths in feet are noted. A. Intercrystaline porosity in relict microbial mat facies with an inverted, styolitized rip-up clast. B. Vugular porosity developed in styolitized lagoonal facies. C. Shoreface collapse breccia with solution-enhanced mineralized fractures. D. Vugular porosity developed in a preserved stromatolite from the uppermost Gunter.

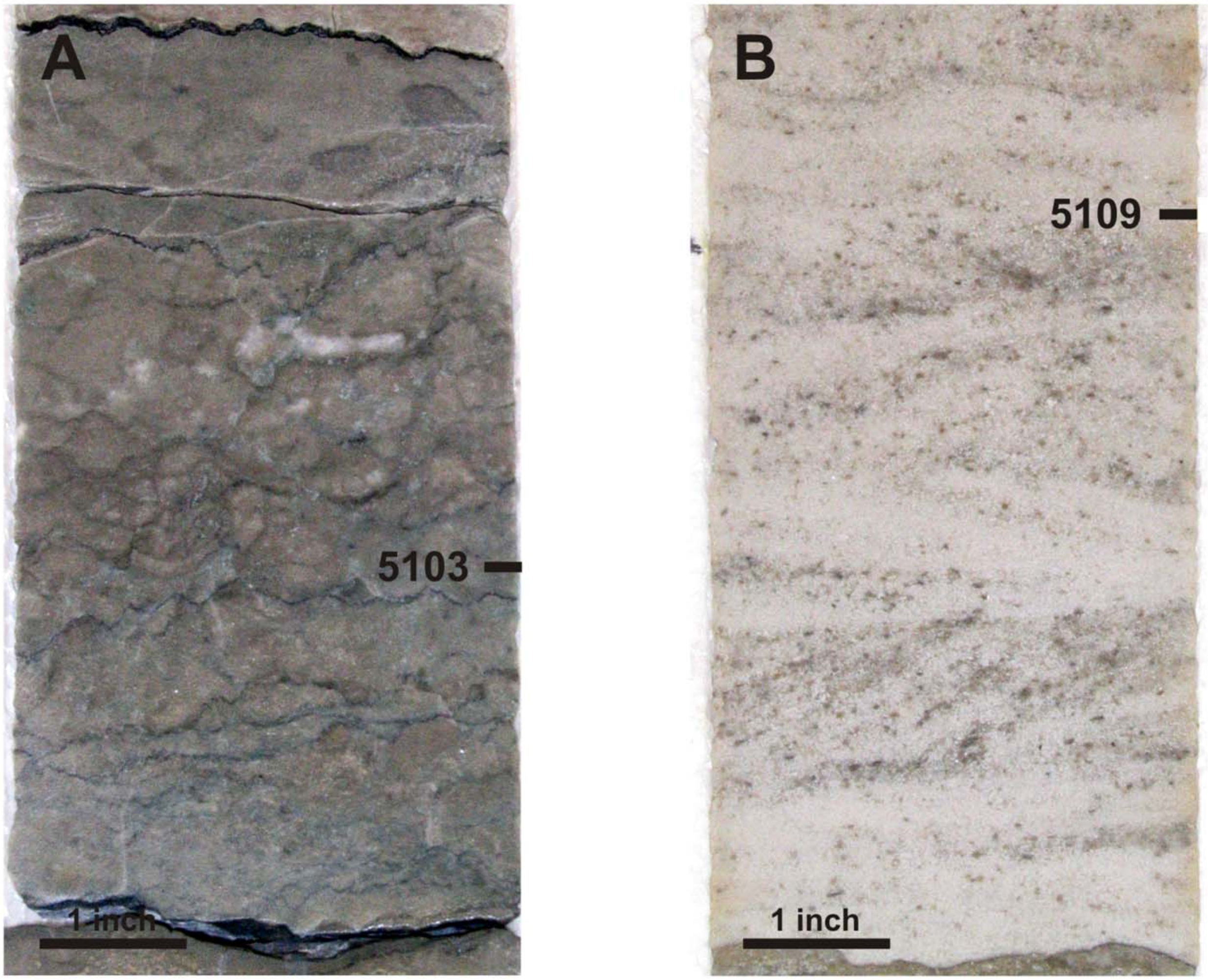

Figure 7. Facies development in the Gunter. A. Heavily styolitized, pervasively bioturbated collapse breccia in a Gunter lagoonal facies. Dolomite facies in the Gunter are generally low porosity (less than 4 percent). B. Herringbone cross beds preserved in the Gunter sandstone facies, indicative of beach and intertidal deposition. Sand facies are have higher porosity, averaging 8.7 percent, developed from the leaching of the dolomite matrix.

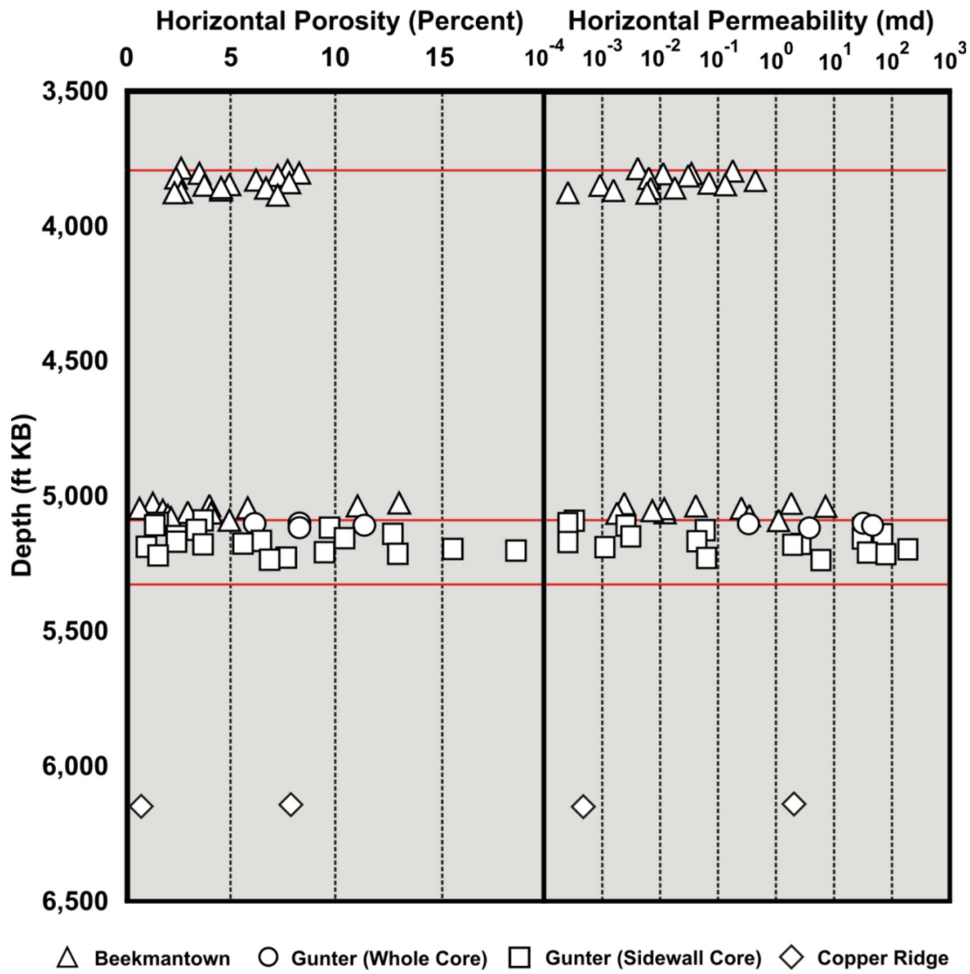

Figure 8. Porosity and permeability measured in horizontal core plugs and sidewall cores from the Knox. Samples from dolomites generally have porosity less than 8 percent, and permeability less than 1 md. In contrast, samples from the Gunter show a wide range of porosity and permeability.

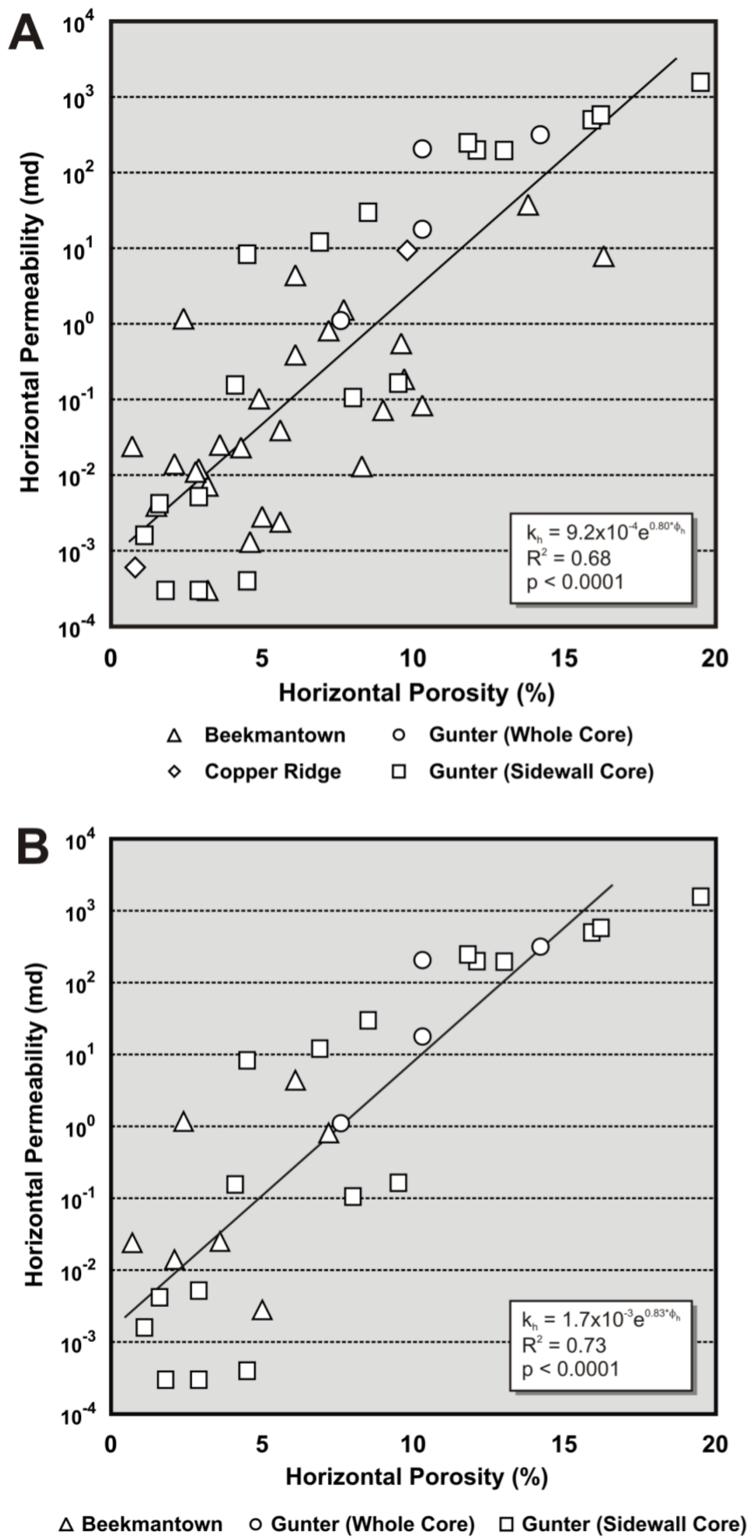

Figure 9. Comparison of permeability versus porosity in horizontal core plugs and sidewall cores. A. Plot of all samples from the Knox shows excellent correlation of permeability and porosity. B. Plot of samples from the Phase 2 test interval at 5038-5068 ft shows correlation comparable the larger sample set in A.

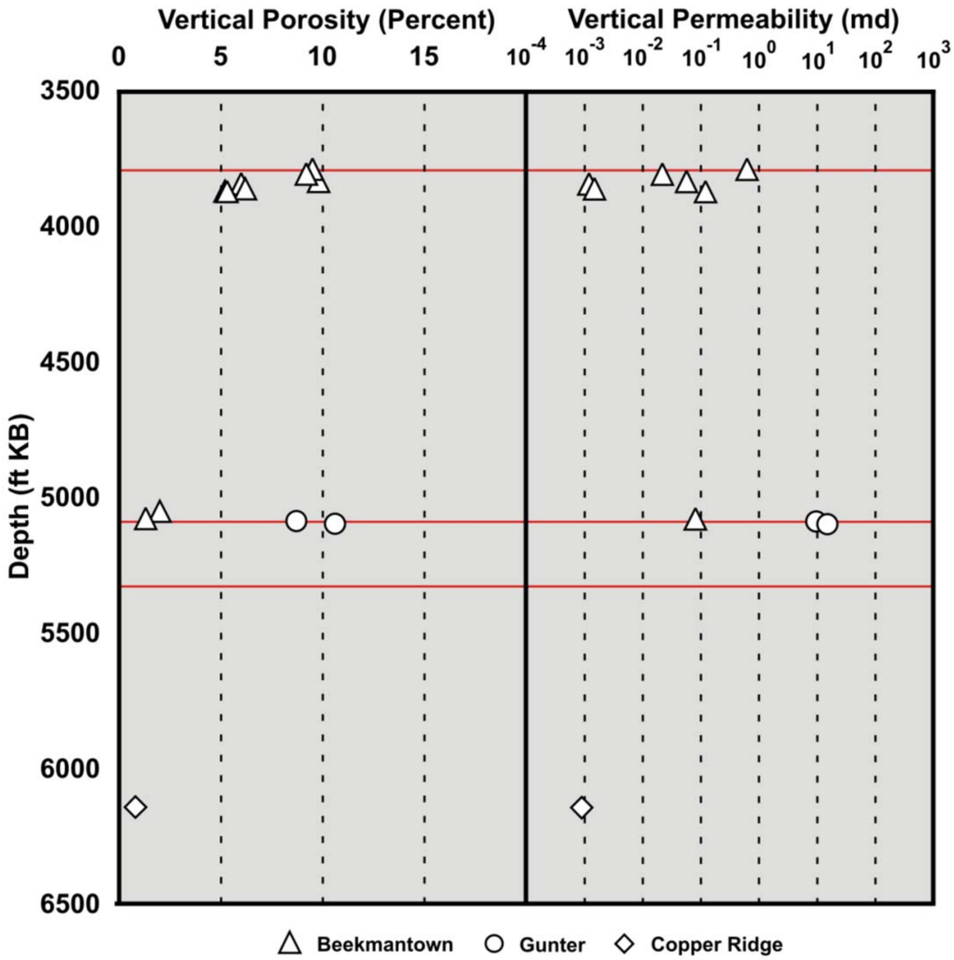

Figure 10. Porosity and permeability measured in vertical core plugs from the Knox. Porosity and permeability values measured in vertical core plugs approximate those from horizontal core plugs (Fig. 8).

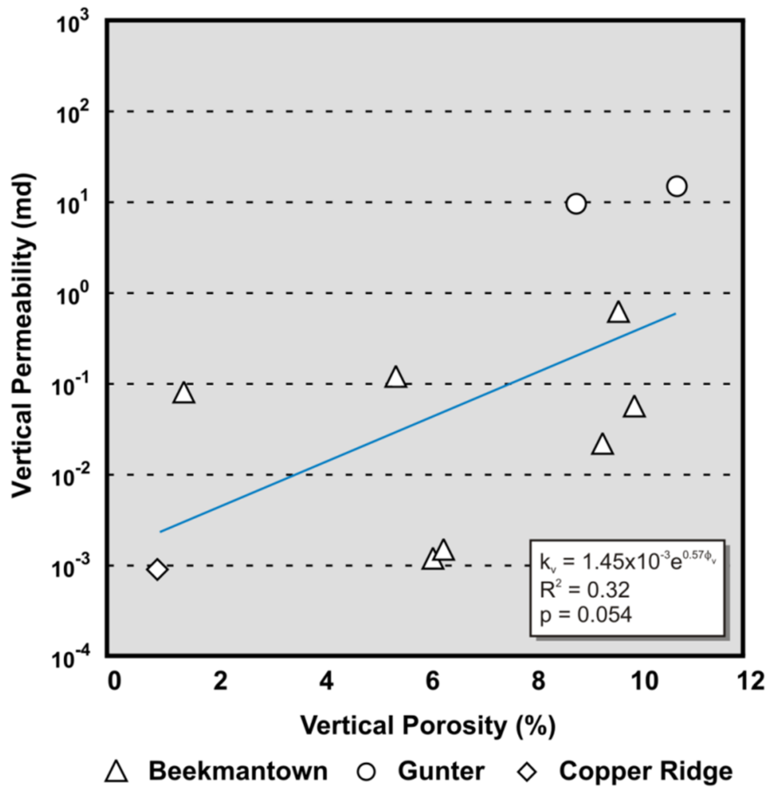

Figure11. Correlation of porosity and permeability measured in vertical core plugs from the Knox is poor. Although the sampled intervals may have well-developed vugular porosity, the vugs are poorly connected vertically.

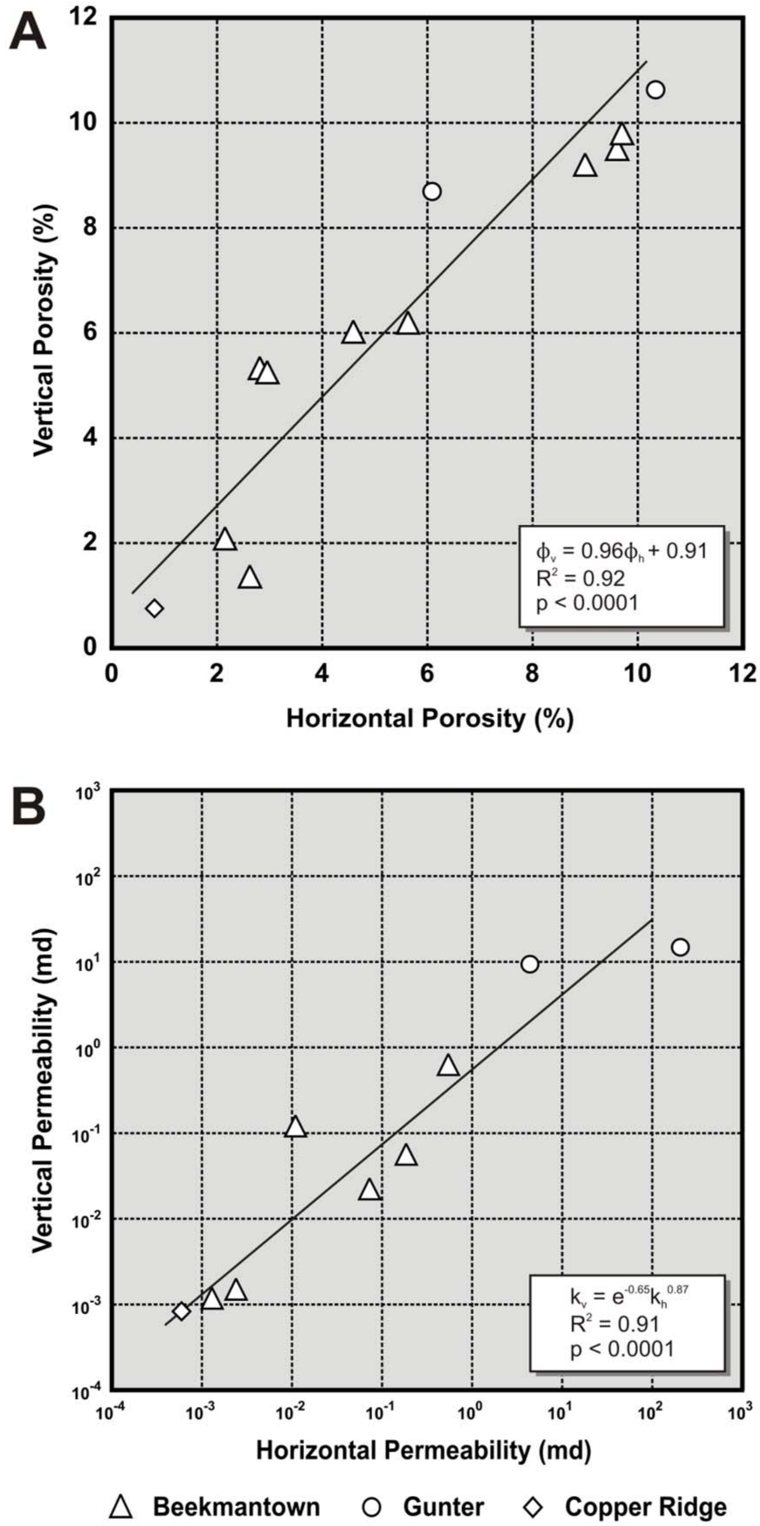

Figure 12. Correlation of vertical porosity and horizontal porosity and vertical permeability and horizontal permeability measured in adjacent core plugs.

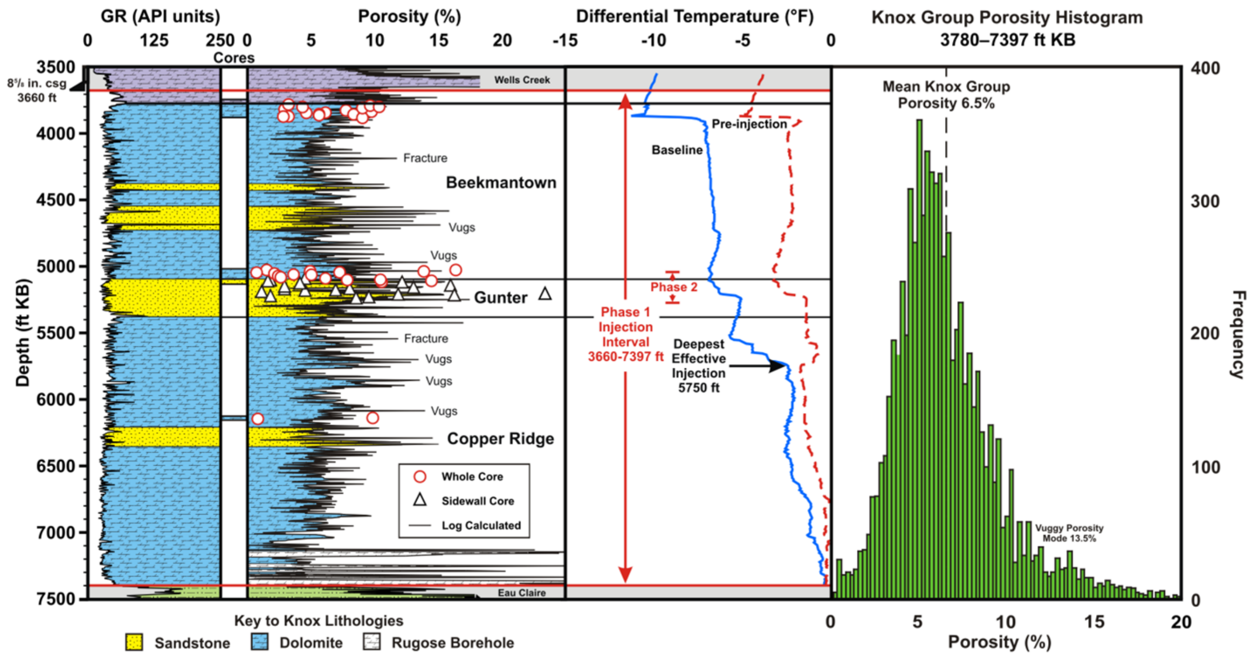

Figure 13. Reservoir characteristics of the Knox (left and right panels) and results of the Phase 1 injection testing (center panel). Left panel key is the same as Figure 5. Differential temperature is calculated by comparing the post injection temperature survey with the initial baseline temperature survey recorded prior to any injection (blue curve), and with the temperature survey recorded immediately before injection CO_2 injection (red-dashed curve). These surveys suggest that the deepest effective injection depth was about 5,750 ft, and that the Gunter and the immediately overlying Beekmantown accounted for the greatest volume of injected CO_2. The porosity histogram shows Knox porosity to be positively skewed because of vugular intervals with, a mode at 13.5 percent porosity, and higher porosity sandstone sections (left panel).

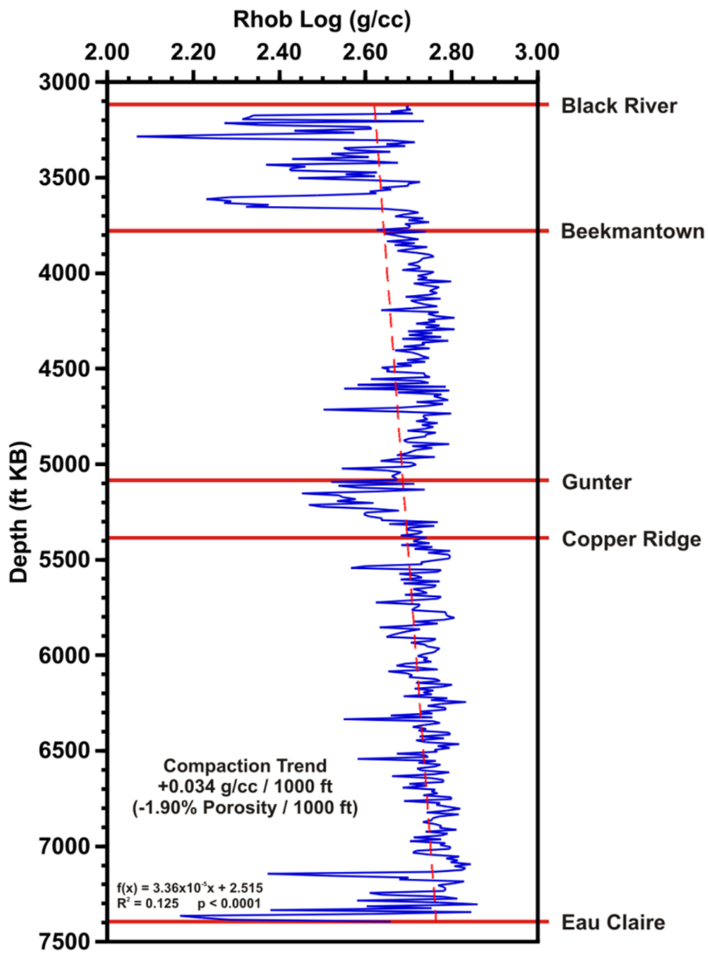

Figure 14. Compaction within the Knox, and associated loss of porosity with increasing depth, is demonstrated by increasing bulk density (Rhob Log) recorded by the density log. Compaction calculated from the density log decreases porosity in the Knox by 1.19 percent per 1,000 ft of depth increase. Rugose boreholes in the Black River and basal Copper Ridge sections appear as low-bulk density departures, to the left of the red-dashed regression curve. Higher porosity sandstone facies in the middle Beekmantown at about 4,500 ft and Gunter are evident as much smaller low-bulk density departures. Less porous intervals in the Beekmantown show as bulk density departures to the right of the regression curve.

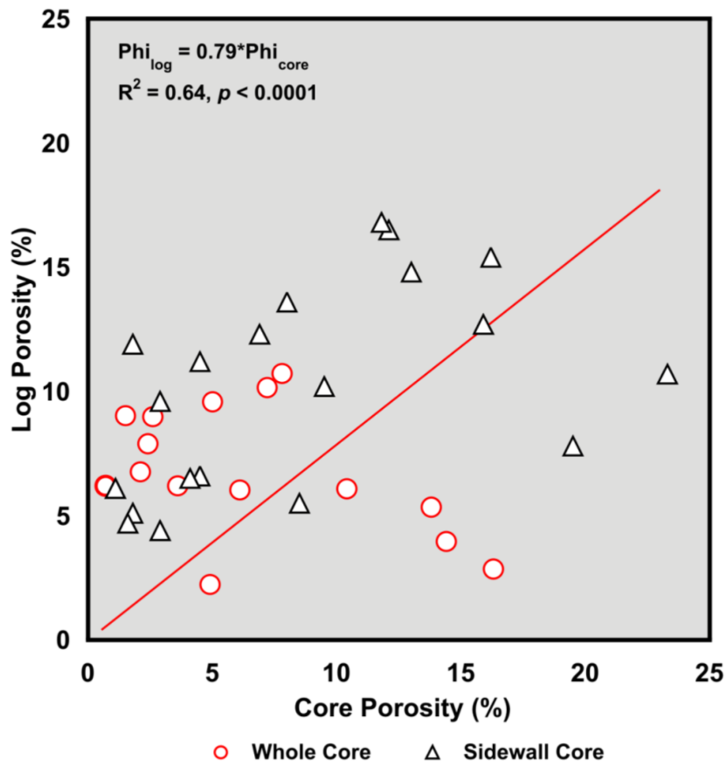

Figure 15. Comparison of porosity calculated from the density log versus porosity measured in whole core plugs and sidewall cores. Although there is a good correlation between these porosity values, the appearance of a porosity trend above the regression curve suggests that porosity calculated from the density log may be about 3 percent higher than that measured in core samples.

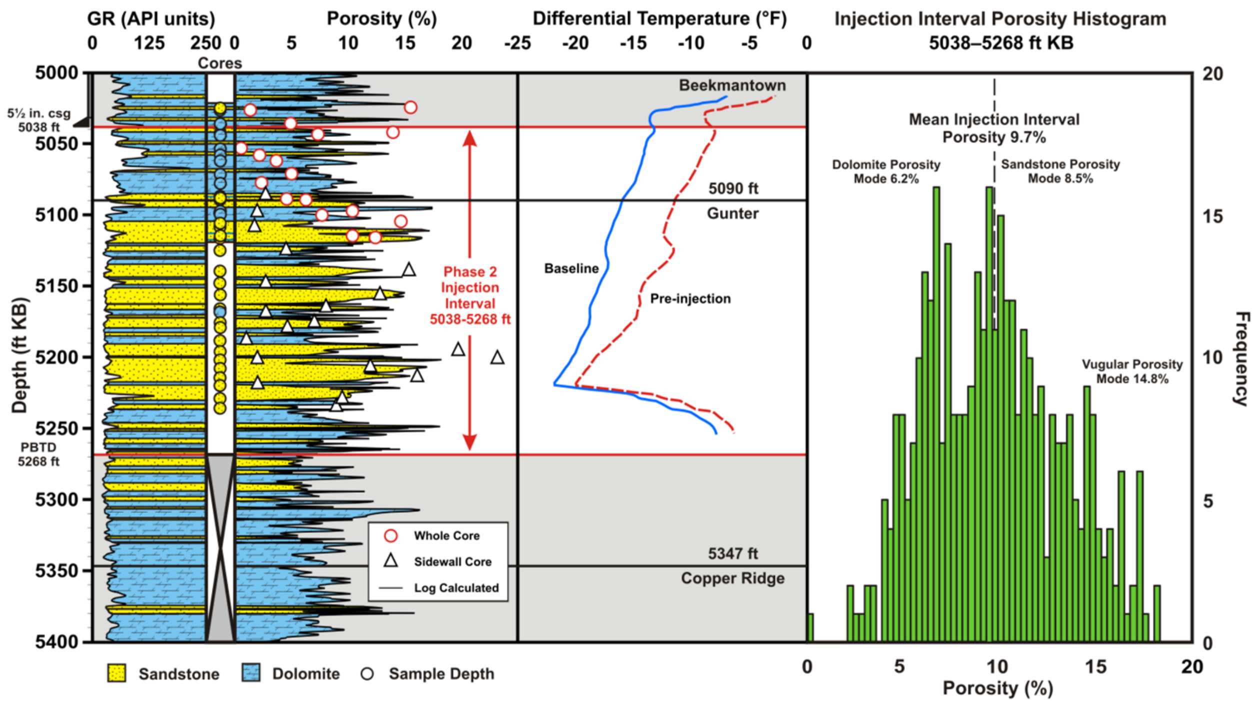

Figure 16. Reservoir characteristics of the Gunter and Phase 2 injection interval (left and right panels) and results of the Phase 2 injection testing (center panel). Left panel key is the same as Figure 5 and 13. Differential temperature is calculated by comparing the post injection temperature survey with the initial baseline temperature survey recorded prior to any injection (blue curve), and with the temperature survey recorded immediately before injection CO_2 injection (red-dashed curve). These surveys suggest that the deepest effective injection depth was about 5,230 ft, with the greatest volume of CO_2 being injected into the sandstone facies at 5,150-5,230 ft, with little CO_2 being injected into the dolomite facies below 5,230 ft. The porosity histogram shows trimodal porosity, with a modal peak in the dolomitic facies at 6.2 percent porosity, a modal peak for the sandstone facies at 8.5 percent porosity, and a modla peak for vugular porosity at 14.8 percent.

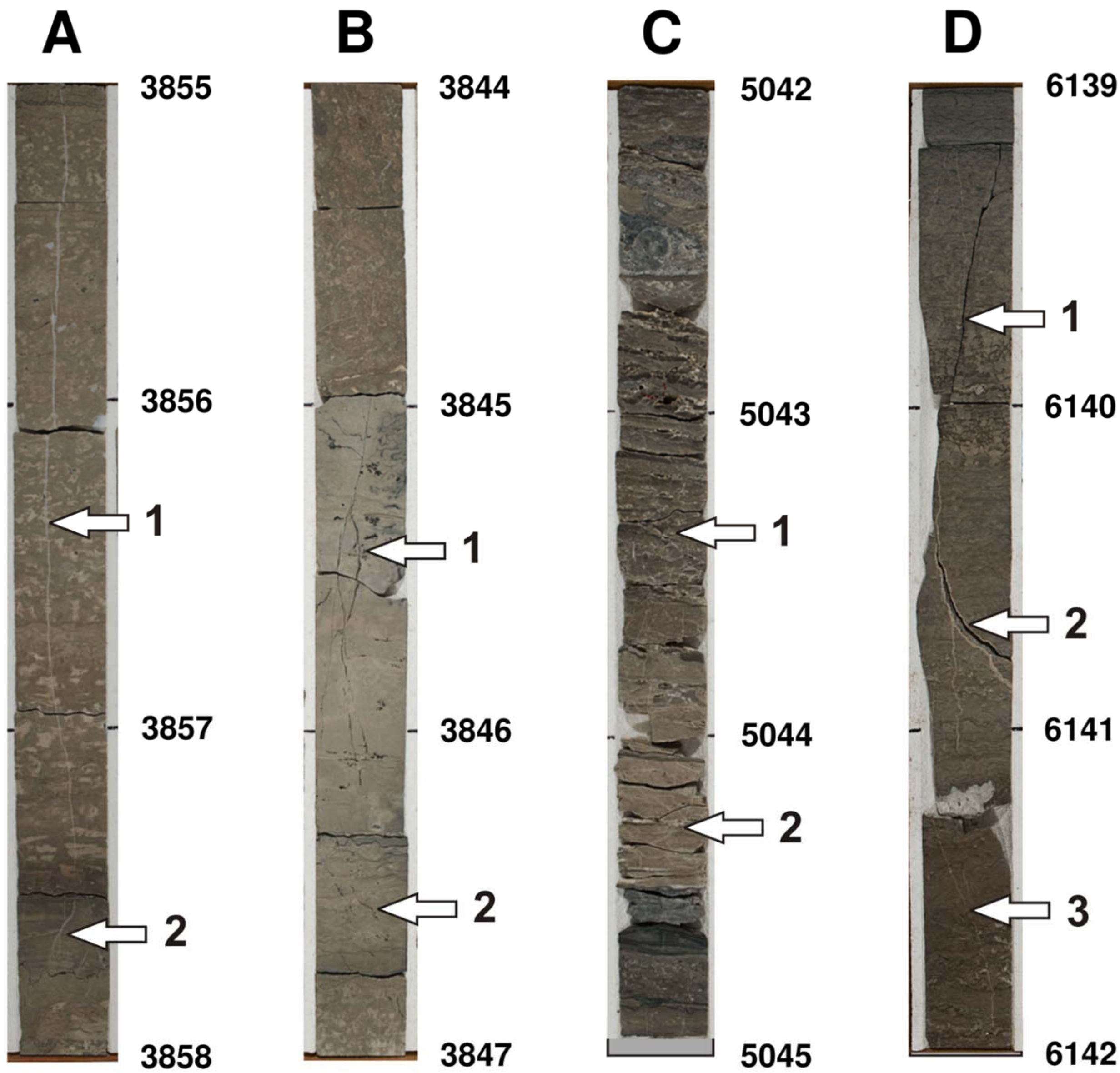

Figure 17. Examples of fractured and brecciated intervals observed in cores from the Knox in the Marvin Blan No. 1. A. Vertical mineralized fracture in bioturbated dolomitized mudstone (1) approximately 3.5 ft high (extends beyond the top of the core section), and mineralized fractures with cross-cutting mineralized fractures (2). B. Solution-enhanced fractures in dolomite mudstone (1) and solution-enhanced fractures in styolitized dolomite mudstone. Note the development of vugs along bedding planes. C. Collapse breccia with solution-enhanced fractures (1), and collapse breccia with mineralized fractures (2). D. Open fracture (1) and partially open, mineralized fracture (2). Mineralized fractures in dolomitized mudstone (3) trend similarly to the mineralized fracture below the partially open fracture at 2.

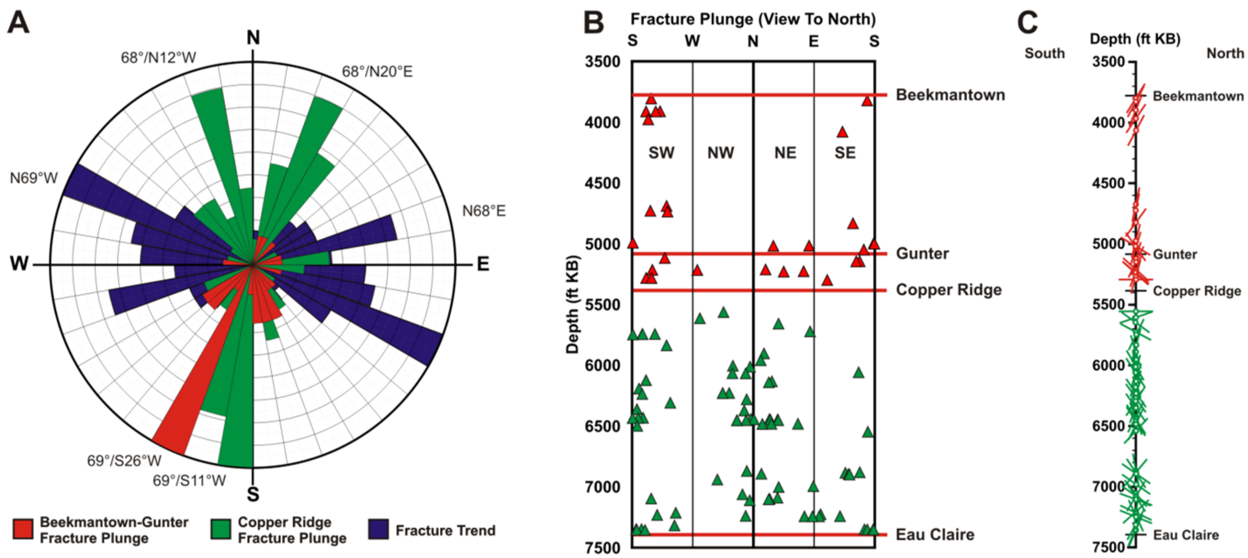

Figure 18. Open fracture orientations in the Knox interpreted from the imaging log. A. Rose diagram of fracture orientations suggests that fractures are shear fractures oriented parallel to the modern stress field in western Kentucky. Beekmantown and Gunter fractures generally plunge south, whereas Copper Ridge fractures generally plunge north. B. Fracture plunge shows the general southern plunge of Beekmantown and Gunter fractures versus the northern plunge of Copper Ridge fractures. Although Gunter fractures largely plunge south, a group of fractures fall in northeastern quadrant. C. Fracture plunge projected into a north view demonstrates that Copper Ridge and Gunter fractures occur as conjugates, whereas Beekmantown fractures generally occur as parallel planes.

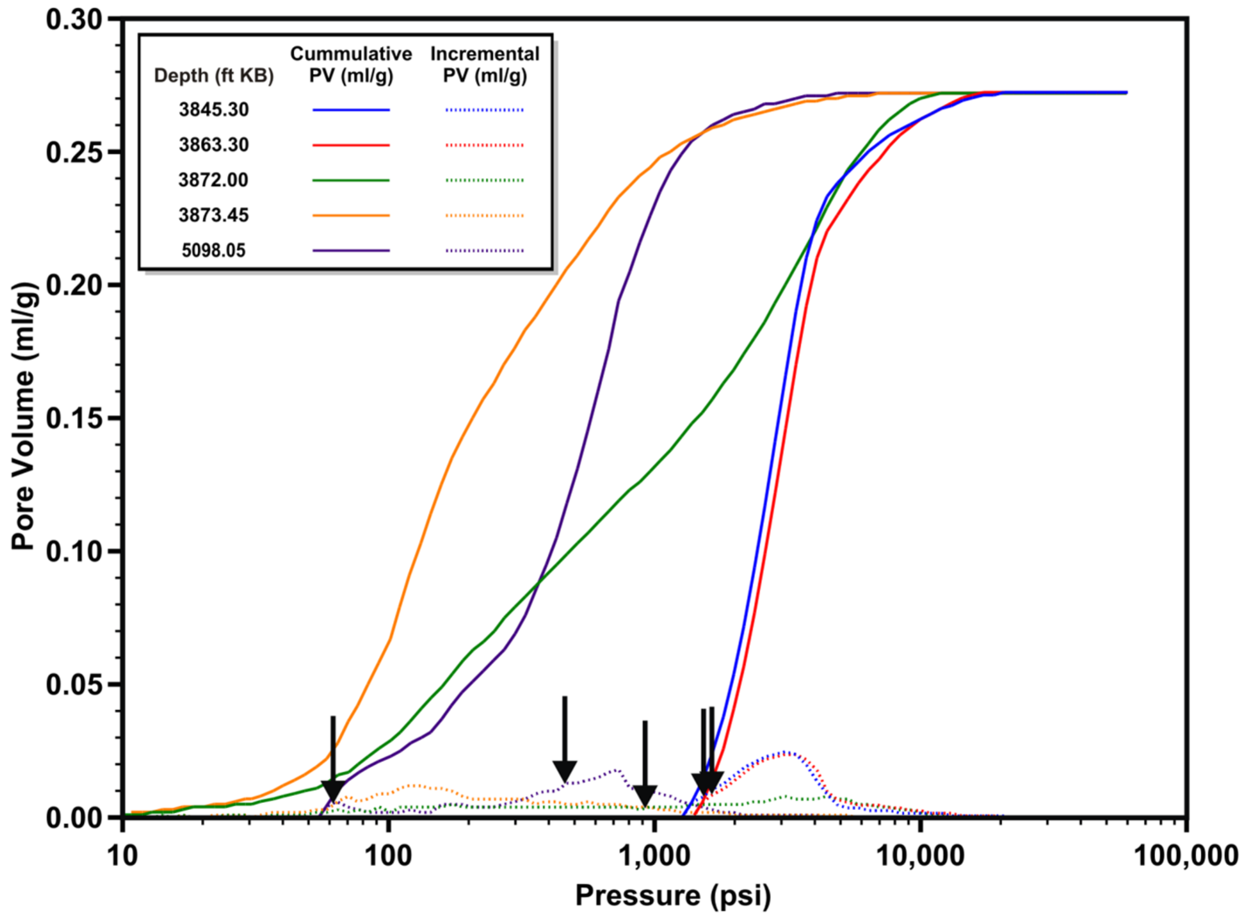

Figure 19. Mercury-injection capillary pressure measurements of intraformational seals in the Knox. Data is presented as cumulative pore volume and incremental pore volumes of mercury injected. Threshold pressure is determined at the greatest slope change of incremental pore volume curve.

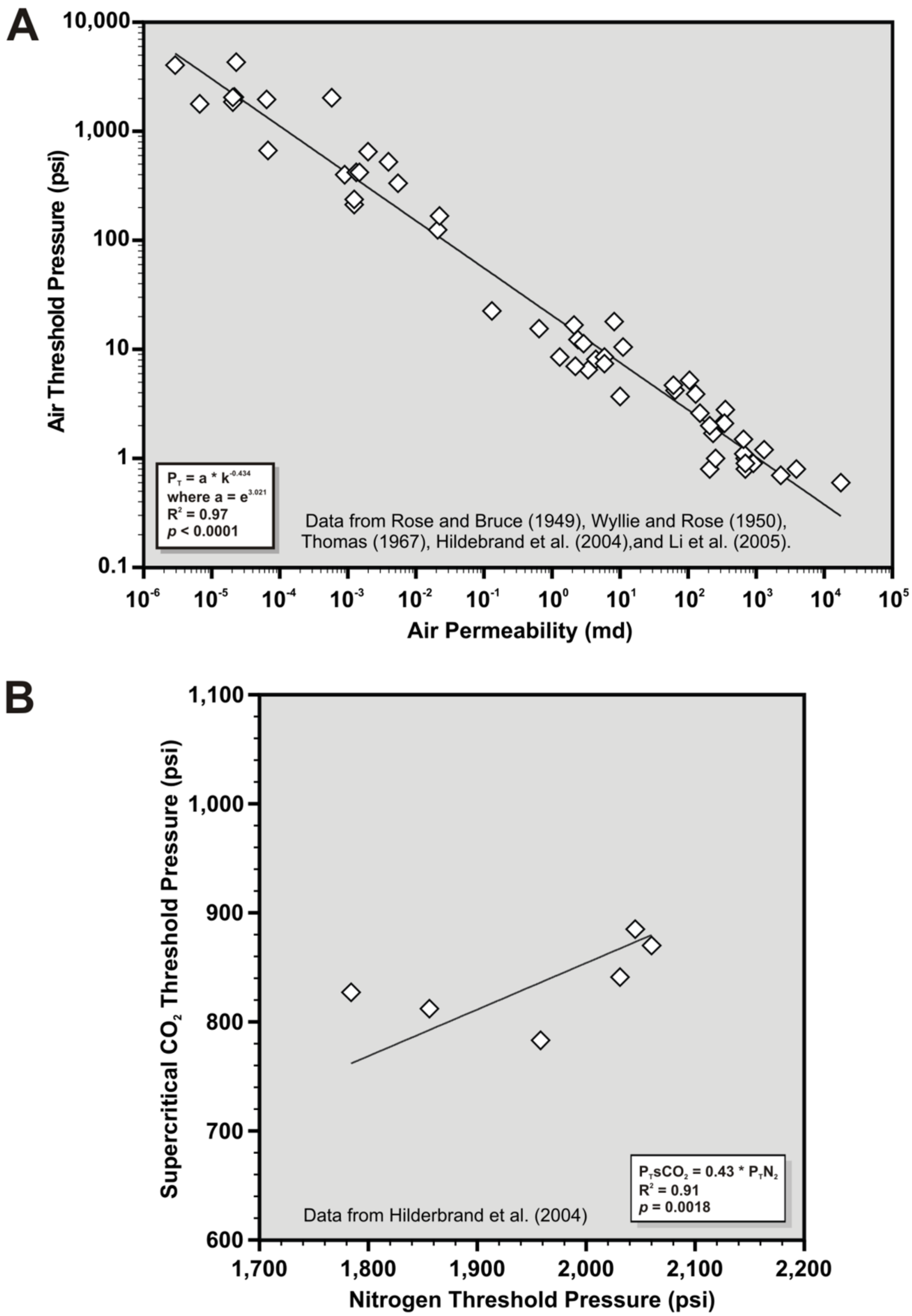

Figure 20. Correlation of permeability and threshold pressure and nitrogen-supercritical CO_2 threshold pressures. A. Correlation of threshold air/N_2 threshold pressure versus permeability from measurements in five studies. Air/N_2 has much higher threshold pressure than supercritical CO_2. B. Relationship between N_2 threshold pressure and supercritical CO_2 threshold pressure. Supercritical CO_2 threshold pressure is about 43 percent of N_2 threshold pressure.

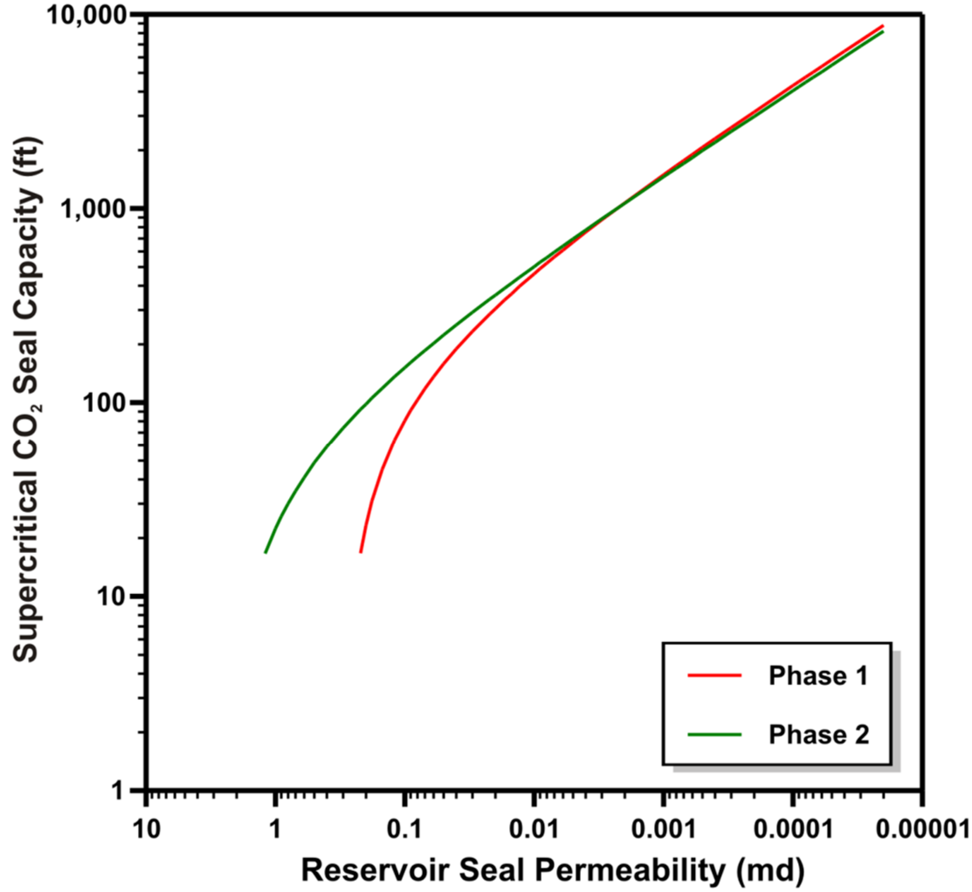

Figure 21. Seal capacity for supercritical CO_2 calculated from synthetic data sets representing the Phase 1 and Phase 2 injection tests. The difference between the two curves is because of the affect of the differences in reservoir temperature and pressure in the two tests on the density of supercritical CO_2 in the reservoir.

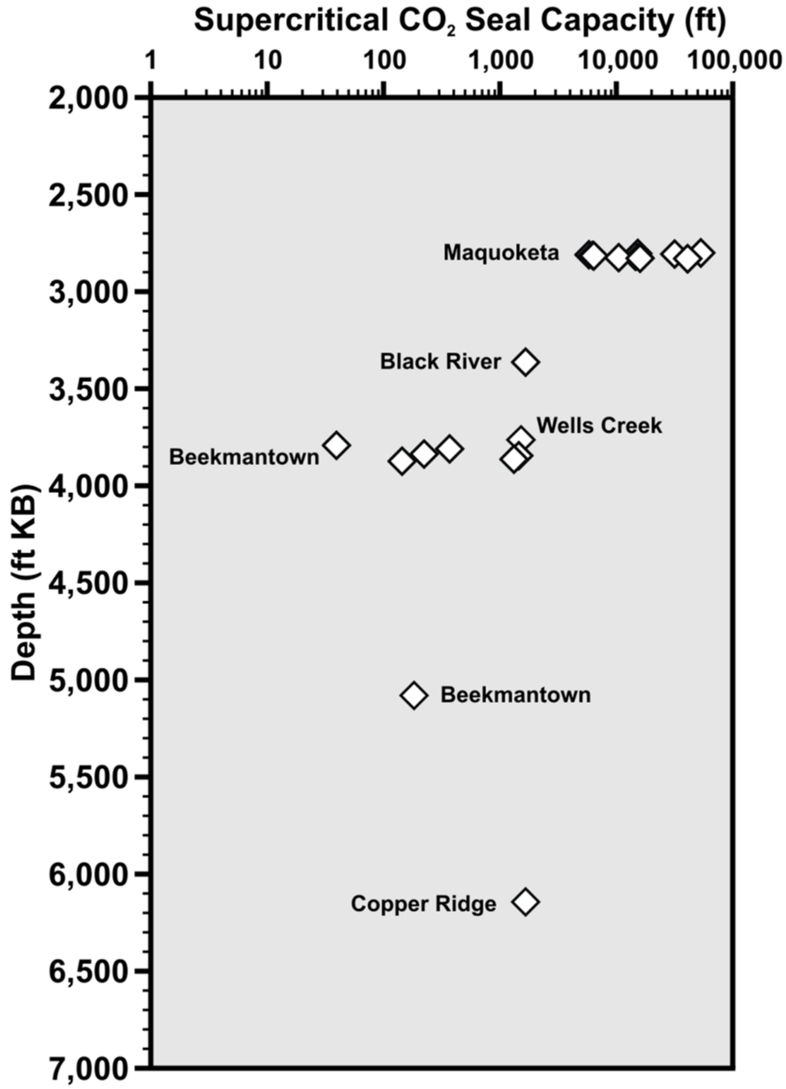

Figure 22. **S**upercritical CO_2 seal capacity calculated from permeability measured in vertical core plugs. This demonstrates that the Maquoketa would be the primary seal for **s**upercritical CO_2 storage in western Kentucky, whereas the Black River, Wells Creek, and intraformational seals in the Knox are individually inadequate.

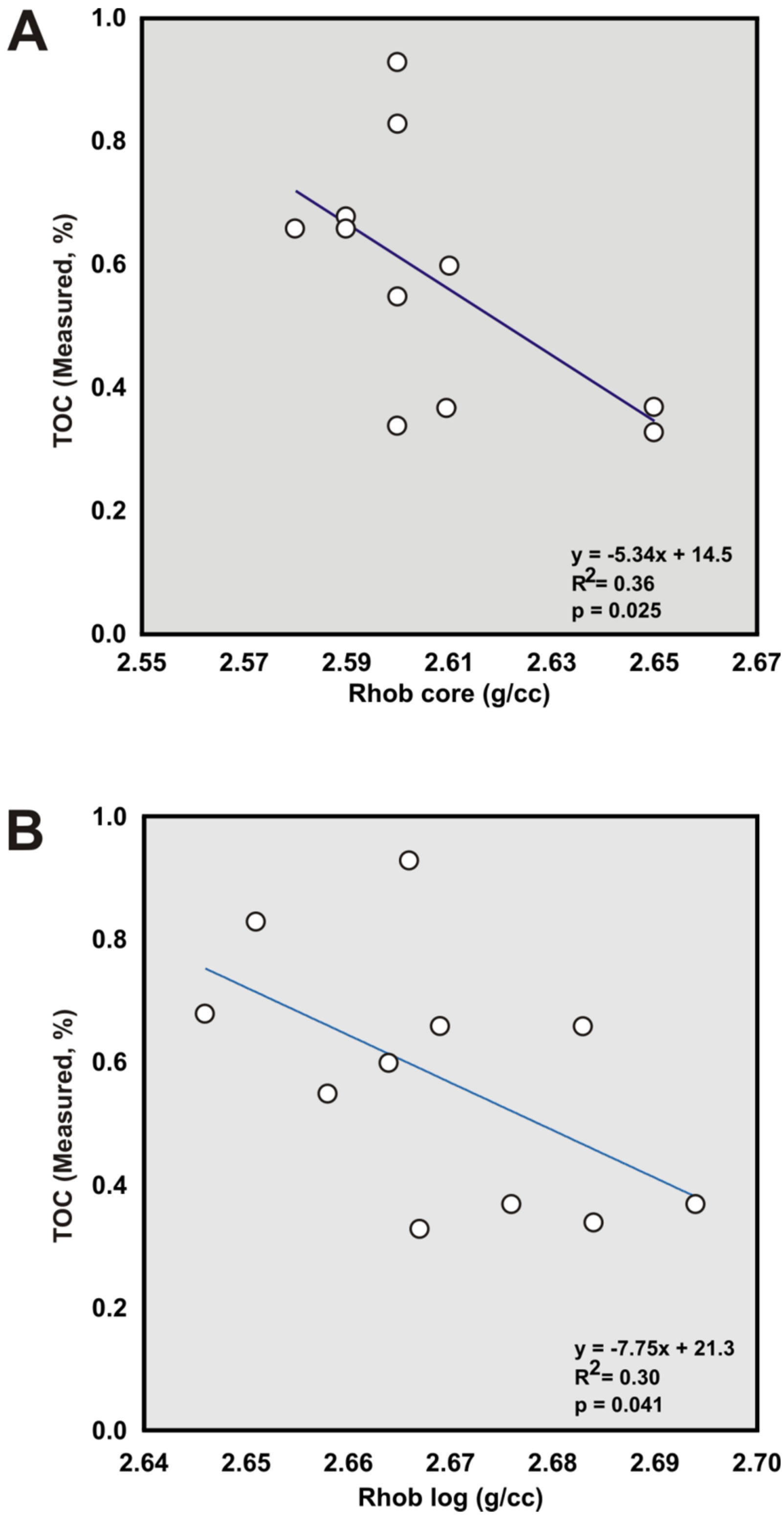

Figure 23. Total organic carbon (TOC) in the Maquoketa versus bulk density (Rhob). A. TOC versus bulk density measured in core plugs from the Maquoketa. B. TOC versus bulk density recorded by the density log. In both cases there is good correlation between TOC and bulk density.

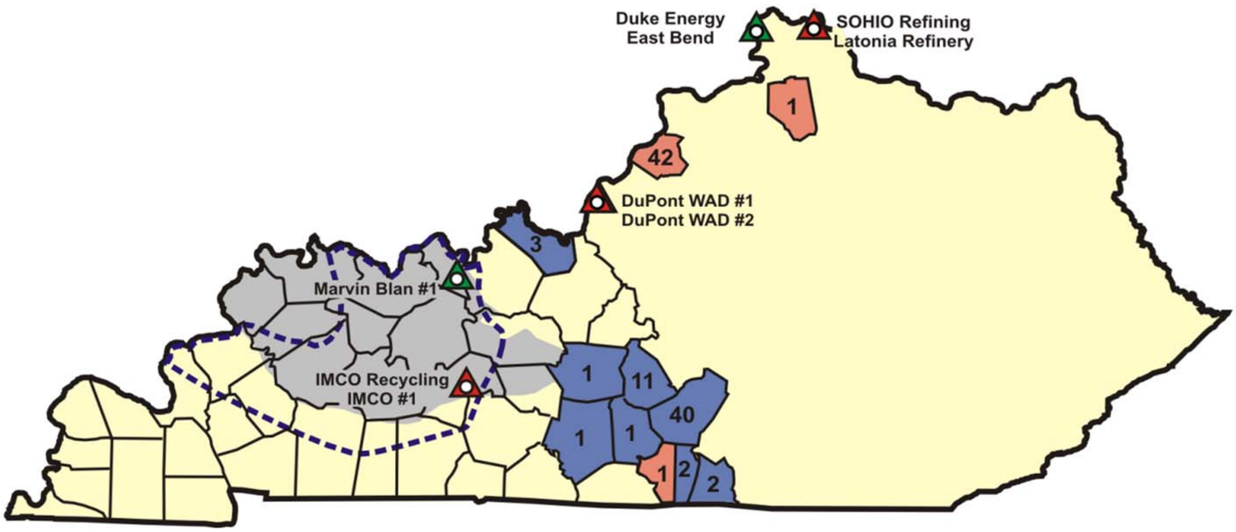

Figure 24. Distribution by county of injection wells developed in Knox reservoirs in Kentucky. Counties with salt water injection wells are shaded blue and counties with natural gas storage wells are shaded red. U.S. Environmental Protection Agency UIC Class I injection wells are noted by red triangles, and CO_2 injection test wells are noted with green triangles.

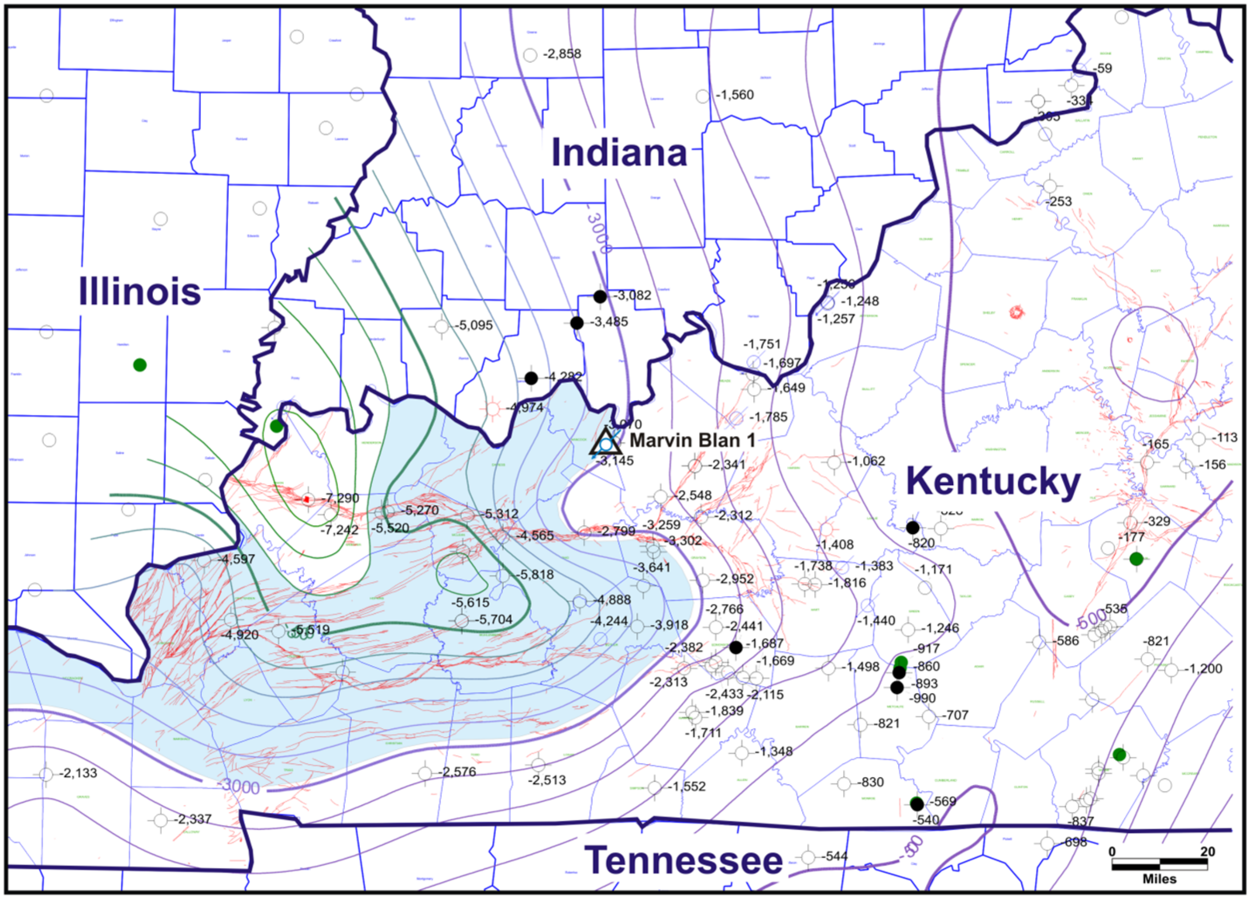

Figure 25. Prospective region for supercritical CO_2 storage in western Kentucky Knox reservoirs is shaded blue, an area of about 6,000 mi^2. Contours are generalized structural contours on top of the Knox. Location of the Marvin Blan No. 1 noted by the triangle. The prospective region is limited to the east and south where the base of the Maquoketa is shallower than 3,100 ft. This depth approximates the -3,150-ft subsea elevation contour on top of the Knox. The region is about is limited to the northwest where the base a 2,500-ft thick is deeper than an estimated economic depth of an injection well at 9,000 ft. This maximum economic depth limit approximates the -6,000-ft contour on top of the Knox. Within the prospective region the proximity of faults in the subsurface that cut the Maquoketa will further limit the area available for development as supercritical CO_2 storage reservoirs.

Figure 26. Distribution of Cambro-Ordovician carbonate rock in the Midcontinent of the U.S (after Cook and Bally, 1975, and Ettensohn, 2008). Successful injection testing in the Marvin Blan No. 1 suggests that much of this region may be prospective for supercritical CO_2 storage in Cambro-Ordovician carbonate reservoirs.

Table 1. Selected formation tops penetrated in the 1 Marvin Blan well.

Age[1]	Formation	KGS Monitor Well		Marvin Blan #1				Knight Brothers No. 1	
	Well:	**KGS Monitor Well**		**Marvin Blan #1**				**Knight Brothers No. 1**	
	Datum Elevation:	**Log Run 1**		**Log Run 1**		**Log Run 2–3**		**Log Run 1–2**	
	Total Depth:	**625 ft GL**	**191 m GL**	**635 ft KB***	**194 m KB***	**635 ft KB***	**194 m KB***	**407 ft KB****	**124 m KB****
Age[1]	**Formation**	**427 ft**	**130 m**	**442 ft**	**135 m**	**8126 ft**	**1116 m**	**6035 ft**	1839 m
	Surface	0	0	NL	NL	NL	NL		
Early Pennsylvanian									
	Caseyville Sandstone	8	2	26	8	22	7		
Late Mississippian									
	Buffalo Wallow Shale	15	5	32	10	28	9		
	Palestine Sandstone	64	20	56	17	52	16		
	Menard Limestone	86	26	83	25	79	24		
	Vienna Limestone	226	69	241	73	237	72		
	Glen Dean Limestone	284	87	301	92	297	91	NL	NL
	Golconda Limestone	373	114	387	118	383	117	111	34
	Jackson Sandstone	NP	NP	NP	NP	459	140	166	51
	Barlow Limestone					486	148	212	65
	Cypress Sandstone					501	153	243	74
	Renault Limestone					599	183	333	101
Middle Mississippian									
	Ste. Genevieve Limestone					663	202	406	124
	St. Louis Limestone					858	262	629	192
	Salem Limestone					1049	320	949	289
	Fort Payne Formation					1417	432	1143	348
Early Mississippian									
	New Providence Shale					1837	560	1550	472
Late Devonian									
	New Albany Shale					1857	566	1570	479
	Base of New Albany Shale					1973	601	1678	511
Middle Devonian									
	Sellersburg Limestone					1973	601	1678	511
	Jeffersonville Limestone					2124	647	1791	546
Early Devonian									
	Clear Creek Limestone					2292	699	1853	565
Silurian									
	Bailey Limestone					2438	743	1951	595
	Laurel Dolomite					2486	758	2162	659
Late Ordovician									
	Maquoketa Group					2705	824		
	Maquoketa Shale					2786	849	2402	732
	Black River Group					3124	952	2811	857
	Pecatonica Limestone					3563	1086	3250	970
Middle Ordovician									
	Joachim Dolomite					3585	1093	3272	997
	Dutchtown Limestone					3645	1111	3334	1016
Early Ordovician									
	Knox Group					3780	1152	3472	1058
	Beekmantown Dolomite					3780	1152	3472	1058
	Gunter Sandstone					5040	1536	4750	1448
Late Cambrian									
	Copper Ridge Dolomite					5347	1630	5020	1530
Middle Cambrian									
	Eau Claire Formation[2]					7397	2255	NP	NP
Precambrian: Neoproterozoic									
	Middle Run Sandstone					7584	2312		

GL = Ground Level
KB = Rotary Kelly Bushing
MSL = Mean Sea Level

*KB 14.5 ft above GL
**KB 5 ft above GL

NL = not logged
NP = not penetrated

[1]Swezey (2009) and sources cited therein
[2]Babcock (1994)

Table 2. Depths of cores from the 1 Marvin Blan well.

Core	Formation	Core Interval (ft KB)	Core Interval (m KB)	Core Recovered (ft)	Core Recovered (m)
1	**New Albany Shale**	1875 – 1905	571.5 – 580.6	30	9.1
2	**Maquoketa Shale**	2800 – 2831	853.4 – 862.9	31	9.4
3	**Black River Limestone**	3335 – 3396	1016.5 – 1035.1	61	18.6
4	**Wells Creek-Beekmantown**	3760 – 3883	1146.0 – 1183.5	123	37.5
5	**Beekmantown-Gunter**	5021 – 5122	1530.4 – 1561.2	101	30.8
6	**Copper Ridge**	6130 – 6149	1868.4 – 1874.2	19	5.8
7	**Middle Run Sandstone**	8000 – 8030	2438.4 – 2447.5	30	9.1
			Total Core	**395**	**120.4**

TIME-LAPSE THREE-DIMENSIONAL VERTICAL SEISMIC PROFILE (3D-VSP) OF SEQUESTRATION TARGET INTERVAL WITH INJECTED FLUIDS

EXECUTIVE SUMMARY

Two three-dimensional vertical seismic profiles (3D-VSPs) were acquired at the Marvin Blan No. 1 CO_2 sequestration research well in Hancock County, Kentucky. These surveys (one just before CO_2 injection and one immediately following injection) were combined to produce a time-lapse 3-D VSP data volume in an attempt to monitor the subsurface changes caused by the injection. While less than optimum surface access and ambient subsurface noise from a nearby active petroleum pipeline hampered quality of the results, some changes in the seismic response post-injection are interpreted to be a result of the injection process.

This report documents the results of Subtasks 3.6 and 3.8 of the project, *An Evaluation of the Carbon Sequestration Potential of the Cambro-Ordovician Strata of the Illinois and Michigan Basins*. This project was funded by the United States Department of Energy (USDOE) through Recovery Act: Site Characterization of Promising Geologic Formations for CO_2 Storage, Number: DE-FOA-0000033, under cooperative agreement DE-FE0002068 from 08 December 2009, through 31 September 2013.

OBJECTIVES

The objectives of the time-lapse 3D-VSP at the Marvin Blan No. 1 research well was to test the feasibility of using well-based 3D-VSPs to verify the CO_2 plume emplacement location (both vertically and horizontally) within the Gunter Sandstone reservoir, Cambro-Ordovician Knox Group, as well as attempt to monitor any initial local migration of those injected fluids into high-permeability zones or fractures.

INTRODUCTION AND BACKGROUND

In order for future industrial-scale carbon capture and storage projects to succeed safely, verification of CO_2 emplacement within the target reservoir and monitoring of the injected reservoir intervals will be required. One possible method of monitoring these subsurface reservoirs is through the differential analysis of repeated seismic surveys (Li, 2003; Majer, et al., 2006; Dahlhaus, et al., 2012). Fluids injected into a reservoir (supercritical CO_2 and saline water) alter the local pressure regime within the host rock, as well as change the bulk density of that rock where the injected fluid displace pore fluids that are of a different density. These localized pressure and density changes alter the elastic properties of the rock body, which therefore affect the seismic response it produces. By acquiring two duplicate surveys immediately before and after injection, using identical source, receiver and processing parameters, any differences in the resulting datasets can be assumed to be a product of that injection.

EXPERIMENTAL PROCEDURES

Objectives and General Methodology for 3D Vertical Seismic Profile Design

A three-dimensional (3D) vertical seismic profile (VSP) survey was conducted in conjunction with the Phase 2 CO_2 injection test program of the Marvin Blan No. 1 well. The objective of this survey was to model the extent of the CO_2 plume migration in the Gunter. Reports discussing data acquisition and processing methods and results of this task are in Appendix 3. The vendor, SeisRes-2020, Inc. (SR2020), was chosen to provide and operate the 3D-VSP down-hole survey tools, and to process the acquired digital seismic data. The seismic receiver array tool was comprised of 80 3-component geophones (X, Y, and Z-axis sensors), spaced 7.6 m apart vertically along production tubing (Fig. 1). Once lowered into place, expandable bladders were inflated that stabilized and coupled the geophone sensors to the sides of the wellbore (Fig. 2). For this project, the base of the geophone string was placed at the bottom of casing at 1115.6 m depth, about 457 m above the injection interval in the Gunter. This placement was recommended by SR2020 and allowed the geophone string to be placed within the well casing to ensure good acoustic coupling (there were concerns the rugosity of the wellbore below casing would negatively affect acquisition).

Initially, SR2020 recommended a source layout that consisted of a grid of 1022 surface source locations (with 22.9 m spacing between points) within a 427 m radius of the Marvin Blan No. 1 wellhead, and two "walk-away" profile lines for calibration purposes that would cross at the wellhead (a 1524 m north-south line and a 1166 m east-west line). This plan was later modified because much of the area within the recommended 427 m radius around the well included areas with steep surface slopes or were heavily wooded. These aspects made these areas inaccessible to the mobile seismic sources (2.4 m x 9 m vibrator trucks) required for the acquisition. The total number of available source locations was further limited by the presence of an active oil pipeline that crosses the Blan farm property just south of the Marvin Blan No. 1 wellhead. Because of safety concerns expressed by the operator of the pipeline related to the weight and potential pipeline damage from the vibrator trucks, a 15-m -wide buffer zone was defined over the pipeline right-of-way where seismic source vibrations were not permitted (Fig. 3).

Following discussions with SeisRes-2020, a revised source survey was designed to accommodate these survey acquisition issues. To compensate for the reduced survey area, a source grid with tighter spacing between source points (15.3 m) was defined for the main survey, along with a tighter spacing between sources along the two walk-away lines (7.6 m). Figure 3 shows the final survey layout design details. Appalachian Geophysical Services of Killbuck, Ohio, was chosen as the vendor to provide three Vibroseis® source vehicles for the seismic survey. The Vibroseis® source inputs used for both surveys were 12 second linear sweeps through 12 to 130 Hertz (Hz) frequencies.

Objectives and General Methodology for Seismic Survey Acquisition

In an attempt to monitor the effects of CO_2 injection, a time-lapse 3D-VSP survey was conducted. This was accomplished by performing adaptive subtraction of a pre-injection 3D-VSP's seismic response from the post-injection VSP's seismic response dataset. Prior to the VSP acquisitions, SR2020's proprietary downhole VSP tool was installed in the wellbore. SR2020 personnel operated the downhole equipment, monitored the seismograph recordings, and synchronized the hydraulic vibrators (seismic sources onboard the Appalachian Geophysical Services source trucks) during both acquisitions. During the acquisition stage of the two surveys, multi-frequency seismic waves were input into the subsurface at over 700 surface locations surrounding the Marvin Blan No. 1 research well (yellow points in Fig. 3). For each of these source locations points, raw seismogram data recordings (Fig. 4) were made by each of the 80 geophones within the well. These data were then compiled and processed by SeisRes-2020 staff.

The initial, pre-injection, survey was performed at the Marvin Blan No. 1 well on September 15 and 16, 2010. This was followed on September 22, 2010, by the injection of 333 tonnes of supercritical CO_2 followed 584 m^3 of 2% KCl water to displace CO_2 in the reservoir. After injection was completed, the well was shut-in with a downhole pressure of 17.5 MPa at the injected reservoir depth of 1545.3 m. The second 3D-VSP was acquired on September 25-26, 2010, after the reservoir pressure falloff test was completed.

Objectives and General Methodology for Seismic Data Processing

Seismic data processing was performed using a proprietary model developed by SR2020 for monitoring CO_2 plume migration at sequestration well sites. After examining the data recordings taken from both VSP acquisitions, SeisRes2020 selected records from 719 source locations which contained acceptable results from both VSP surveys for final data processing. The VSP data were processed by SeisRes2020 using the following steps:

1. Data QC on Raw VSP data
2. Geometry Assignment
3. Geophone Orientation Estimation
4. Spectral Analysis
5. Standard Zero Offset (ZO) processing
6. P-wave Direct Arrival Inversion
7. ZO Velocity Profile Estimation
8. 3D Velocity Model Extrapolation
9. Deconvolution Operator Design
10. P-Reflection 3C Wave Field Separation
11. Pre-stack Depth Migration
12. Time-lapse Comparisons

In order to depth-migrate the seismic data, a 3-D subsurface sonic velocity model was created (Fig. 5). The input data for this model was constructed from both the Marvin Blan No. 1 geophysical well logs as well as the near-well recorded VSP data travel times. The process of depth-migrating the seismic data (which is originally recorded in units of time) results in in a data volume for which all three axial dimensions are in units of distance. Depth-migrated seismic data thereby allows for direct comparison with conventional drill-hole data (see geophysical log overlay on Fig. 5).

RESULTS AND DISCUSSION

After processing the data, 3-D data volumes for the pre-injection and post-injection VSP's, along with the 3-D velocity model used for seismic processing, were made available to the Kentucky Geological Survey by SR2020 in January 2011. In addition, two limited-depth-interval "3-D difference volumes" were provided: one at the injection level (1534.6–1605.6 m depth) and one at a shallower "marker horizon" level (762–1219 m depth). The 3-D difference data volumes were created by subtracting the pre-injection seismic response from the post-injection seismic response datasets. Theoretically, this difference method should isolate only the changes in seismic response, in this case the injection of 333 tonnes of supercritical CO_2. The dimensions of the full VSP data volumes (Fig. 6–7) are 488 m x 488 m x 2590 m deep (lateral extent equivalent to the blue square in Fig. 8). The limited-depth-interval difference volumes encompassed a volume of 488 m x 488 m x 457 m thick. The desired intent or "best case scenario" for this task was to image the injected plume of CO_2 within the subsurface in three dimensions, and, if successful, potentially act as a model technique for future subsurface storage verification tests. While some changes were evident between the pre- and post-injection surveys (Fig. 9–11), the lateral and vertical extent of the plume could not be determined from this data.

The seismic amplitudes and waveforms changed slightly within the injection zone below 1534.6 m (5238 ft) depth (Fig. 9). There are also subtle changes throughout the dataset, however, even at depths in intervals that were too distant and/or stratigraphically compartmentalized to be effected by the injection. This is especially apparent in the 3-D difference volume (Fig. 11). If the technique had worked as designed, the areas without injected CO_2 should have amplitudes approaching zero (after subtracting the post-injection seismic amplitudes from the pre-injection amplitudes). Whereas subdued seismic responses relative to those within the injection zone are present in the interval away from the injection zone (see black oval in Fig. 11), both positive and negative wavelet amplitudes are present in the dataset.

The lack of a single region of post-injection amplitude anomalies made defining the extent of the plume (with only this seismic data) impossible. The most probable reasons for the lack of resolution in these VSP's were low data density and data quality. Because of the uneven terrain and the inability to place seismic source points along the pipeline right-of-way, or anywhere outside of the Blan farm property boundaries (Fig. 3), the data density was less than optimal, especially to the north and east of the well. In addition, the presence of an active pipeline in close proximity to the well (vibrational noise) along with active domestic and well site equipment (electrical noise) led to relatively low signal/noise ratio conditions within the data (Fig. 4). It is possible that a larger plume of CO_2 would have been easier to image, but the ambient noise and limited surface access would still have led to uncertainties in the exact extent of the subsurface plume.

Although we were unable to define the exact lateral extent of the CO_2 plume using the finite difference method, some of the anomalies in the results can be explained by the presence of the supercritical CO_2. In addition to the changes in the wavelet character described above and illustrated in Figures 9–11, there appears to be an anomalous "pull-down" of a reflection within the Gunter injection interval on the post-injection survey. Theoretically, the introduction of a lower density fluid (supercritical CO_2) into pore spaces and open fractures would lower both the bulk density and the average seismic velocity of the host rock. If this new injection-interval seismic velocity is significantly lower than that of the velocity model used to process and depth-migrate the data (Fig. 5), the seismic reflections will take longer to travel back to the recording geophones. This delayed reception of the seismic signal would result in the reflections within and below that horizon being plotted at a greater depth than is appropriate.

The concave-upward shape of high-amplitude reflection in the Gunter on the depth-migrated post-injection survey can be interpreted to be a "pull-down" effect from the introduction of the seismically slower CO_2 (Fig. 12). In an attempt to investigate this possibility, the depth to this reflection was mapped and contoured for both the pre-injection (Fig. 13) and post-injection surveys (Fig. 14). For the majority of the area, the post-injection horizon does indeed plot deeper than the same horizon before injection (Fig. 15). Note that the regions to the north-northeast and southeast in the post injection survey with highly anomalous calculated depths in Figures 14 and 15 correspond to the areas with much lower data densities (Fig. 16), and therefore are probably artifacts and not a true result of the injection. Although this apparent agreement of the data with seismic theory is encouraging, separating the effects of the plume from the effects of the low data density and quality was not possible with this dataset.

CONCLUSIONS AND RECOMMENDATIONS

While the technique of using time-lapse 3-D VSP's for finite difference analysis appears to be a useful and valid tool for subsurface CO_2 storage verification and monitoring, physical limitations such as limited surface access and ambient noise sources can make it impractical and thus not useful for all situations. In industrial sequestration operations, it is likely that the area available for seismic surveying would be larger than was available on the Blan farm, and thus have more potential seismic source locations (producing a greater signal/noise ratio). However, the steep-walled incised creek valleys that prevented seismic source truck access to some of the areas on the Blan farm are a common feature in much of Kentucky, so having a larger survey footprint would not necessarily provide all of the access needed for VSP surveys with sufficient resolution for plume imaging. In light of this, sequestration site selection in the future should consider not only the quality and appropriateness of the reservoir in the subsurface, but also the surface conditions and restrictions present that could affect the ability to monitor the reservoir over time sing seismic data.

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GRAPHICAL MATERIALS

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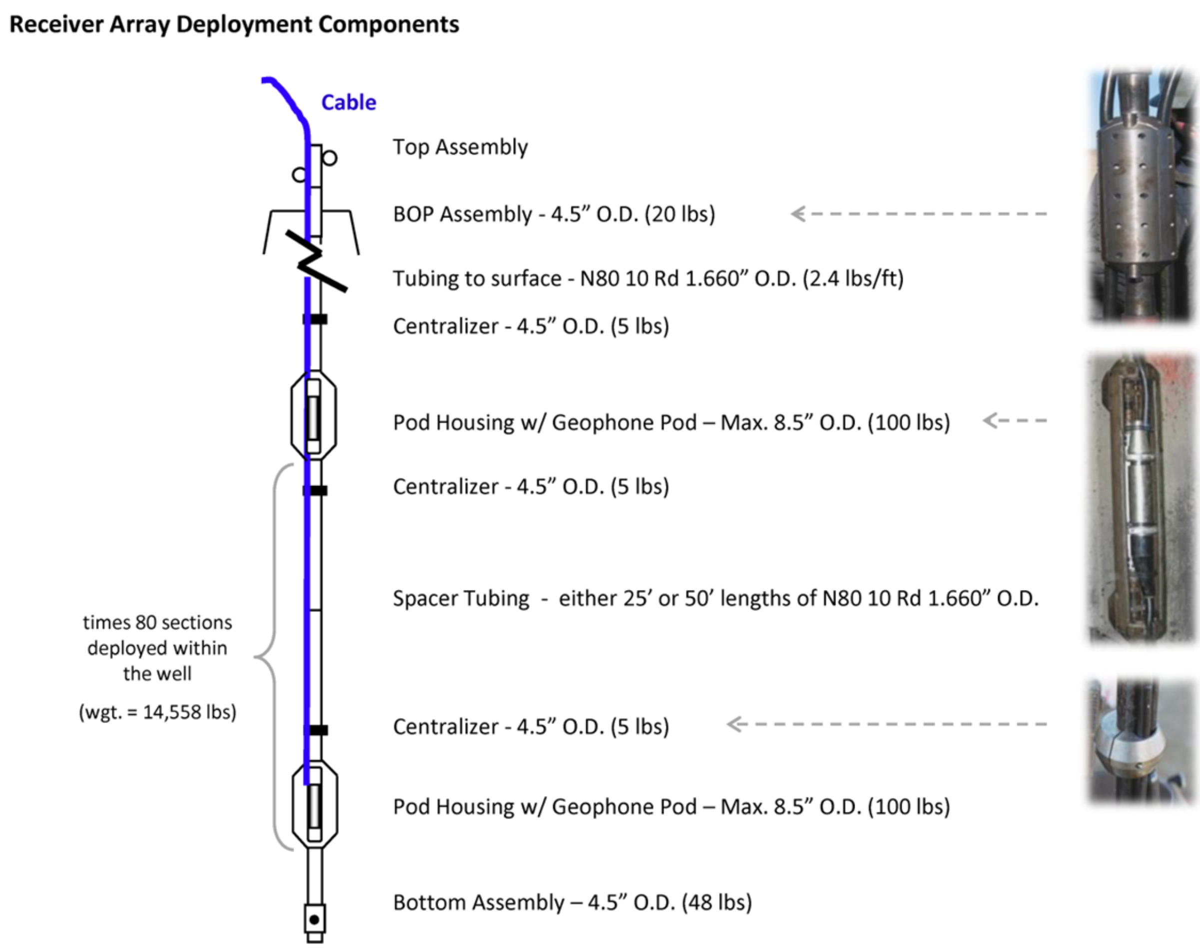


Figure 1. Mechanical component details of SeisRes2020's downhole 80-geophone array tool. Each "pod" housing contains a single 3-component geophone (see Fig. 2).

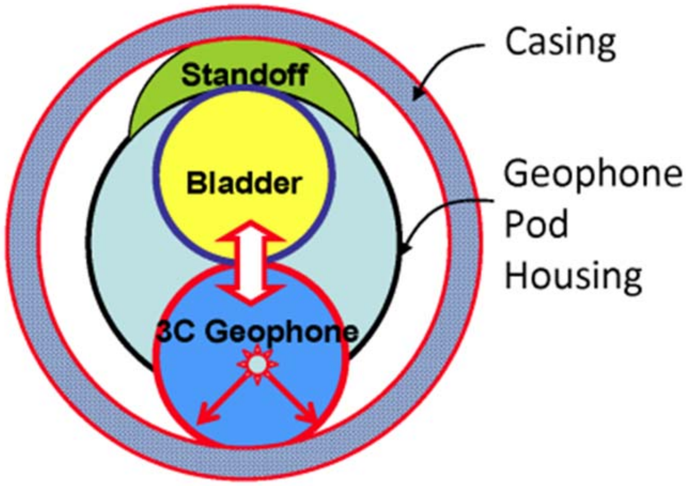


Figure 2. Schematic of geophone placement within wellbore. After lowering to the appropriate depth, the air bladders are inflated which secures the geophones to the well casing assuring adequate acoustical coupling to the surrounding geology.

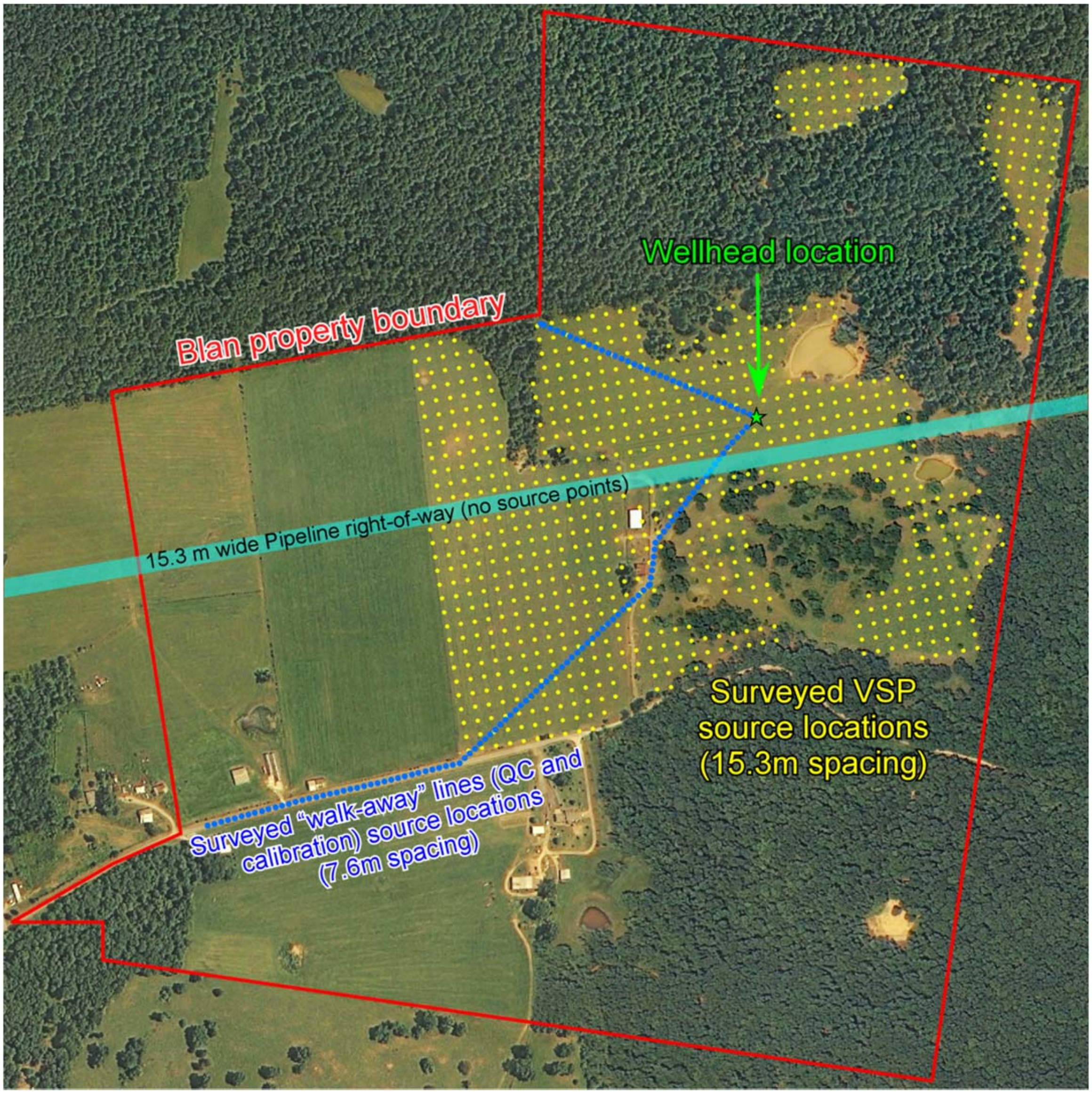


Figure 3. Blan property with locations of seismic source points. See Appendix 3 for additional maps. A vertical array of recording geophones was lowered into the well near the center of the group of source points (well location indicated by green star).

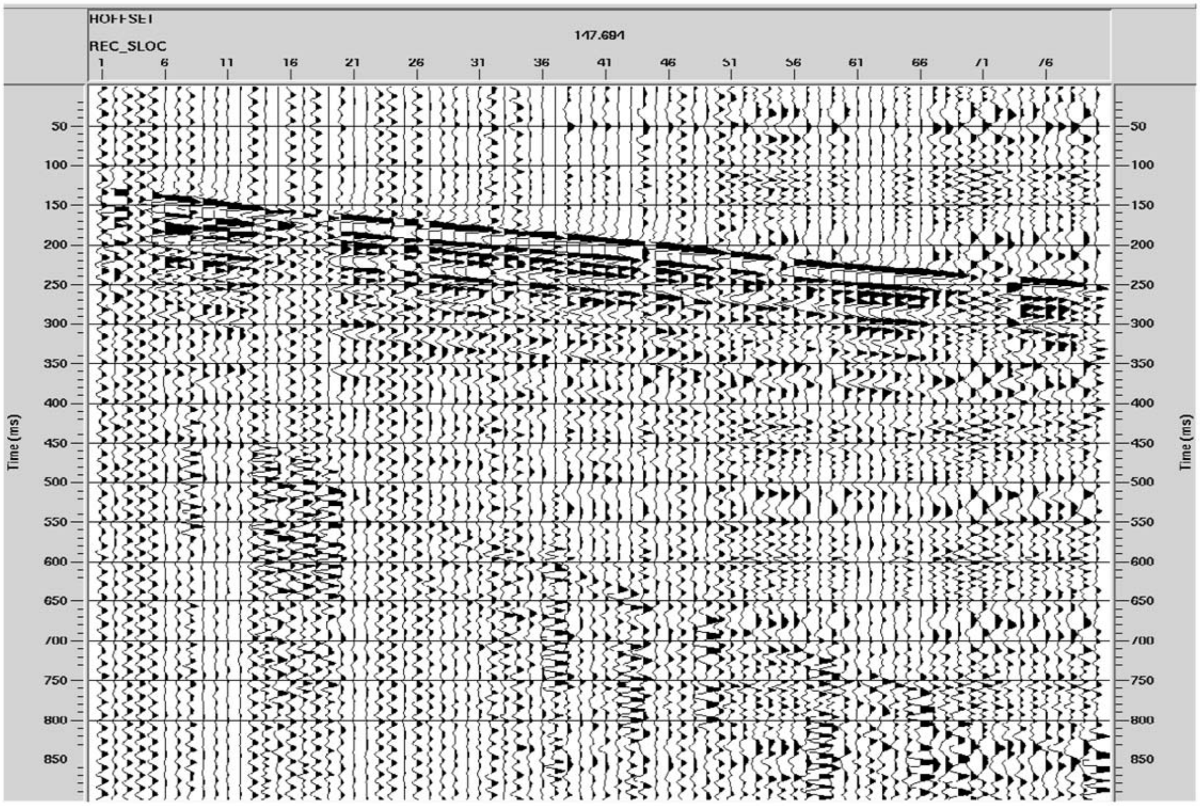


Figure 4. Sample single-event raw seismic data gather from the 80 downhole geophones. Note that the relatively high degree of electrical 60 Hz noise will be reduced later using appropriate frequency filters.

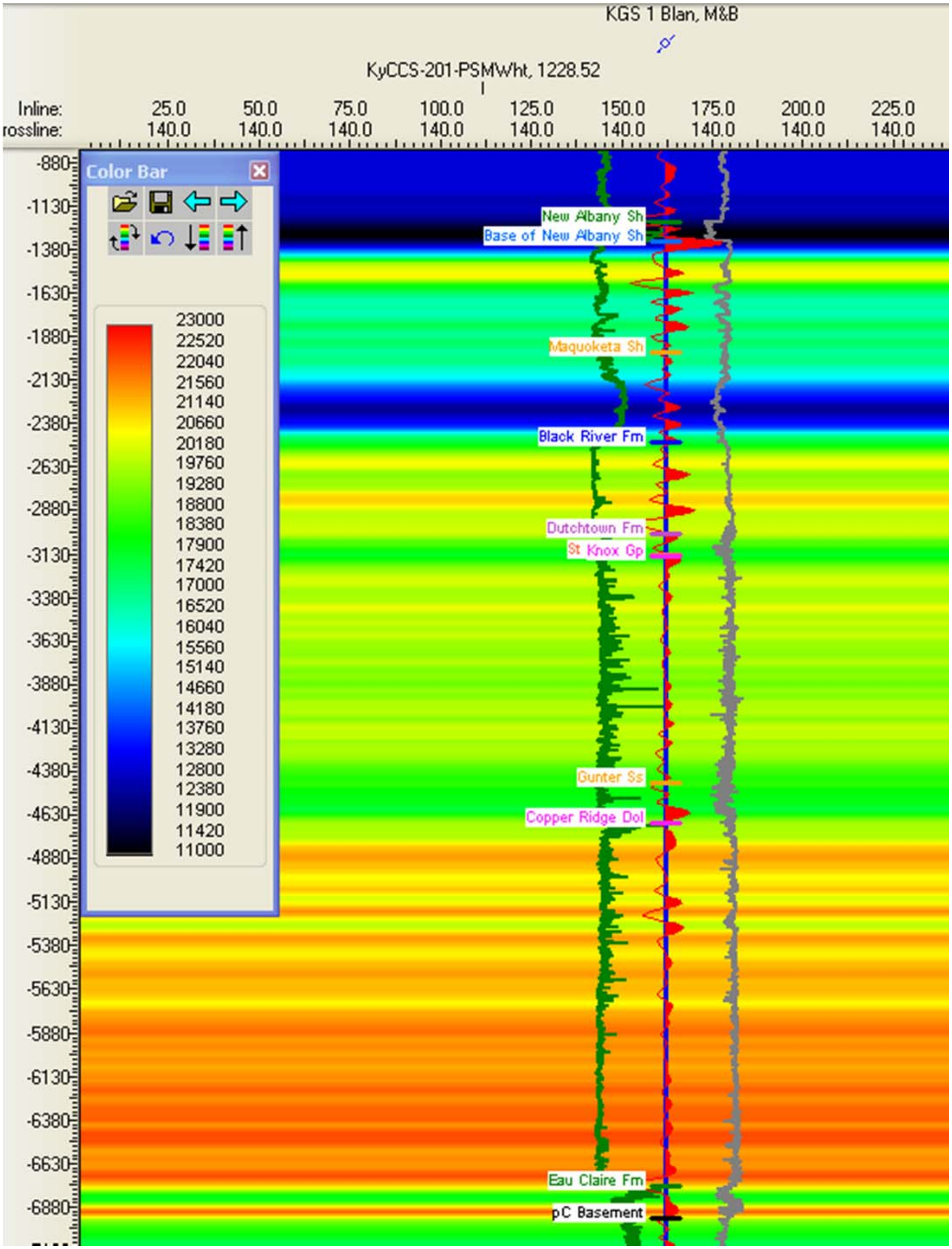


Figure 5. Sonic velocity model (ft/sec) used for VSP correlation and depth conversion. Gamma-ray (green) and acoustic (grey) logs from the Marvin Blan No. 1 well are marked for reference. A synthetic seismogram wavelet produced from the well logs is overlain in red.

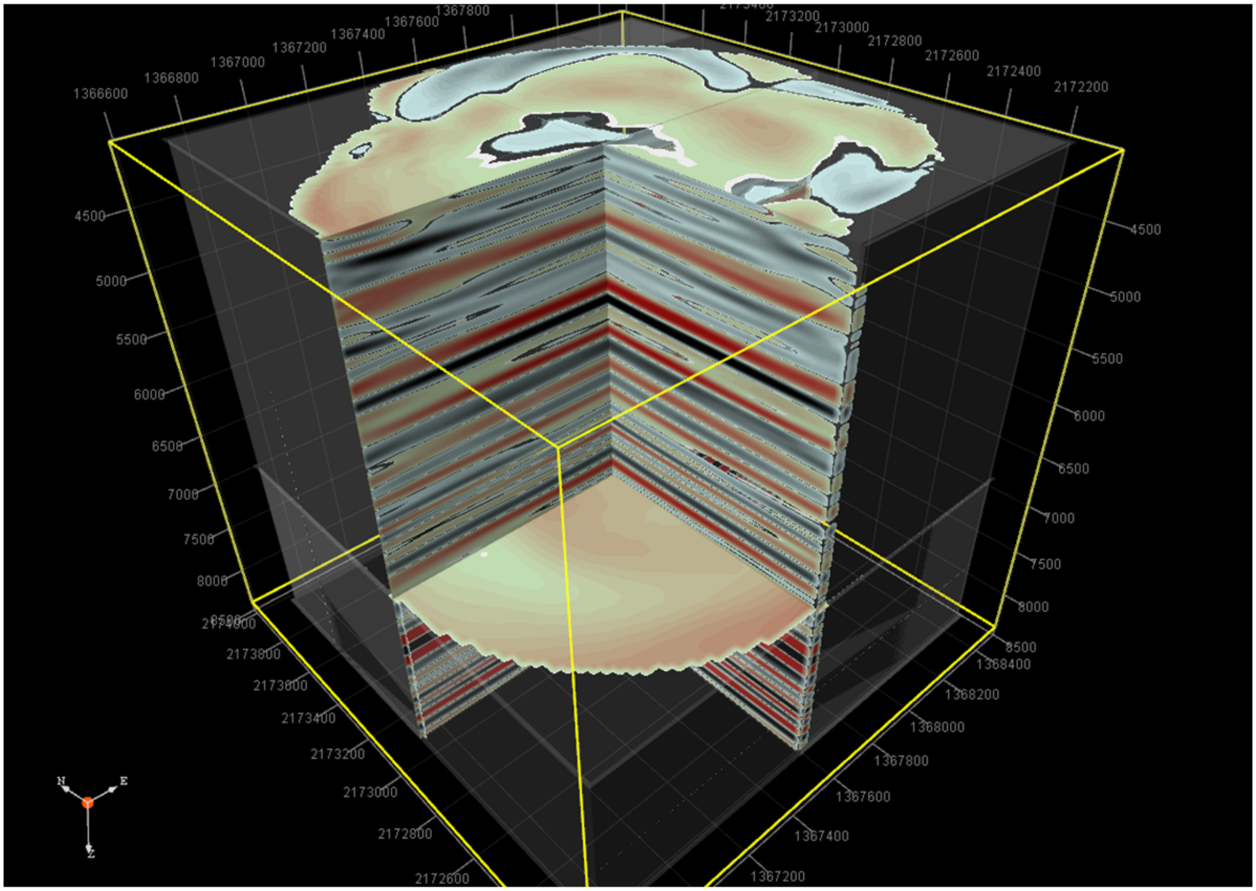


Figure 6. Processed 3D data of pre-injection (baseline) VSP survey centered on well, displayed with the southwest quadrant removed to display internal reflections. Positive reflections are displayed in black and negative wavelet reflections in red. Unlike 3D surface seismic surveys, the data "cube" for a VSP is actually cylindrical because all of the receiving geophones are located in a vertical line within the borehole. The lateral dimensions of the data volume (yellow cube) are equal to those in Figure 7, and equivalent to the blue square in Figure 8.

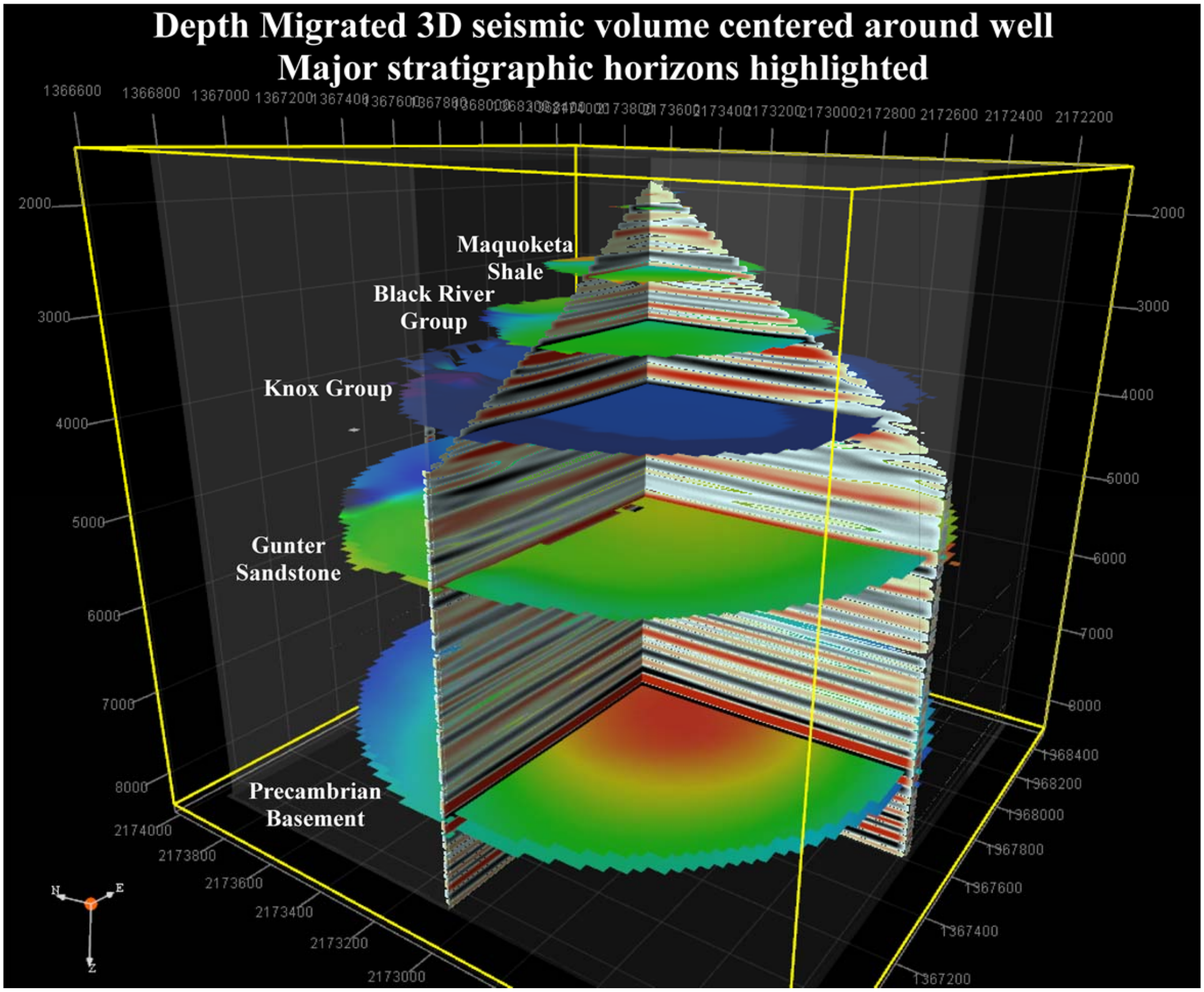


Figure 7. North-South and East-West profiles of pre-injection VSP data with selected stratigraphic horizons interpreted across the 3D space. Positive reflections are displayed in black and negative wavelet reflections in red.

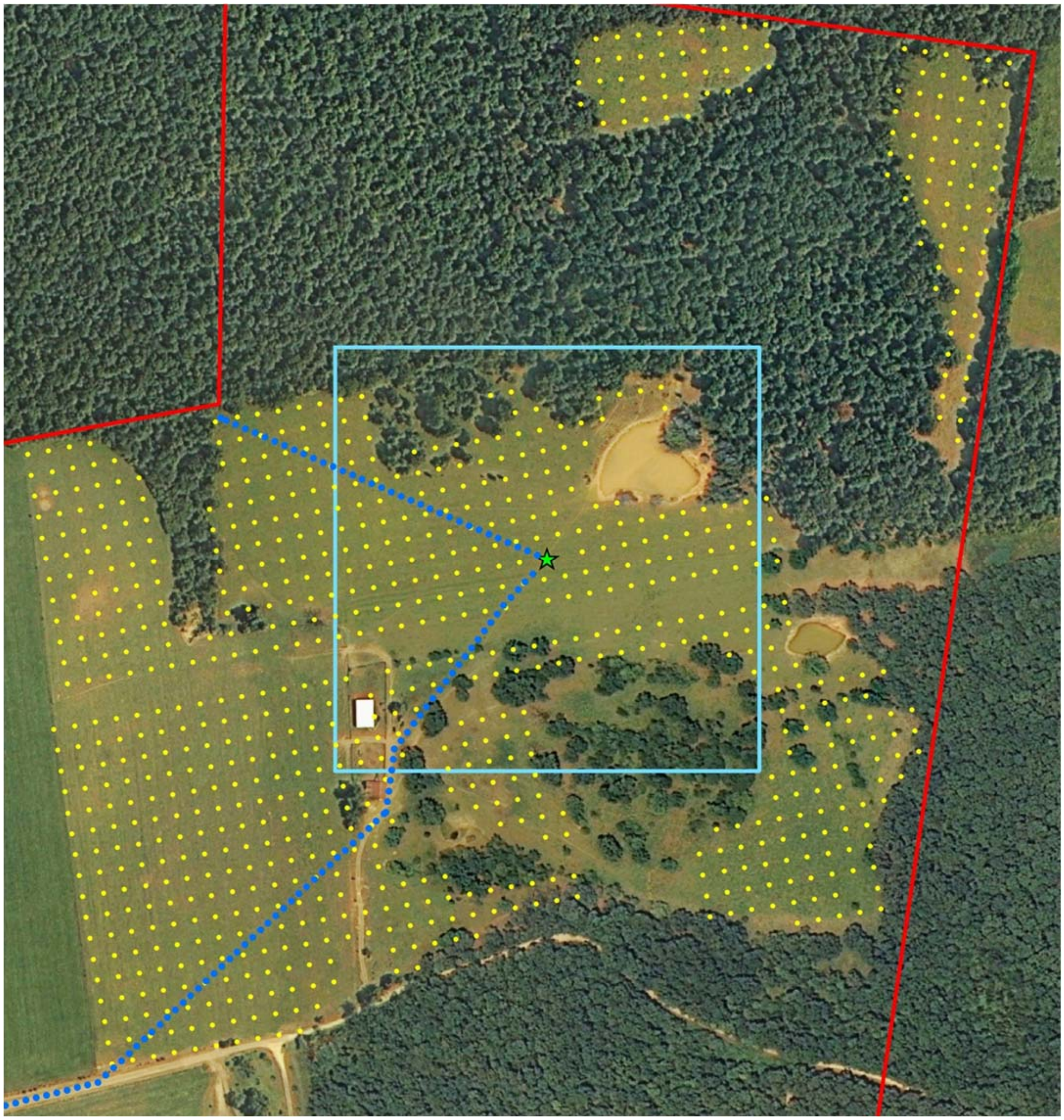
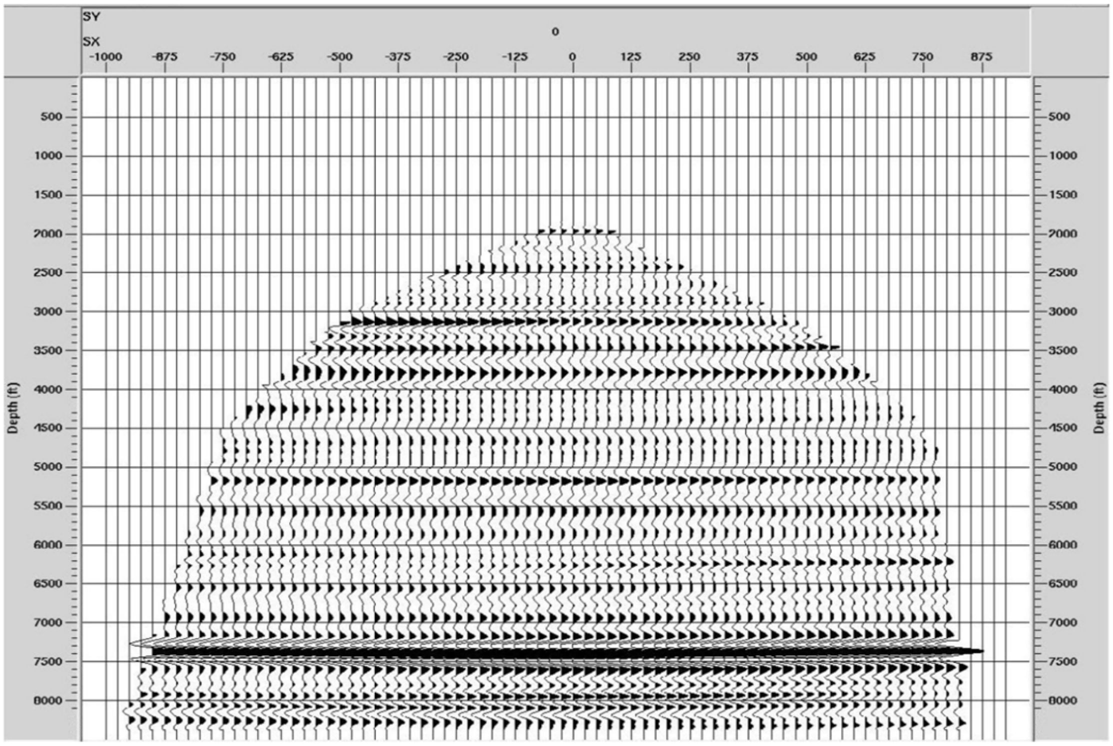


Figure 8. Areal footprint of the processed VSP data cube. Data cube location (highlighted blue square) centered over well head. Yellow points are 3D acquisition source locations and the dark blue points are source locations for the two "walk-away" profiles used for QC and calibration of processing techniques.



Depth migrated monitor image (West-East).

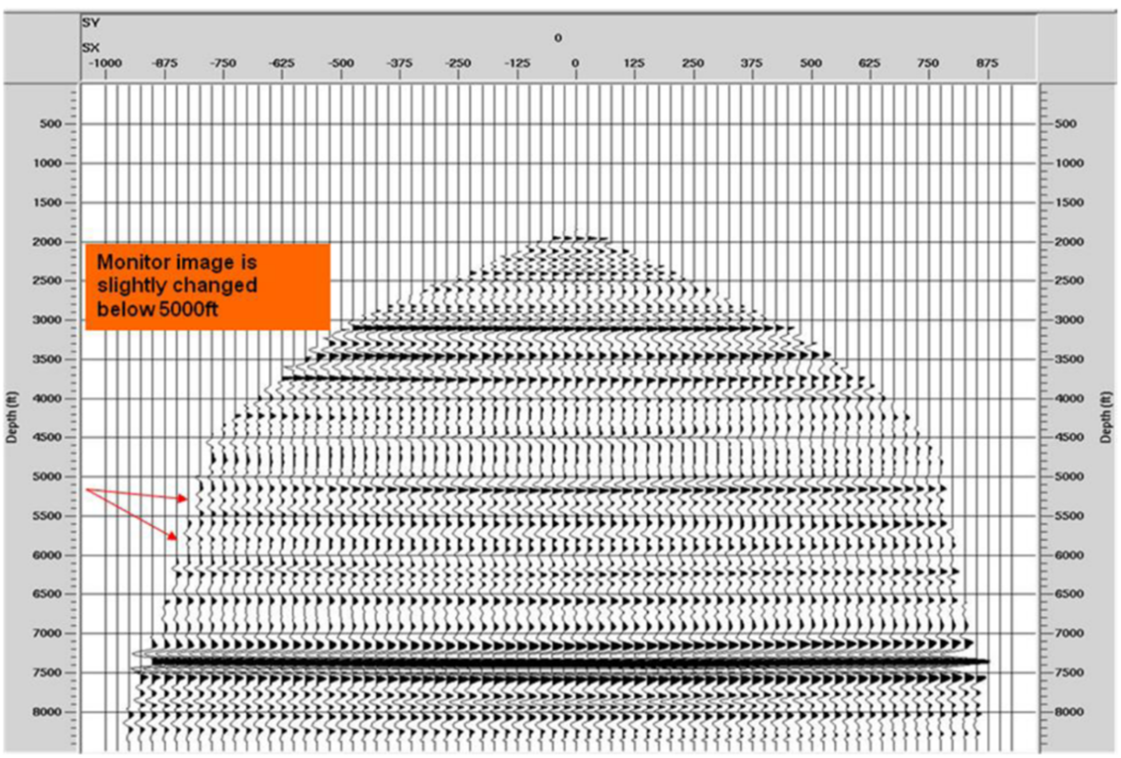


Figure 9. Example profiles across the post-injection VSP survey illustrating subtle changes within and below the injection zone of the waveform amplitudes following injection. Positive reflection amplitudes are colored black.

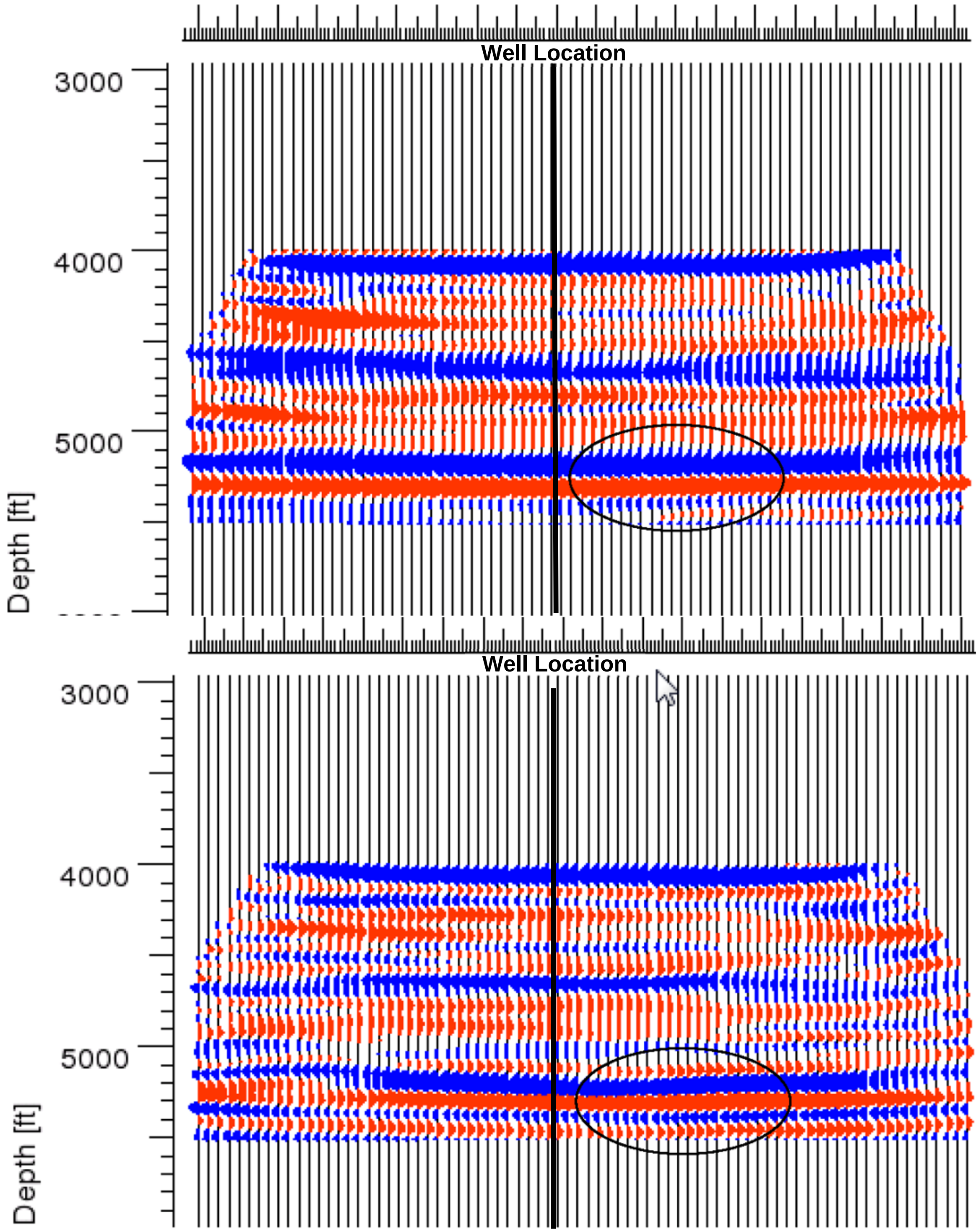


Figure 10. West-East depth migrated image slices centered on the well location, focused on the depths within and just above the injection zone. Upper image is from the pre-injection survey and the lower image is the post-injection image of the same profile. Note the difference in wavelet character (highlighted by black oval) within the injection zone (Gunter Sandstone). Positive reflections are displayed in red and negative wavelet amplitudes are in blue.

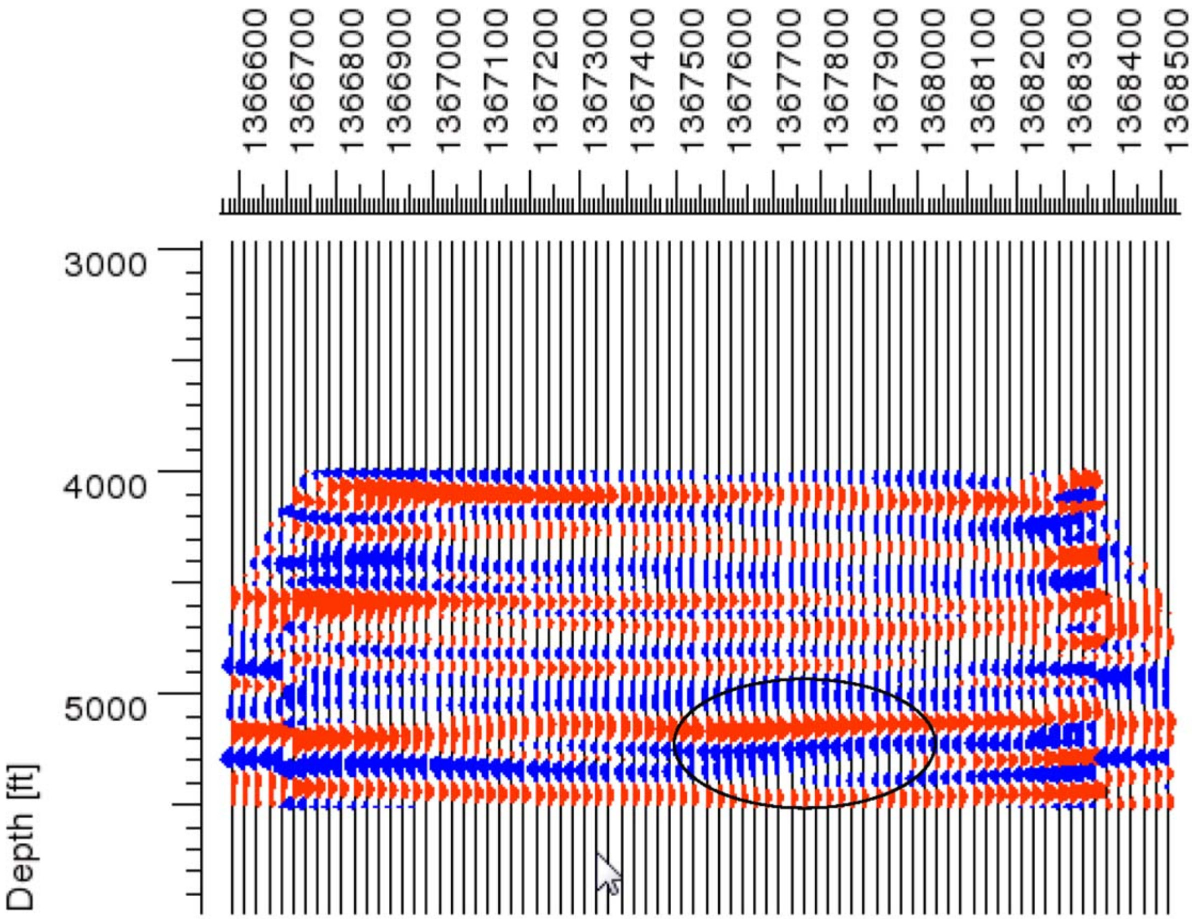


Figure 11. Depth-migrated West-East slice difference image (post-injection seismic response subtracted from the pre-injection response), focused on the injection depth. Positive reflections are displayed in red and negative wavelet amplitudes are in blue.

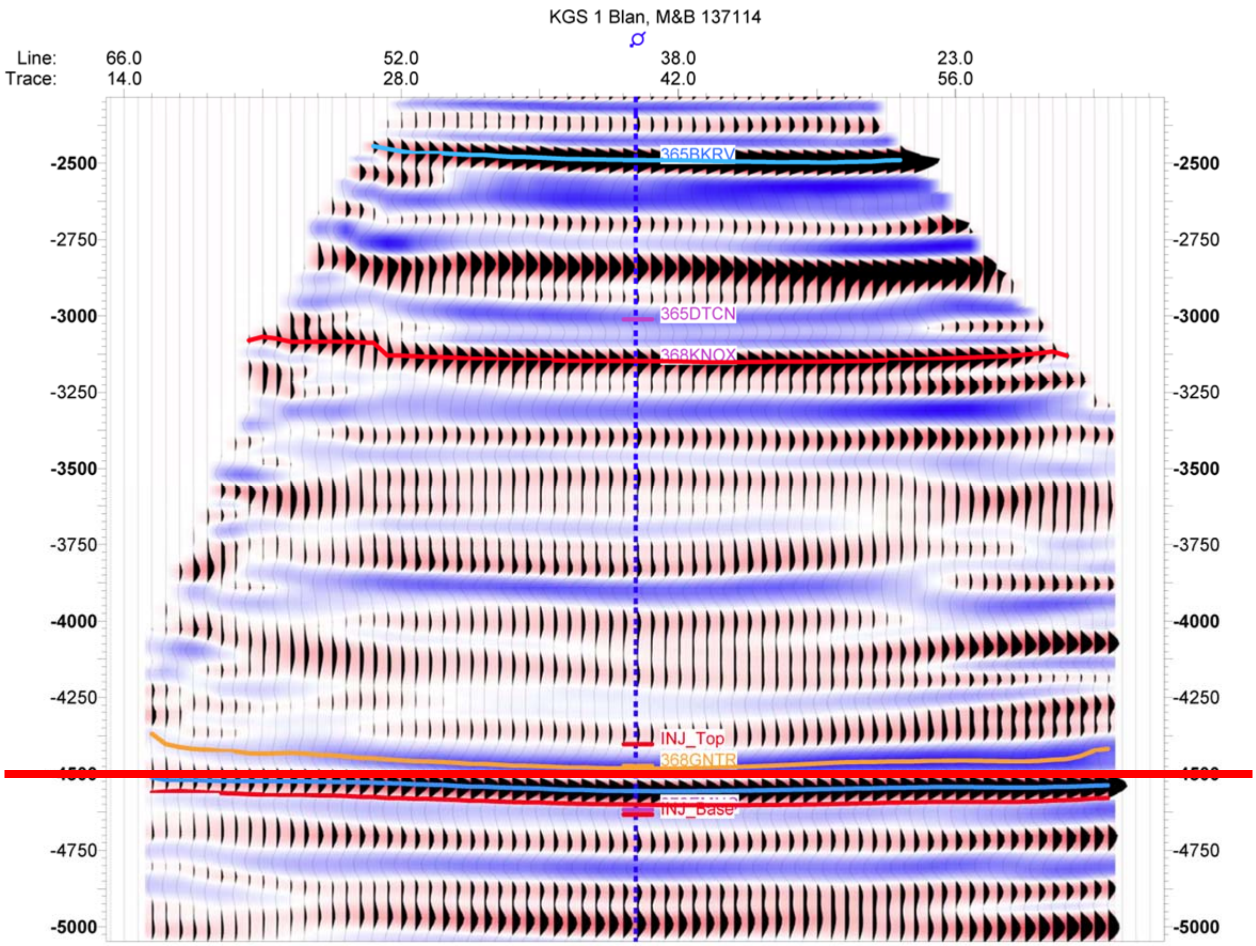


Figure 12. Northwest-Southeast depth-migrated seismic amplitude profile of post-injection survey. Note slight apparent down warping or "pull-down" of light blue horizon relative to horizontal (bold red line overlay at -4500 feet) near the well location (dashed blue vertical line). The top and base of the injection zone within the well bore are indicated by red dashes at -4403 and -4633 feet, respectively. Positive reflections are displayed in red and negative wavelet amplitudes are in blue.

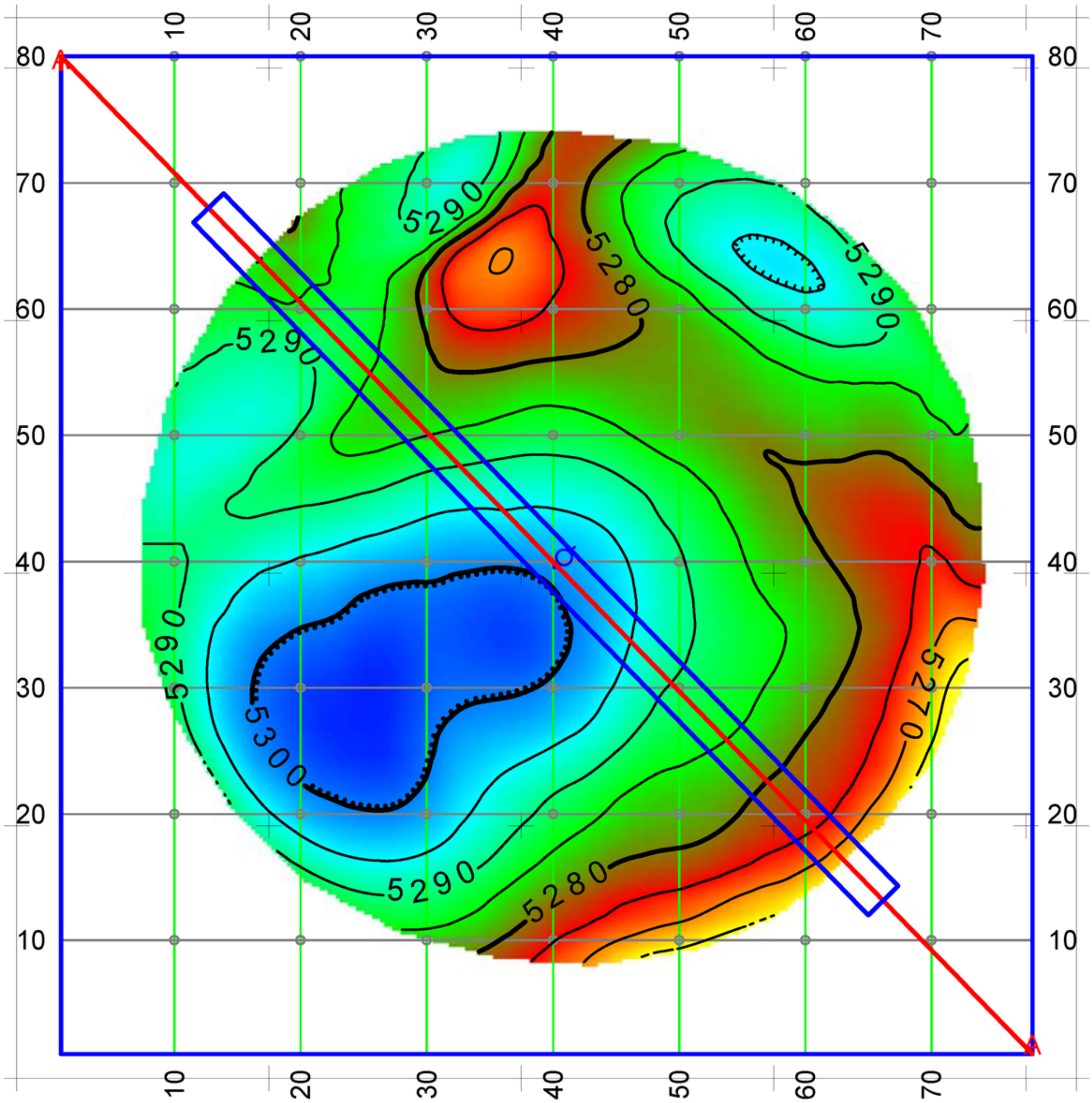


Figure 13. Calculated depth of the mid-Gunter reflection prior CO_2 to injection. Depth is in feet below the reference datum. The light blue horizon corresponds to the mid-Gunter reflection in Figure 12, and the bold red Northwest-Southeast line corresponds to the location of the profile shown in Figure 12.

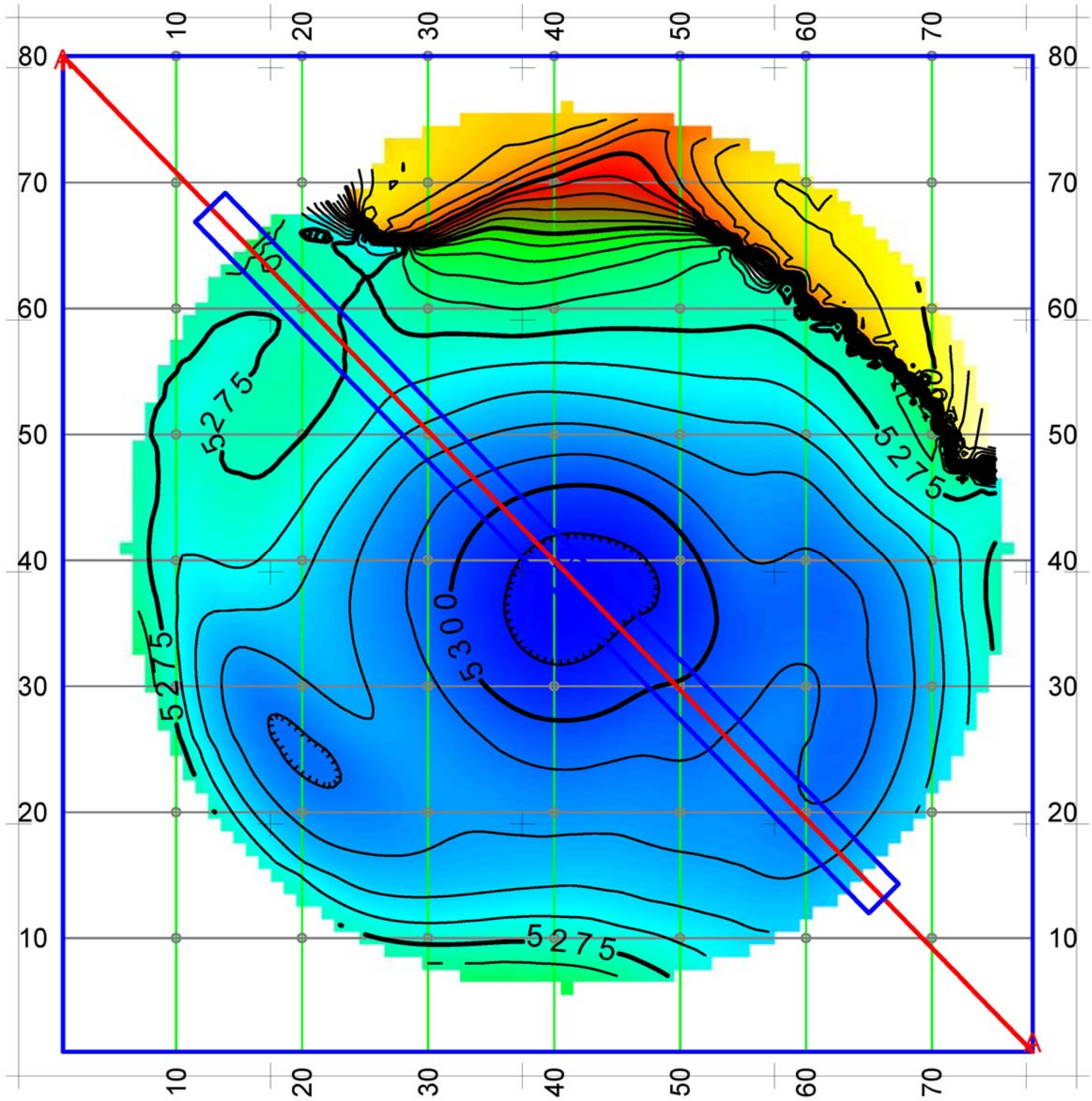


Figure 14. Calculated depth of the mid-Gunter reflection after CO_2 injection. Depth is in feet below the reference datum. The bold red Northwest-Southeast line corresponds to the location of the profile shown in Figure 12.

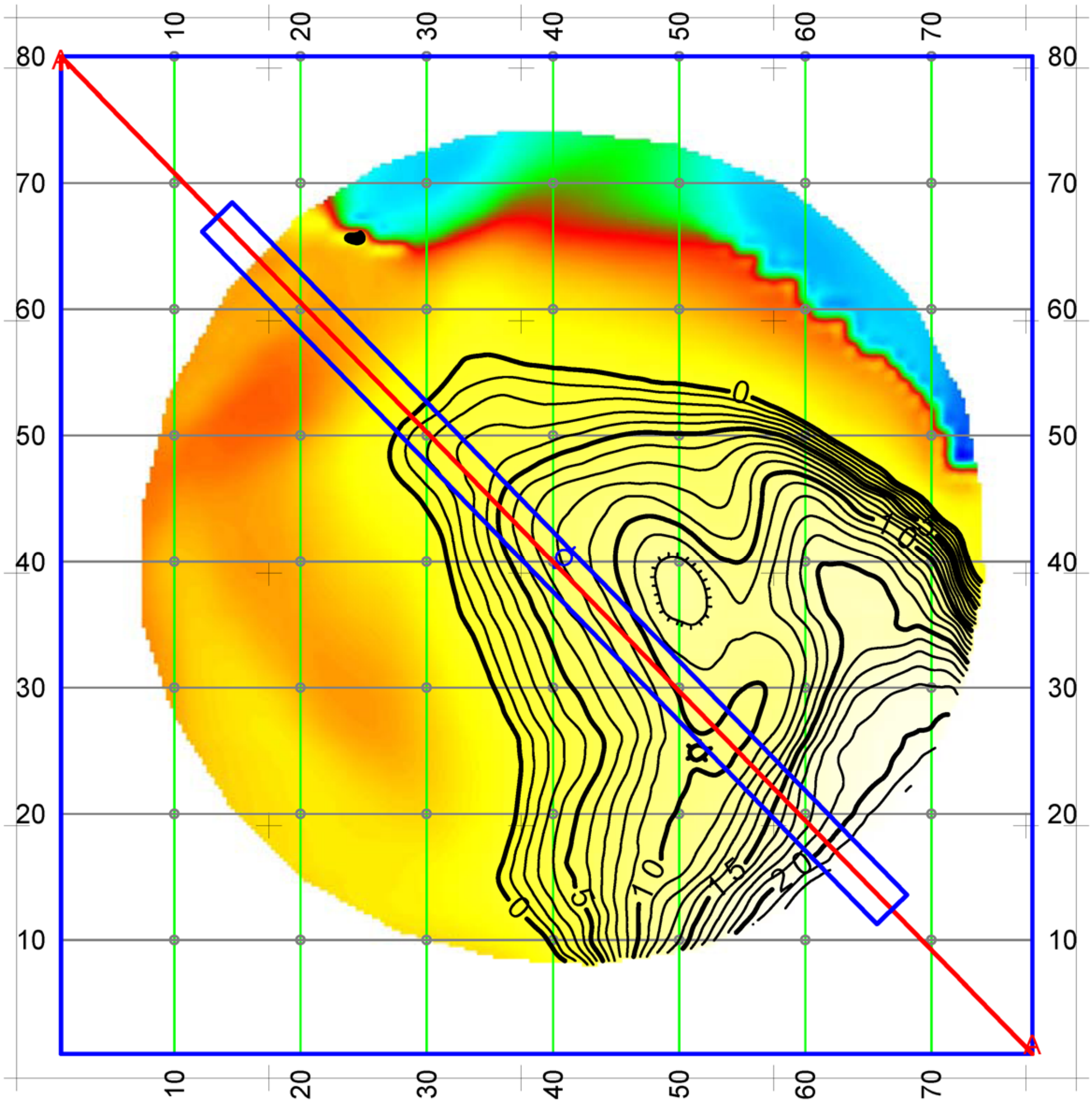


Figure 15. Calculated depth differential of the mid-Gunter reflection between the pre- and post-injection surveys. Positive values ("deeper" after injection) are contoured in feet.

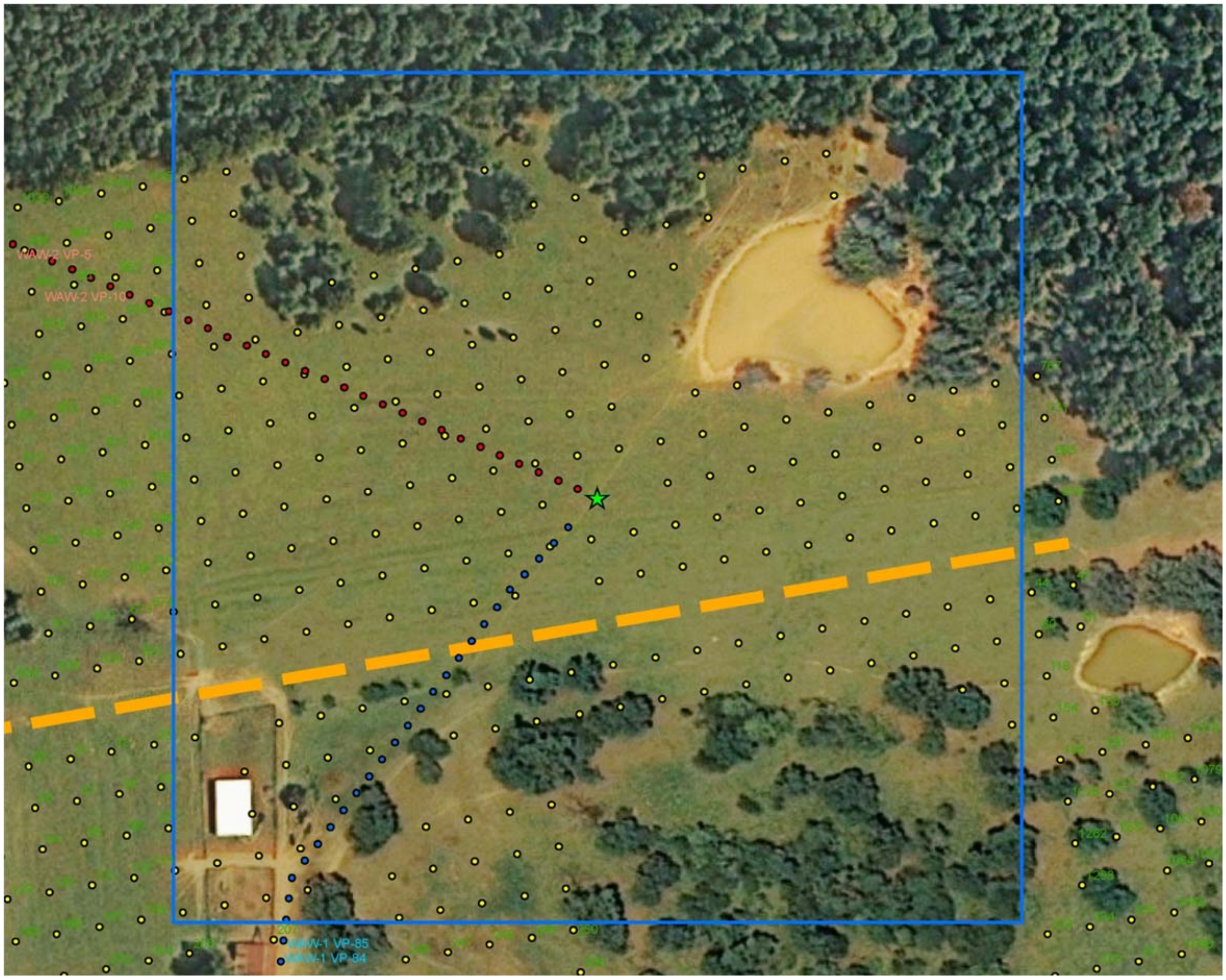


Figure 16. Detailed view of VSP survey area oulining the extent of the final data volume. Note that the areas in Figures 13–15 with highly anomalous values correspond to the regions with the least amount of input data because of limited seismic source points.

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Appendix 1

Core Analysis Reports

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Appendix 1A

Routine Core Analysis of Rotary Sidewall Cores Report

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Weatherford LABORATORIES

SUMMARY OF ROTARY CORE ANALYSES RESULTS

Vacuum Dried at 180°F Net Confining Stress: 1900 psi

Kentucky Geological Survey
Marvin Blan No. 1 Phase 2 Test Program Well

File: HH-48815
Date: 9-29-10

WFT Sample Number	Client Sample Number	Sample Depth, feet	Permeability, millidarcys		Porosity, percent		Grain Density, gm/cc	Lithological Descriptions
			to Air	Klinkenberg	Ambient	NCS		
1-1R	20	5089.0	0.0004	<0.0001	4.5	4.4	2.69	Chert sdol vpyr sdy
1-2R	19	5098.0	0.0003	<0.0001	1.8	1.7	2.86	Dol lt gry
1-3R	18	5107.0	0.0042	0.0012	1.6	1.4	2.83	Dol lt gry
1-4R	17	5116.0	199.	181.	12.1	11.9	2.63	Ss mg-crs
1-5R	16	5124.0	0.156	0.097	4.1	4.0	2.69	Ss mg scalc spyr shy streak
1-6R	15	5139.0	500.	468.	15.9	15.8	2.64	Ss mg
1-7R	14	5147.0	0.0052	0.0015	2.9	2.8	2.69	Ss fg-mg sdol
1-8R	13	5155.0	196.	179.	13.0	12.8	2.64	Ss mg
1-9R	12	5165.0	0.106	0.062	8.0	7.8	2.63	Ss vfg ool
1-10R	11	5168.0	0.0003	<0.0001	2.9	2.8	2.82	Dol xln
1-11R	10	5175.0	12.1	9.70	6.9	6.7	2.65	Ss fg-mg
1-12R	9	5178.0	8.34	6.58	4.5	4.3	2.71	Ss fg-mg sdol
1-13R	8	5187.0	0.0016	0.0003	1.1	0.9	2.74	Ss fg-mg sdol w/shy strks
1-14R	7	5195.0	1570.	1500.	19.5	19.3	2.67	Ss mg vugs
1-15R	6	5201.0		+	23.3	23.1	2.63	Ss fg chlky ool qtz incl
1-16R	5	5207.0	248.	228.	11.8	11.6	2.64	Ss fg-mg
1-17R	4	5213.0	580.	544.	16.2	16.0	2.64	Ss mg
1-18R	3	5219.0		<0.0001	1.8	1.6	2.76	Ss vfg-fg dol
1-19R	2	5227.0	0.165	0.103	9.5	9.3	2.72	Ss vfg foss sdol
1-20R	1	5235.0	30.0	25.2	8.5	8.3	2.64	Ss fg-mg
		Average values:	186.	209.	8.5	8.3	2.70	

+ Indicates the sample is unsuitable for this type of measurement

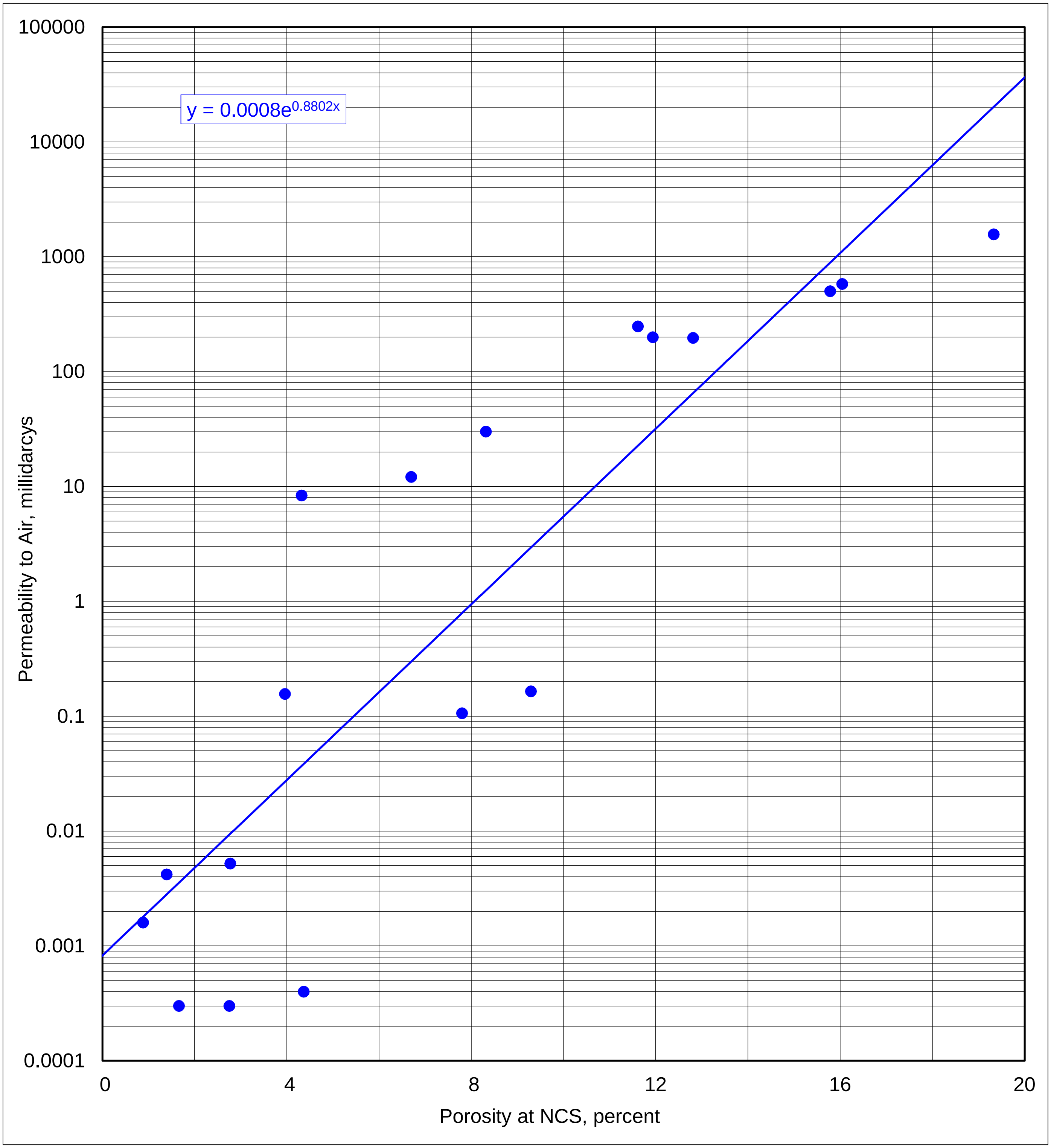
Weatherford LABORATORIES

PERMEABILITY VERSUS POROSITY

Vacuum Dried at 180°F Net Confining Stress: 1900 psi

Kentucky Geological Survey
Marvin Blan No. 1 Phase 2 Test Program Well

File: HH-48815
Date: 9-29-10



Appendix 1B

CO_2/Brine Relative Permeability Tests Report

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Weatherford
LABORATORIES

SUMMARY OF CO_2 - WATER RELATIVE PERMEABILITY TEST RESULTS

Steady-State Method Extracted-State Samples

Net Confining Stress: Samples 4-104A and 4-114A (1400 psi), Samples 5-32A and 5-78A (1900 psi)

Kentucky Geological Survey
Marvin Blan No. 1 Well
Class V CO2 Test Well

Hancock County, Kentucky
File: HH-43701
Date: 11-19-10

Sample Number	Sample Depth, feet	Permeability, millidarcys		Porosity, fraction	Initial Conditions			Terminal Conditions				Fluid Recovery	
					Fluid Saturation, fraction pore space		Specific Permeability to Brine, millidarcys	Fluid Saturation, fraction pore space		Effective Permeability to Fluid, millidarcys	Relative Permeability to Fluid*, fraction		
		to Air	Klinkenberg		water	CO_2		water	CO_2			fraction pore space	fraction FIP
4-104A	3863.55	0.0034	0.0009	0.063	Permeability too Low for Steady-State Testing								
4-114A	3873.80				Sample Fractured (Unsuitable for Steady-State Testing)								
5-32A	5052.85	0.212	0.138	0.043	1.000	0.000	0.023	0.528	0.472	0.014	0.099	0.472	0.472
	Post Test	*0.113*	*0.067*	*0.045*									
5-78A	5098.50	11.2	8.86	0.093	1.000	0.000	3.68	0.202	0.798	0.051	0.0058	0.798	0.798
	Post Test	*1.88*	*1.37*	*0.099*									
Average values:		**5.71**	**4.5**	**0.069**	**1.000**	**0.000**	**1.85**	**0.365**	**0.635**	**0.033**	**0.052**	**0.635**	**0.635**

* Relative to Klinkenberg Permeability

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CO_2-WATER RELATIVE PERMEABILITY

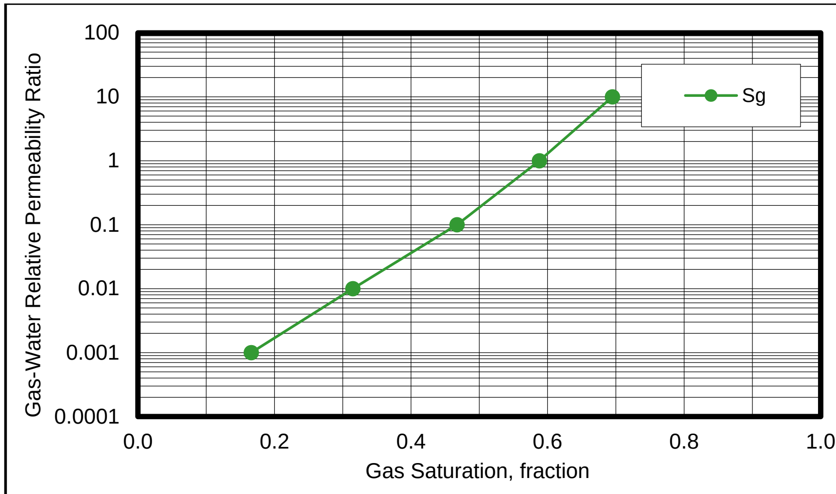
Steady-State Extracted-State Sample

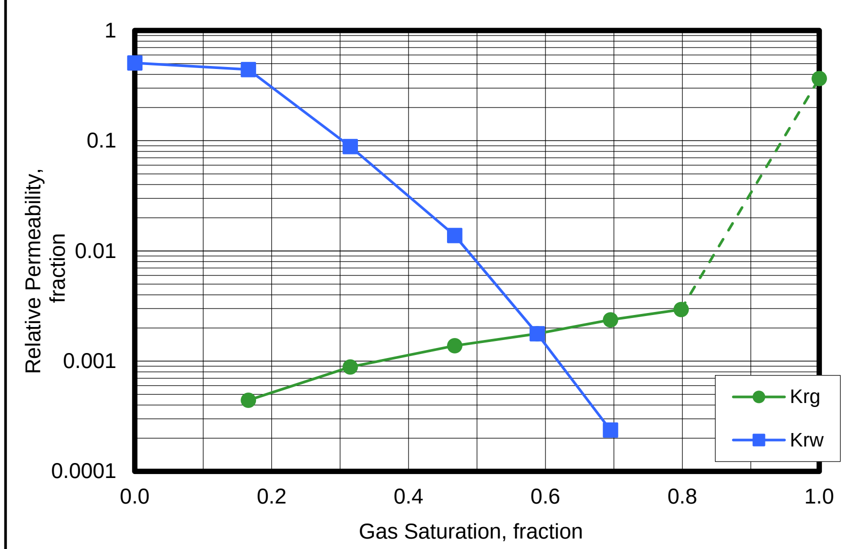
Net Confining Stress: 1900 psi   Temperature: 125°F

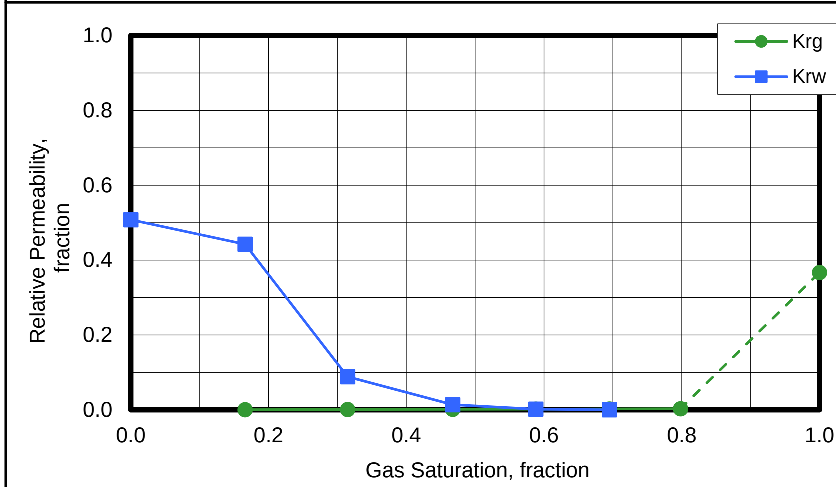
Kentucky Geological Survey
Marvin Blan No. 1
Hancock, KY
File: HH-43701
Date: 11-19-10

Sample Number:	5-78A
Sample Depth, feet:	5098.50
Permeability to Air, md:	11.2
Klinkenberg Permeability, md:	8.86
Porosity, fraction:	0.093
Initial Water Saturation, fraction:	1.00
Permeability to Brine, md:	3.68

Gas Saturation, fraction	Gas-Water Relative Permeability Ratio	Relative Permeability to Gas*, fraction	Relative Permeability to Water*, fraction
Gas Saturation Inecreasing			
0.000			0.508
0.166	0.001	0.00044	0.442
0.315	0.01	0.00089	0.0886
0.467	0.1	0.00138	0.0138
0.588	1.	0.00177	0.00177
0.695	10.	0.00237	0.00024
0.798		0.00294	
1.00		0.367	







Weatherford LABORATORIES

CO_2-WATER RELATIVE PERMEABILITY

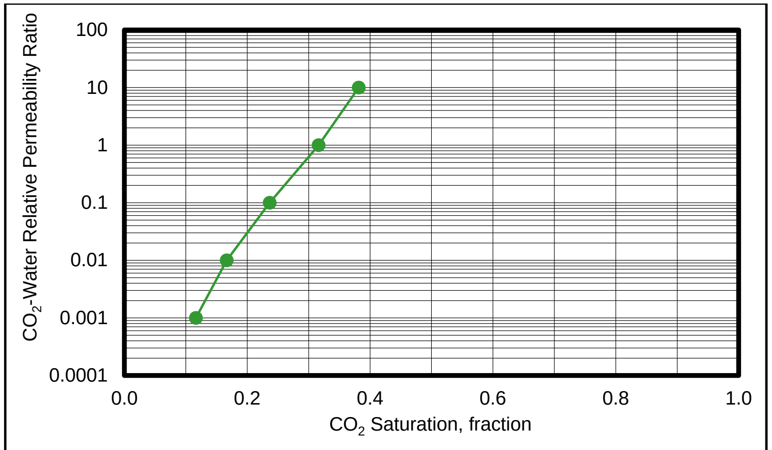
Steady-State Extracted-State Sample

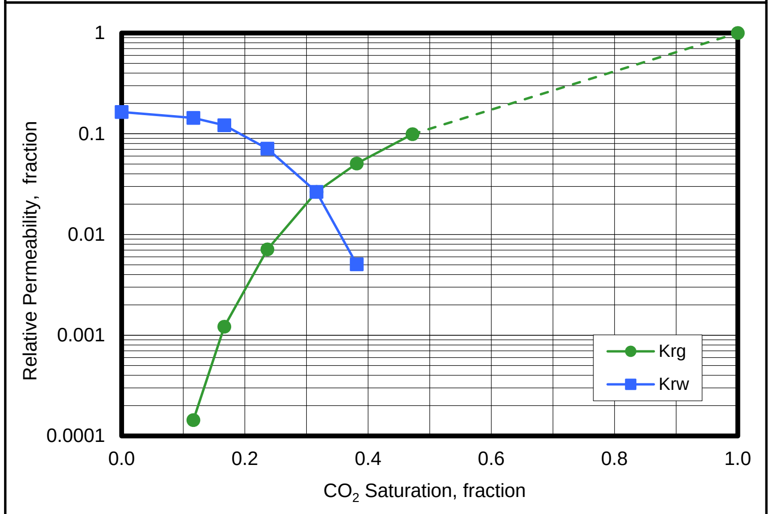
Net Confining Stress: 1900 psi Temperature: 125°F

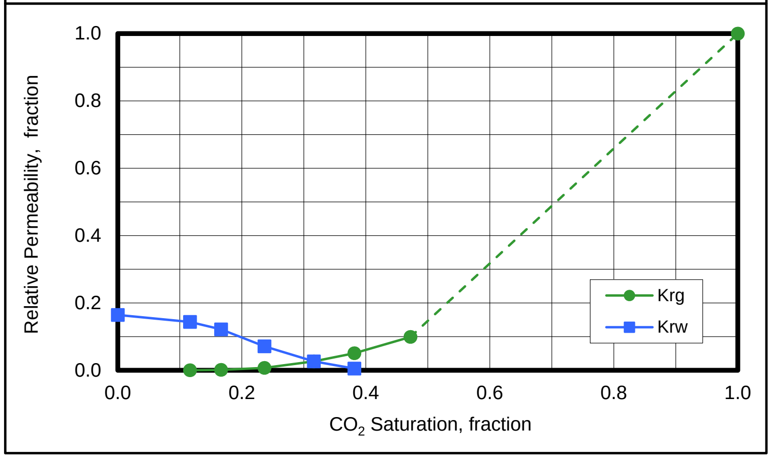
Kentucky Geological Survey
Marvin Blan No. 1 Well
Hancock, KY
File: HH-43701
Date: 11-19-10

Sample Number:	5-32A
Sample Depth, feet:	5052.85
Permeability to Air, md:	0.212
Klinkenberg Permeability, md:	0.138
Porosity, fraction:	0.043
Initial Water Saturation, fraction:	1.00
Permeability to Brine, md:	0.023

CO_2 Saturation, fraction	CO_2-Water Relative Permeability Ratio	Relative Permeability to CO_2*, fraction	Relative Permeability to Water*, fraction
	CO_2 Saturation Increasing		
0.000	0.0000	0.0000	0.16
0.116	0.0010	0.0001	0.144
0.167	0.010	0.0012	0.121
0.237	0.100	0.007	0.071
0.316	1.00	0.026	0.026
0.382	10.0	0.051	0.005
0.472		0.099	
1.00		1.00	







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Appendix 1C

Petrographic Study of Conventional Core
for
Kentucky Geological Survey Marvin Blan No. 1,
Hancock County, Ky
[Maquoketa Shale Samples Only]

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PETROGRAPHIC STUDY
OF CONVENTIONAL CORE
FOR
KENTUCKY GEOLOGICAL SURVEY
MARVIN BLAN NO. 1
HANCOCK COUNTY, KY

WEATHERFORD LABORATORIES FILE NUMBER: HH-43701

Weatherford
LABORATORIES

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5200 North Sam Houston Parkway West, Suite 500
Houston, Texas 77086
832-375-6800

October 10, 2010

Attn: Rick Bowersox
Kentucky Geological Survey
228 Mining Minerals and Resources Building
University of Kentucky
Lexington, KY 40506-0107

SUBJECT: *Data Report - Petrographic Study of Conventional Core*
Marvin Blan No. 1
Hancock County, Kentucky
Weatherford File Number: HH-43701

Dear Mr. Bowersox:

Eleven (11) conventional core plugs from the above referenced well were submitted for thin section preparation. These samples were selected for further analysis utilizing X-ray diffraction (XRD) and detailed thin section analysis. Detailed thin section analysis includes quantitative point count tabulation, graincoating estimates, grain size analysis, and porosity differentiation. This report provides all data and pho tomicrographs associated with these analyses. One (1) report copy and one (1) data CD of this report are provided; additional copies can be prepared upon request. It has been a pleasure to provide this study for the Kentucky Geological Survey. Please feel free to contact us if you have any questions concerning this report or if we can be of further service.

Sincerely,
Weatherford Labs

Keith Goggin R.P.G.
Manager, Sedimentology

Bradley J. Walls
Project Geologist

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PETROGRAPHIC RESULTS

Three hundred (300) feet of conventional core from Kentucky Geological Survey, Marvin Blan No. 1, Hancock County, Kentucky were submitted for petrographic and sedimentologic analysis; specifically, a detailed core description, eighteen (18) samples for X-ray diffraction (XRD) analysis, forty eight (48) samples for thin section preparation, of which eleven (11) were photographed and selected for detailed thin section descriptions. This report contains petrographic data only; no interpretation or integration of the data was requested. A summary of the petrographic analytical procedures are provided in Appendix A, thin section photographs with facing page captions and the thin section modal analysis are provided in Appendix B, and a summary of the X-ray diffraction (XRD) analysis data is provided in Appendix C. Table 1 provides a list of samples analyzed in this study.

Table 1
Analyses Clustered by Well Name

Sample Depth (feet)	XRD Analysis	Thin Section Preparation	Detailed Thin Section Analysis	Thin Section Analysis Photography
2800.85	◆	◆	◆	◆
2803.85	◆	◆	◆	◆
2806.90	◆	◆	◆	◆
2809.80	◆	◆	◆	◆
2812.80	◆	◆	◆	◆
2815.90	◆	◆	◆	◆
2818.80	◆	◆	◆	◆
2821.90	◆	◆	◆	◆
2824.90	◆	◆	◆	◆
2827.90	◆	◆	◆	◆
2830.85	◆	◆	◆	◆
3363.50		◆		
3364.50	◆	◆		
3384.20		◆		
3764.00		◆		
3768.30		◆		
3779.45		◆		
3782.30		◆		
3794.20		◆		
3826.90		◆		
3840.00		◆		
3845.55		◆		
3858.60	◆			
3863.55		◆		
3865.20		◆		

3866.90	◆	◆		
3872.90		◆		
3873.80		◆		
3882.10-3882.70		◆		
5024.90		◆		
5025.30		◆		
5030.10		◆		
5042.90		◆		
5043.00		◆		
5044.70	◆			
5052.85		◆		
5053.65		◆		
5061.50	◆	◆		
5066.65		◆		
5080.30		◆		
5083.40		◆		
5092.20		◆		
5095.50		◆		
5098.50		◆		
5110.40		◆		
5116.90	◆			
6132.70		◆		
6135.50	◆	◆		
6138.70		◆		
6145.80		◆		
6148.80		◆		

APPENDIX A:

PETROGRAPHIC ANALYTICAL PROCEDURES

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Cleaning Samples for Petrographic Analysis:

Samples are wrapped, for the cleaning process, in a cotton cloth to help keep the sample from disaggregating and for identification purposes. The wrapped samples are put into a cold cleaning soxhlet and extracted of hydrocarbons using a chloroform-methanol azeotrope (70% Chloroform, 30% Methanol). After one to two days, samples are tested to make sure hydrocarbons are fully extracted. This is done by washing the samples with dichloromethane while under a UV light; if the sample fluoresces a yellow/green the samples are considered still "dirty" and are put back into the azeotrope or azeo soxhlet. "Dirty" azeotrope is replaced with fresh azeotrope. Samples will be retested every one to two days until clean.

Samples clean of hydrocarbons (no fluorescence) are placed in the cold cleaning soxhlet containing 100% methanol to further leach samples of salts. After one to two days, samples are tested to make sure salts are completely leached out. This is done by pouring approximately 6 ml of the methanol (in which the samples are submerged) into a beaker. Approximately 4 drops of silver nitrate are added to this methanol. If the methanol-silver nitrate solution becomes milky-white and cloudy the samples are still salty and will need to remain in methanol. "Dirty" methanol is replaced with fresh methanol. The samples will be retested every one to two days until clean. Samples clean of salts are taken out of the soxhlet and placed under a hood to vent all solvent fumes from samples and cloth. Once completely vented, samples are dried in a convection oven at approximately 85-95 degrees Celsius and turned over to their respective labs.

Samples selected for thin section analysis were prepared by first vacuum impregnating with blue-dyed epoxy. The samples were then mounted on an optical glass slide and cut and lapped in water to a thickness of 0.03 mm (30 microns). The samples were stained for potassium feldspar (K-feldspar) using the method described by Bailey and Stevens in 1960, and by Laniz and others in 1964. First, hydrofluoric acid (HF) is used to etch the surface. Then sodium cobaltinitrite is used to stain any K-feldspar on that surface a yellow color. Next, the sections were stained using Alizarin Red S for calcite, and potassium ferricyanide for ferroan dolomite/calcite. When present, dolomite will appear clear, ankerite will appear turquoise blue, calcite will appear red, and ferroan calcite will appear purple. The prepared sections were then covered with index oil and temporary cover slips, and then analyzed using standard petrographic techniques.

X-Ray Diffraction (XRD) Analysis

A representative portion (preferably 2 grams) of each sample is typically cleaned utilizing a mixture of chloroform and methyl alcohol (85%: 15% respectively). The chloroform is used to remove any oil. The methyl alcohol is used to remove any salts associated with the mud system. However, if indigenous salt is to be retained in the sample, only chloroform is used in the cleaning process.

The sample is dried in a laboratory oven at a temperature of 110°C for a minimum of 1 hour. The sample is then ground in a Retsch MM-400 ball mill to a fine powder (1-5 microns). A portion of the ground sample is then loaded into a stainless steel sample holder. The sample holder has been modified to accommodate a side loading method. This side loading method allows the sample to be sifted and retain a random particle orientation. This procedure helps minimize preferred orientation.

This "bulk" sample mount is scanned with a Bruker AXS D4 Endeavor X-ray diffractometer using copper K-alpha radiation. A nickel filter slit is in place to eliminate K-beta peaks and an air scatter screen to help reduce background noise. The scanning parameters for a bulk scan are from 5° 2-theta to 70° 2-theta. The step size is 0.020° and the dwell time at each step is 0.5 seconds.

Computer analysis of the diffractograms provide identification of mineral phases and quantitative analysis of the relative abundance (in weight percent) of the various mineral phases. MDI Jade 9+ 2009 and PDF 4+ 2009 software and the ICDD JCPDS mineral database, with over 600,000 known compounds, are used to identify mineral phases present. It should also be noted that X-ray diffraction does not allow the identification of non-crystalline (amorphous) material, such as organic material and volcanic glass.

An oriented clay fraction mount is prepared for each sample from the ground powder. The samples will be checked for any carbonate minerals using 10% HCl. If carbonate material is present then the samples will be treated with 10% HCl to remove all carbonate material. The samples are then washed using a small amount of sodium hexa-meta-phosphate (a deflocculating agent) mixed with distilled water. The samples are then dismembrated using a Fisher Scientific Ultra Sonifier to bring the clays into suspension.

The samples are further size fractionated by accelerating Stokes Law in a centrifuge to separate the size fraction to between 2 and 15 microns. The supernatant containing the clay fraction is passed through a Fisher filter membrane apparatus allowing the solids to be collected on a cellulose metrucel membrane filter.

These solids are mounted on a glass slide, dried, and scanned in the Bruker AXS diffractometer. The following scan parameters are utilized for clay separates: 2° 2-theta to 30° 2-theta at a step size of 0.025° per step and a dwell time of 0.25 seconds at each step.

The oriented clay mount is then glycolated using 99.9% ethylene glycol for 12 hours at a temperature of 110°C. The sample is loaded by hand one at a time to ensure maximum sample glycolation. The glycolated clay is scanned at the previously mentioned parameters to identify the expandable, water sensitive minerals. The slide is then heat-treated in a furnace at a temperature of 565°C and scanned with the same parameters to aid in distinguishing kaolinite and chlorite. After the clay is heated the kaolinite peak is collapsed, the chlorite peak is more prominent, and the smectite is collapsed rendering the discrete illite plus the illite associated with the mixed-layer illite/smectite.

The method for determining the ratios of kaolinite, chlorite, illite, a mixed-layer illite/smectite and/or a pure smectite are done using the calculation methods of Schultz, USGS Open File Report 01-041, "A Laboratory Manual for X-ray Powder diffraction", 2001, Poppe, Paskevich, Hathaway, and Blackwood. The diagnostic peak of chlorite is located at 6.1° 2-theta in the heat treated clay. The diagnostic peak for kaolinite is located at 12.3° 2-theta in the glycolated clay. The diagnostic peak of Illite is located at 8.9° 2-theta in both the glycolated and heat treated clay. The peak range for randomly interstratified mixed-layer illite/smectite is from 2.0° to 4.9° and for ordered interstratified mixed-layer illite/smectite is from 5.1° to 8.8° 2-theta on the glycolated clay scan. In this degree range, the angstrom size of the smectite mineral phase is obtained from the MDI Jade software at the maximum peak height using a d-line spacing. The method for calculating the ordered and/or randomly interstratified mixed layers are based upon angstrom size of the smectitic clay as illustrated by the paper "The Nature of Interlayering in Mixed Layer Illite-Montmorillonite", Clays and Clay Minerals 18, 1970, Reynolds and Hower. 5.0° 2-theta is the location of pure 100% expandable smectite.

Once the scanning is complete, the diffractograms of the bulk and clay samples are evaluated using MDI Jade software and the ICDD JCPDS powder diffraction files are applied. The primary peaks are measured using the area under the curve, subtracting the background, to one standard deviation. The area counts are then applied to a mathematical equation using mineral intensity factors. Mineral intensity factors are generated for each diffractometer using pure mineral standards mixed with quartz in a 50-50 weight percent. Once the total area counts are obtained for each mineral present and applied to the equation, the bulk mineral data is rendered onto a table to the nearest whole number as weight percent. Once the bulk data is complete, the total clays obtained from the bulk data, are broken down into their species and values are given to each mineral phase based upon the calculation method mentioned above. Each clay is then examined with a d-line spacing to determine expandability and type of interstratified mixed layering.

Whole pattern fitting and Reitveld refinement are used for quantitative analysis. All methods of Whole Pattern Fitting and Reitveld refinement and Indexing are in accordance with the practices taught at the International Centre of Diffraction Data.

“The Reitveld Method Crystal Structure Refinement”, Fundamentals of Powder Diffraction and Structural Characterization of Materials, V. Pecharsky and P Zavalij, 2005 p. 599-696

Quantitative Analysis “Measurement of Line Intensities, Foundation of Quantitative Phase Analysis, The Absorption-Diffraction Method, Use of Measured Mass Attenuation Coefficients, The International Standard Method of Quantitative Analysis, I/I corundum and the Referenced Ratio Method, Quantitative Analysis with RIRs, Constrained XRD Phase analysis, Quantitative Phase Analysis Using Crystal Structure Constraints, Quantitative Methods Based on Use of Total Pattern, The Reitveld Method, and Full Pattern Fitting”, Introduction to X-Ray Powder Diffractometry, R. Jenkins and R.Snyder 1996,p.355-385

Standard Scanning Parameters: For both bulk and clay

Cu K-alpha1 0.15406nm and K-alpha2 0.1544390nm
Operating voltage is 50Kv
Operating amperage is 40mA
An axial soller slit is in place
Goniometer diameter is 402mm
A Lynx Eye High speed detector with a 2 theta scanning range of 4^{o}
A nickel filter for K beta peaks
A Lynx Iris motorized antiscatter slit
An air scatter screen to reduce fluorescence
A variable divergent slit at 1.5mm for bulk and 0.75mm for clay

Detailed Thin Section Analysis

Samples selected for thin section analysis were prepared by first vacuum impregnating with blue-dyed epoxy. The samples were then mounted on an optical glass slide and cut and lapped in water to a thickness of 0.03 mm. The sections were stained using Alizarin Red S for calcite, and potassium ferricyanide for ferroan dolomite/calcite. The prepared sections were then covered with index oil and temporary cover slips, and then analyzed using standard petrographic techniques.

APPENDIX B:

DETAILED
THIN SECTION PHOTOMICROGRAPHS
WITH FACING PLATE CAPTIONS
AND MODAL ANALYSIS

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SAMPLE DEPTH: 2800.85 FEET
SAMPLE NUMBER: 2-1 P

PLATE 37A

A) A calcareous, argillaceous mudstone comprised of quartz silt (CD9.9, HJ12, A4), undifferentiated, calcareous fragments (stained red; CD15, B11, FG11), authigenic dolomite (E12, CD13.5, BC9.7), and authigenic pyrite (CD9.9, HJ12, A4) within an argillaceous matrix (J10; XRD indicates the clay composition of this sample to be chlorite: 9%; kaolinite: 1%; illite: 22%; mixed illite/smectite: 1%).

Magnification: A: 50X

PLATE 37B

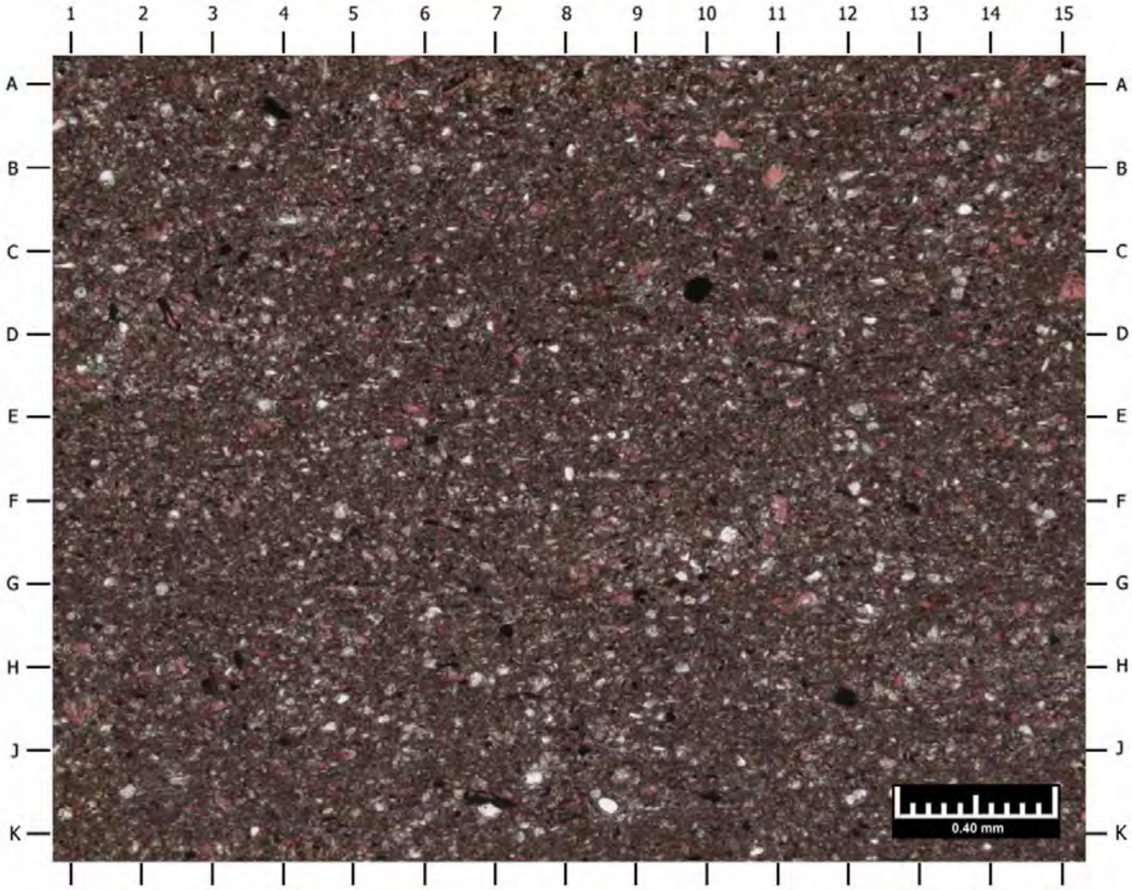
B) High magnification view of area near D7 in photo A displays quartz silt (GH10.4, F5, FG7), undifferentiated, calcareous fragments (stained red; C3, B14, D15), authigenic dolomite (B4, BC4.2), and authigenic pyrite (AB1, J3, G10) within an argillaceous matrix (J6).

Magnification: B: 200X

Kentucky Geological Survey
Marvin Blan No. 1
Hancock County, KY
Conventional Core

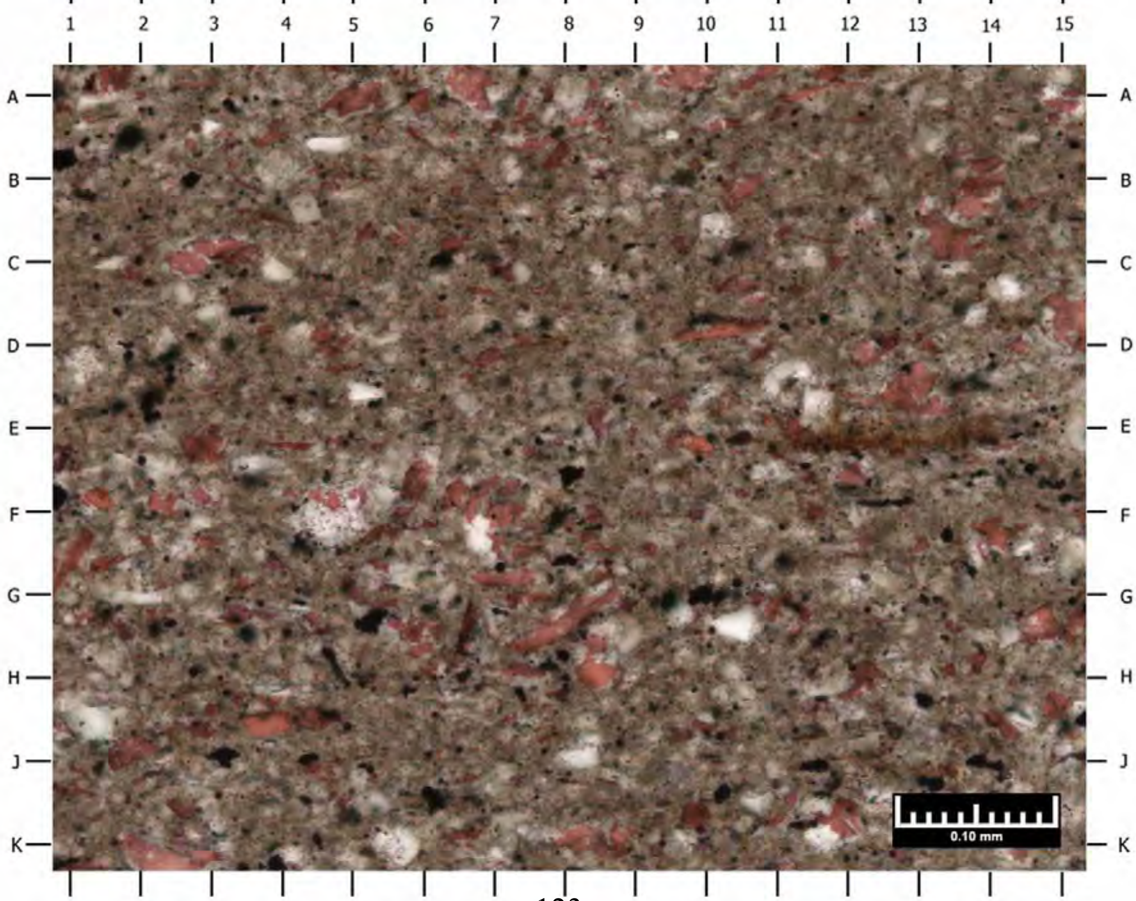
2800.85'
Plate 37

Weatherford LABORATORIES



A

50X



B

200X

SAMPLE DEPTH: 2803.85 FEET
SAMPLE NUMBER: 2-4 P

PLATE 38A

A) An argillaceous, calcareous mudstone comprised of quartz silt (J4.5, HJ7, JK1.9), undifferentiated, calcareous fragments (stained red; K13, GH6.8, C14), authigenic dolomite (C12.2, B12.2, DE11), and authigenic pyrite (J11.3, J5.5, JK2.5) within an argillaceous matrix (XRD indicates the clay composition of this sample to be chlorite: 7%; kaolinite: 1%; illite: 17%; mixed illite/smectite: 1%). A lens of calcareous fragments, dolomite, and silt grains extends from K1 to HK15.

Magnification: A: 50X

PLATE 38B

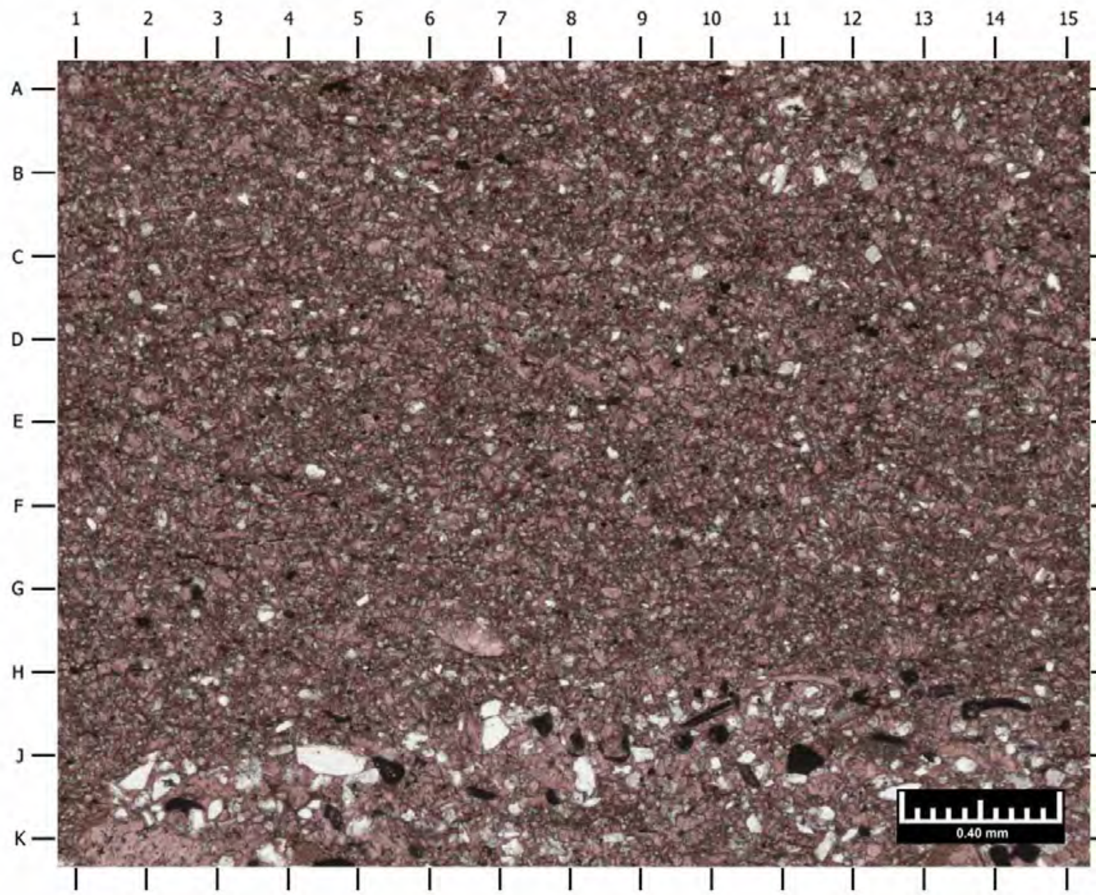
B) High magnification view of area near D6 in photo A depicts quartz silt (G3, F2), undifferentiated, calcareous fragments (stained red; C4, G4, C7), authigenic dolomite (E6, GH10.5, CD13), and authigenic pyrite (FG3.3, J1.5, F6.4) within an argillaceous matrix (CD7).

Magnification: B: 200X

Kentucky Geological Survey
Marvin Blan No. 1
Hancock County, KY
Conventional Core

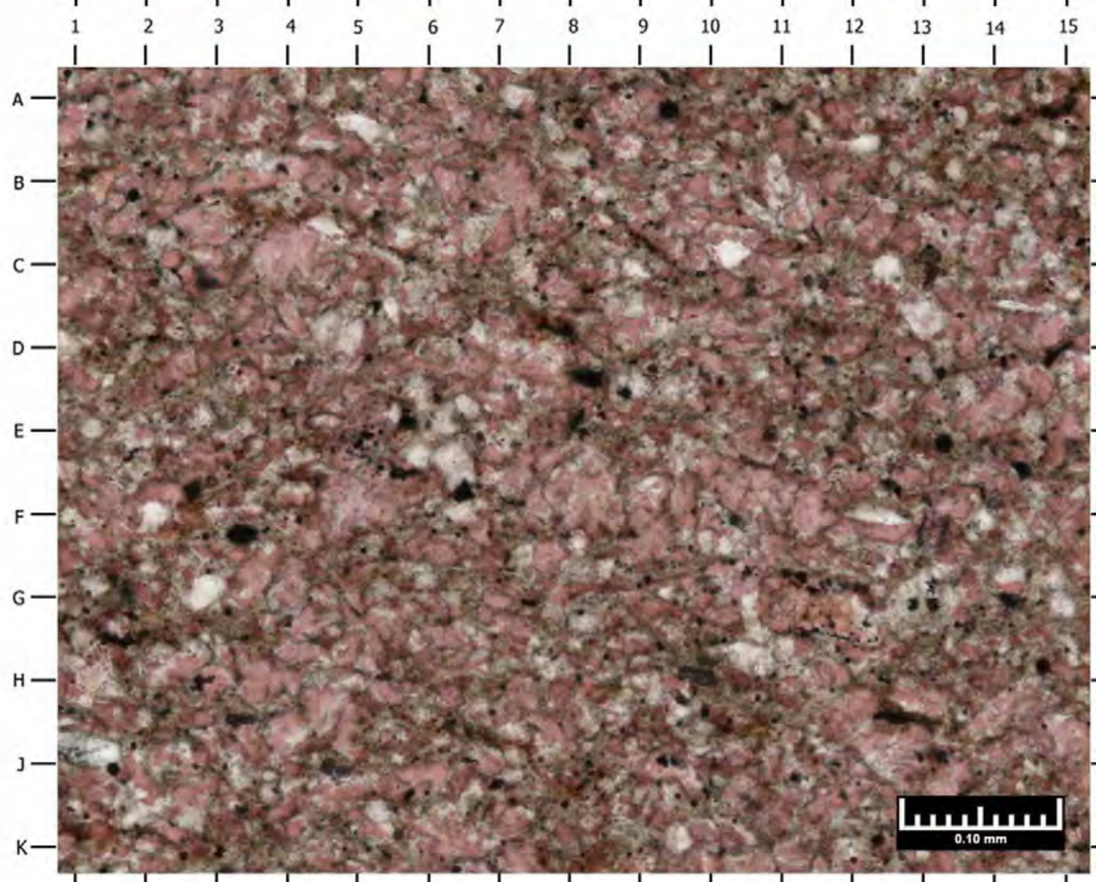
2803.85'
Plate 38

Weatherford
LABORATORIES



A

50X



B

200X

SAMPLE DEPTH: 2806.90 FEET
SAMPLE NUMBER: 2-7 P

PLATE 39A

A) A calcareous, silty, argillaceous mudstone comprised of quartz silt (F8, FG9, DE4.2), undifferentiated, calcareous fragments (stained red; CD1, B12.6, B8.4), authigenic dolomite (BC4.5, DE15, H1.3), authigenic ferroan dolomite (stained blue; K5.2, DE7), and authigenic pyrite (BC4, J3, F11.2) within an argillaceous matrix (XRD indicates the clay composition of this sample to be chlorite: 8%; kaolinite: 1%; illite: 20%; mixed illite/smectite: 1%).

Magnification: A: 50X

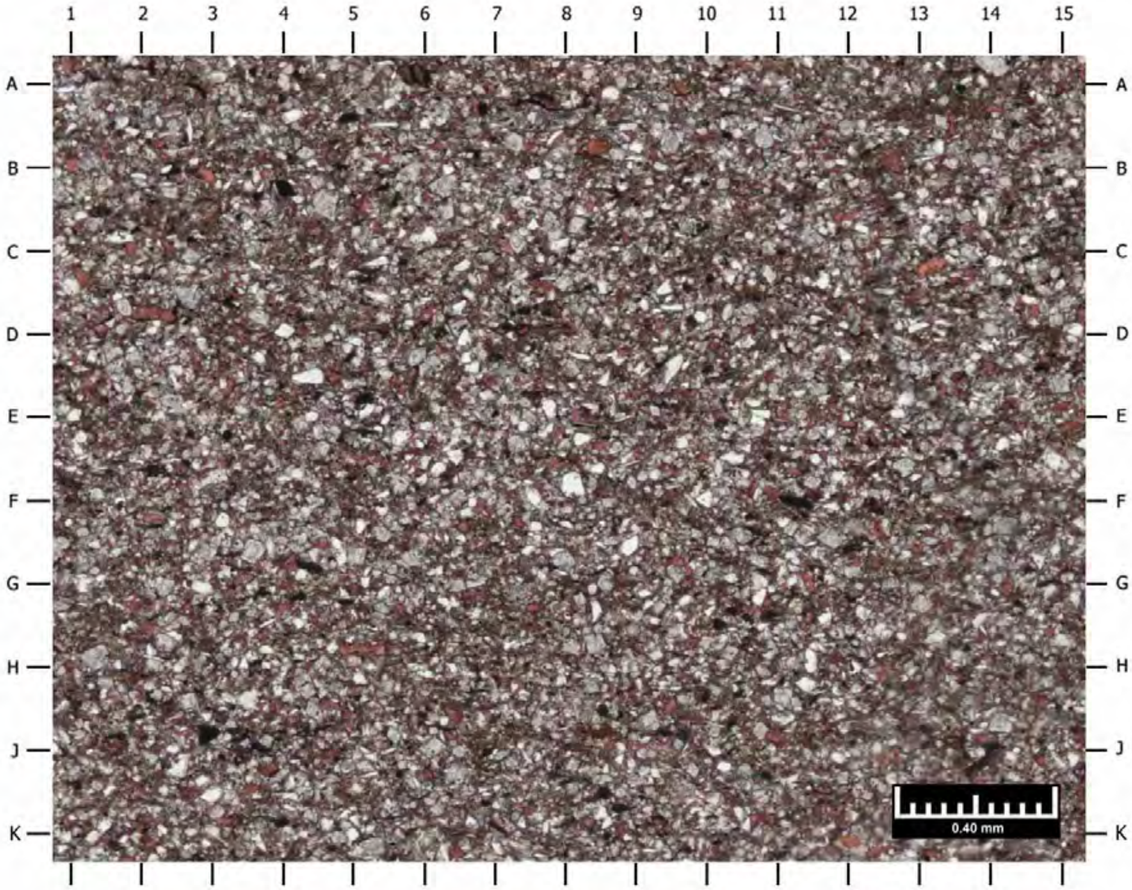
PLATE 39B

B) High magnification view of area near E8 in photo A displays quartz silt (G8, K11, C6.5), undifferentiated, calcareous fragments (stained red; BC14, F1, B3), authigenic dolomite (J15, FG11.2, FG12), authigenic ferroan dolomite (stained blue; AB4, CD1.2, G9), and authigenic pyrite (CD3.5, A13, BC6) within an argillaceous matrix (G11).

Magnification: B: 200X

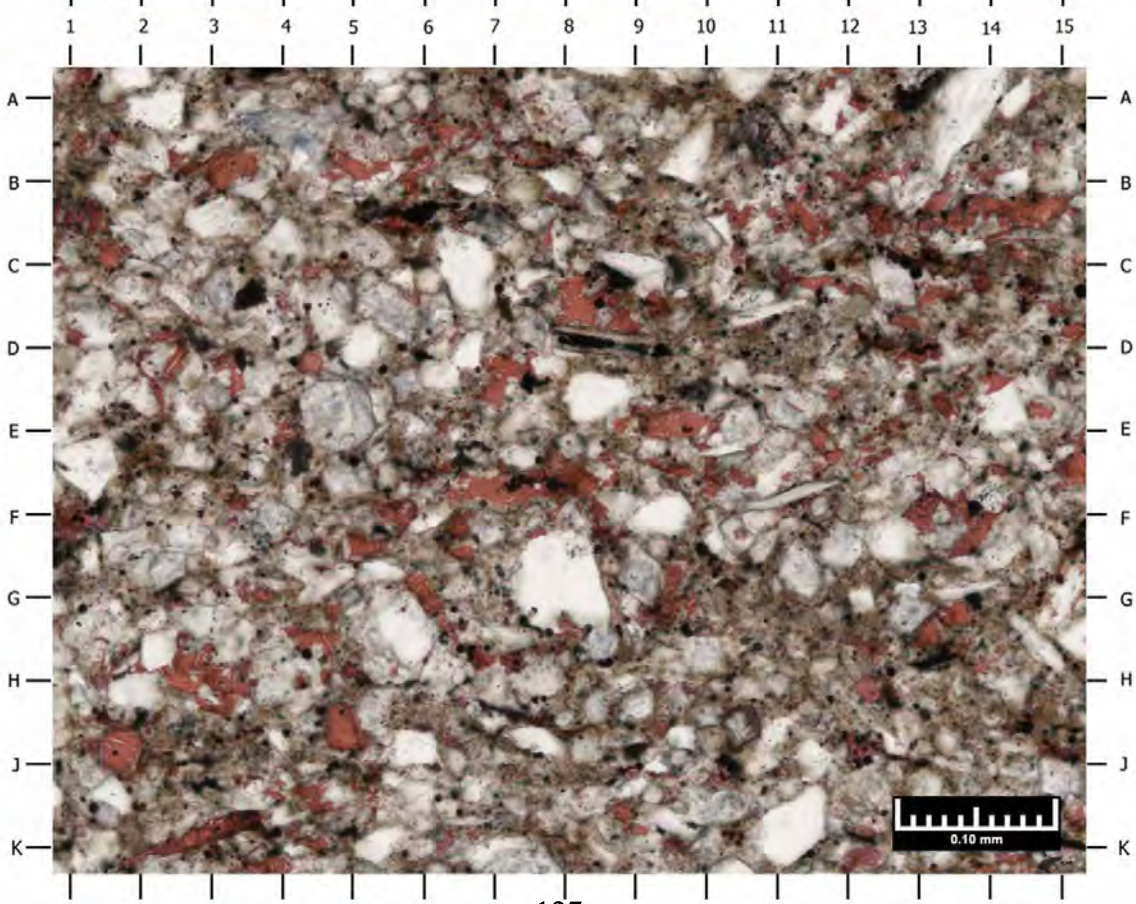
Kentucky Geological Survey
Marvin Blan No. 1
Hancock County, KY
Conventional Core

2806.90'
Plate 39



A

50X



B

200X

SAMPLE DEPTH: 2809.80 FEET
SAMPLE NUMBER: 2-10 P

PLATE 40A

A) A silty, argillaceous mudstone comprised of quartz silt (EF8.5, BC7.2, DE7.6), undifferentiated, calcareous fragments (stained red; CD11, F7.5, BC6.1), authigenic dolomite (DE15, EF3.3, H1.5), authigenic ferroan dolomite (stained blue; E8, EF9.2), and authigenic pyrite (GH13, A12, C6.3) within an argillaceous matrix (G8; XRD indicates the clay composition of this sample to be chlorite: 10%; kaolinite: 2%; illite: 28%; mixed illite/smectite: 2%). The top half of this photograph demonstrates a calcareous, dolomite rich lamination while the bottom half of the photograph illustrates an argillaceous lamination.

Magnification: A: 50X

PLATE 40B

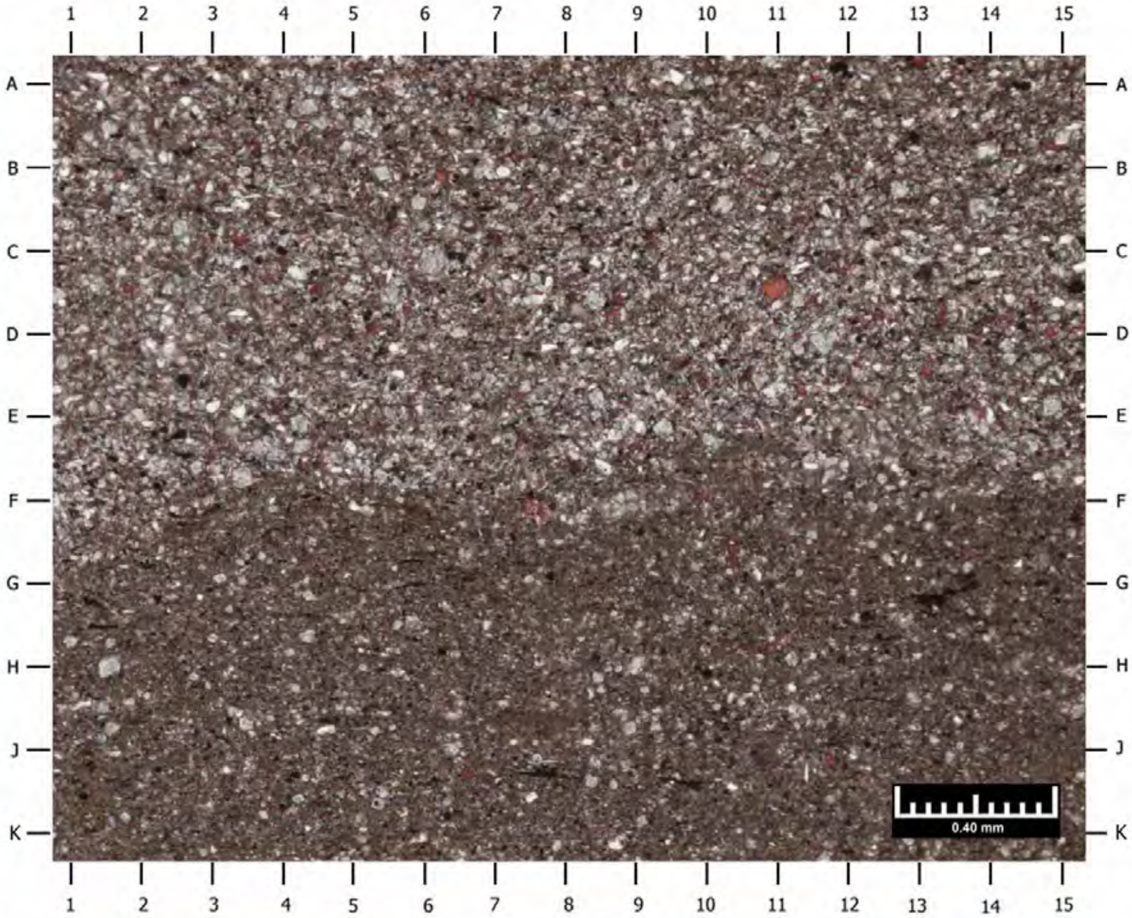
B) High magnification view of area near E8 in photo A depicts quartz silt (F9.5, HJ7.3, C2), undifferentiated, calcareous fragments (stained red; H6, E11.5, GH15), muscovite (EF14.5, FG14), authigenic ferroan dolomite (stained blue; D13, BC9, B3), and authigenic pyrite (G3, J12, C2.5) within an ar gillaceous matrix (J13).

Magnification: B: 200X

Kentucky Geological Survey
Marvin Blan No. 1
Hancock County, KY
Conventional Core

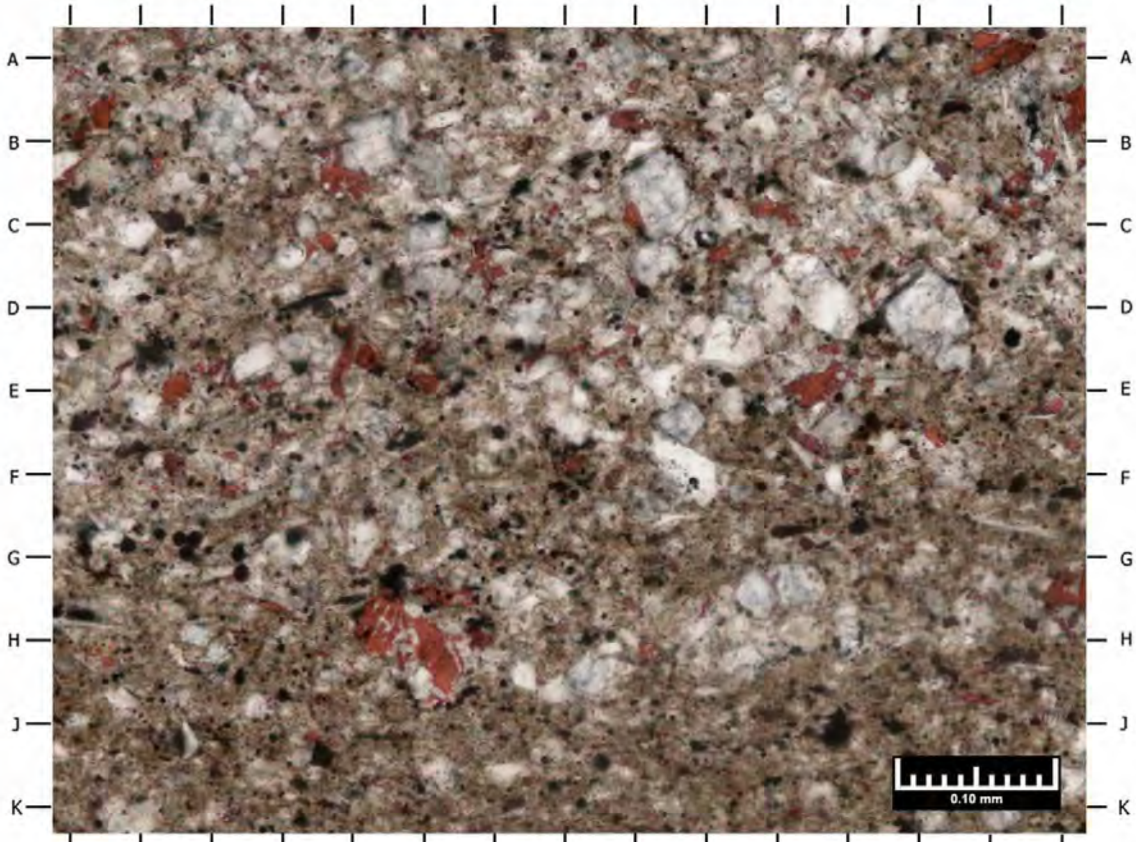
2809.80'
Plate 40

Weatherford
LABORATORIES



A

50X



B

200X

SAMPLE DEPTH: 2812.80 FEET
SAMPLE NUMBER: 2-13 P

PLATE 41A

A) A silty, argillaceous mudstone comprised of quartz silt (B6.1, BC9.4, CD9.2), undifferentiated, calcareous fragments (stained red; CD2, HJ5.4, HJ10), authigenic ferroan dolomite (stained blue; C7.8, DE6.5, C5.6), and authigenic pyrite (HJ5.3, J7.8, F11.5) within an argillaceous matrix (D5; XRD indicates the clay composition of this sample to be chlorite: 12%; kaolinite: 2%; illite: 31%; mixed illite/smectite: 2%). The bottom half of this photograph demonstrates a calcareous, dolomite rich lamination while the top half of the photograph illustrates an argillaceous lamination.

Magnification: A: 50X

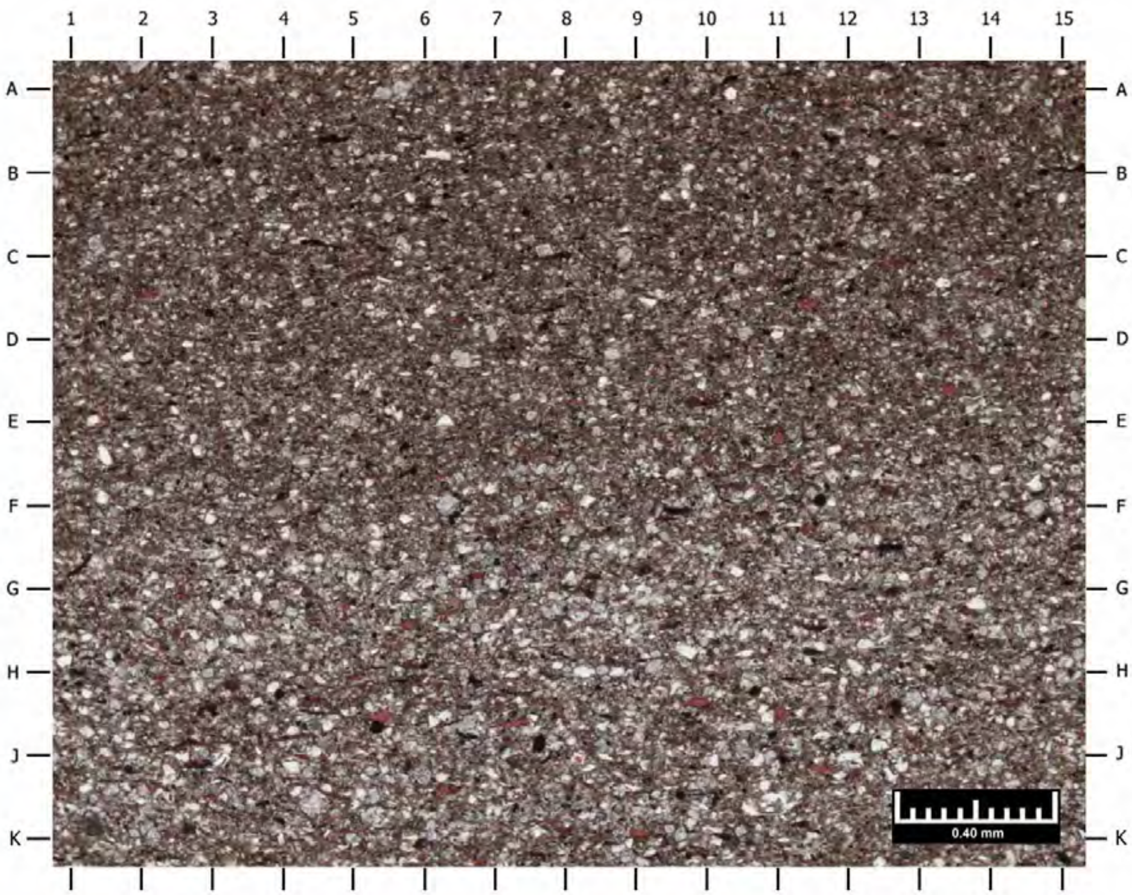
PLATE 41B

B) High magnification view of area near C7 in photo A illustrates quartz silt (GH2, B4, GH5.5), undifferentiated, calcareous fragments (stained red; E1, H7, GH11), muscovite (B3.5, A2.8, HJ2), authigenic ferroan dolomite (stained blue; DE4, AB9, C3), and authigenic pyrite (DE11, BC10.6, B6) within an argillaceous matrix (D7).

Magnification: B: 200X

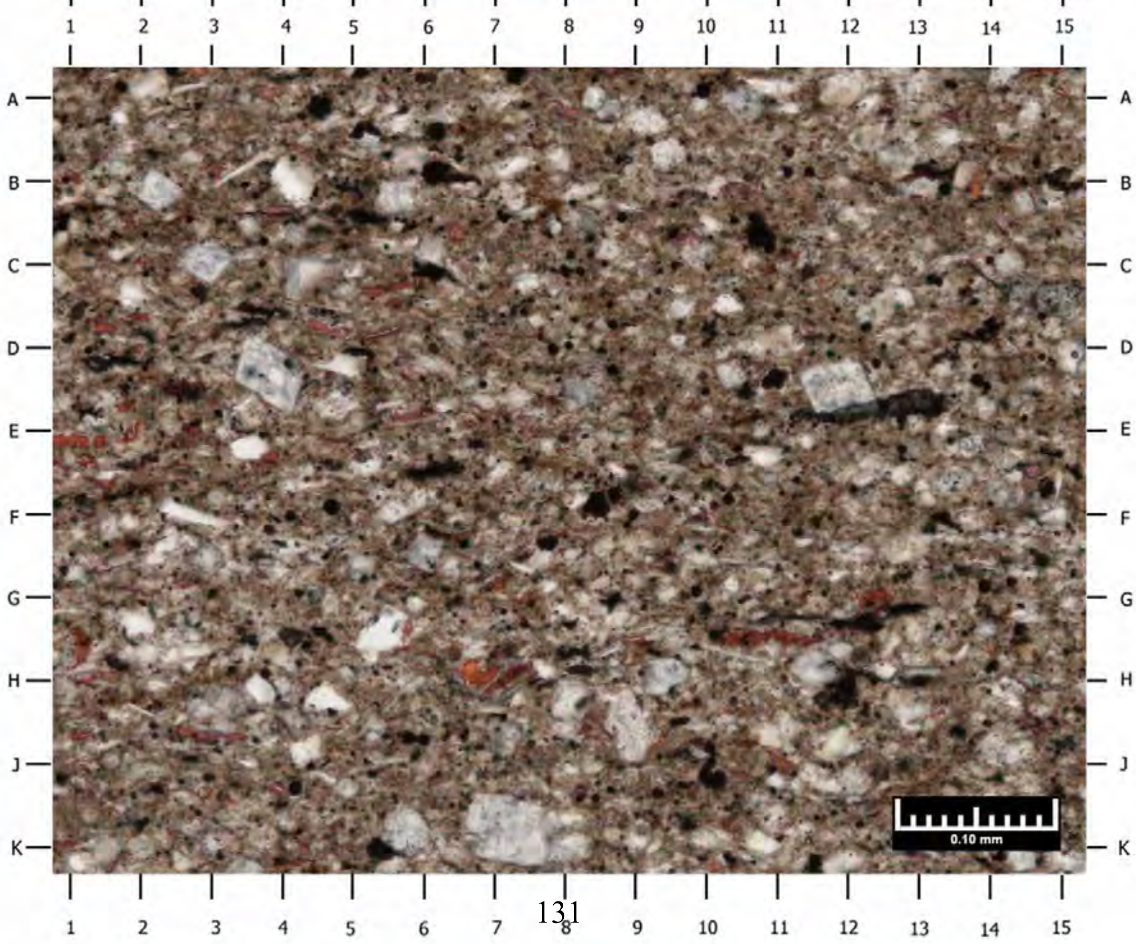
Kentucky Geological Survey
Marvin Blan No. 1
Hancock County, KY
Conventional Core

2812.80'
Plate 41



A

50X



B

200X

Kentucky Geological Survey **Weatherford File Number: HH-43701**
Marvin Blan No. 1
Hancock County, Kentucky
Conventional Core

SAMPLE DEPTH: 2815.90 FEET
SAMPLE NUMBER: 2-16 P

PLATE 42A

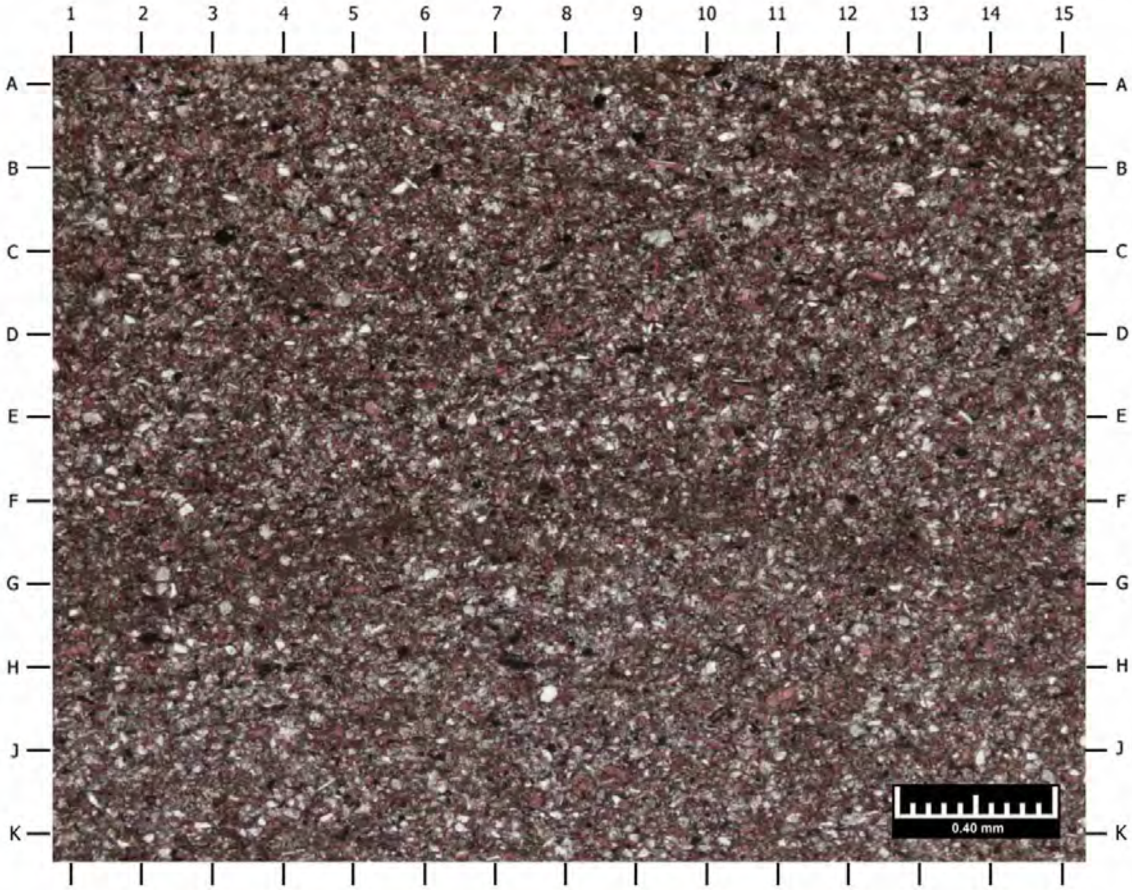
A) A calcareous, silty, argillaceous mudstone comprised of quartz silt (BC5.6, HJ7.8, E6.5), undifferentiated, calcareous fragments (stained red; HJ11, D8, A8), authigenic dolomite (CD4.8, C9.2, G2.5), and authigenic pyrite (C3, AB8.5, H4) within an argillaceous matrix (F10; XRD indicates the clay composition of this sample to be chlorite: 10%; kaolinite: 1%; illite: 22%; mixed illite/smectite: 1%).

Magnification: A: 50X

PLATE 42B

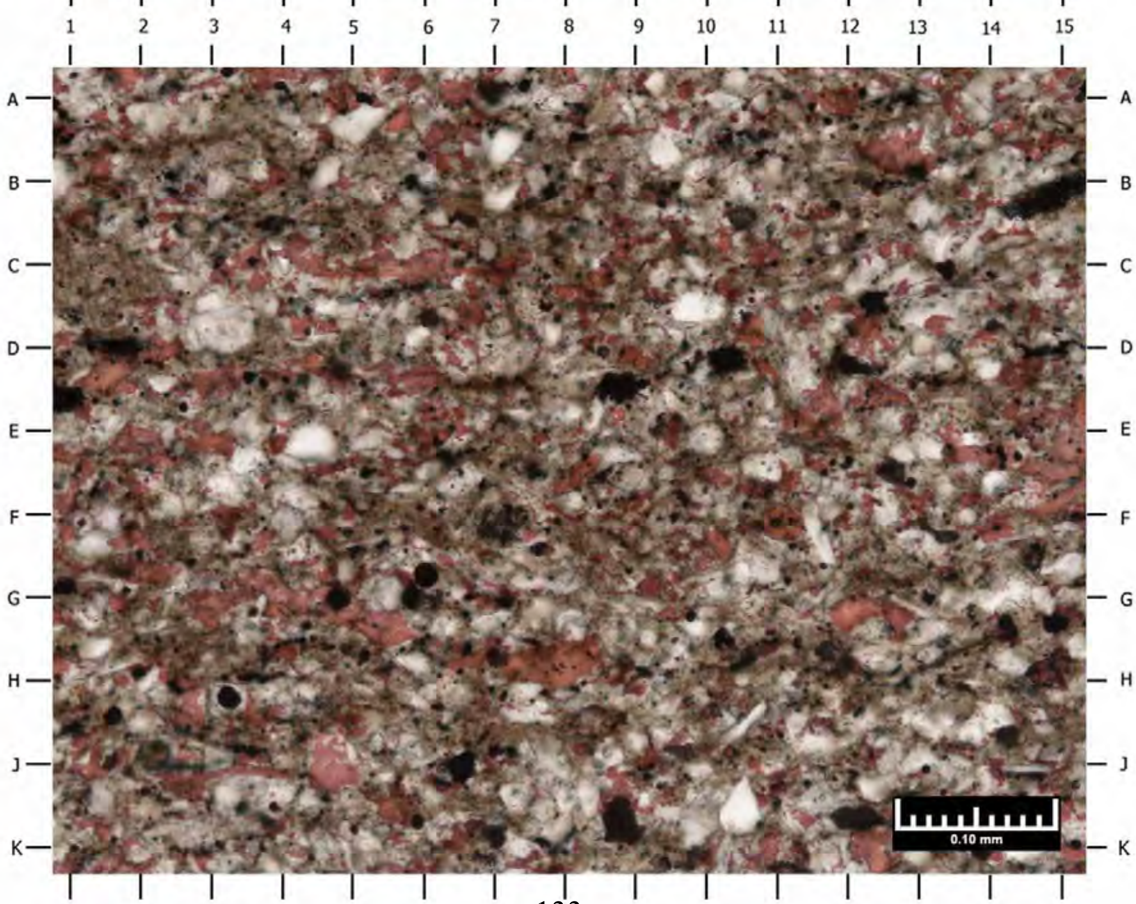
B) High magnification view of area near D6 in photo A depicts quartz silt (E4.5, JK10.5, AB7), undifferentiated, calcareous fragments (stained red; J5, E15, C6), muscovite (G13), authigenic dolomite (JK10, CD3), and authigenic pyrite (HJ3.2, G5, G6) within an argillaceous matrix (F5).

Magnification: B: 200X



A

50X



B

200X

SAMPLE DEPTH: 2818.80 FEET
SAMPLE NUMBER: 2-19 P

PLATE 43A

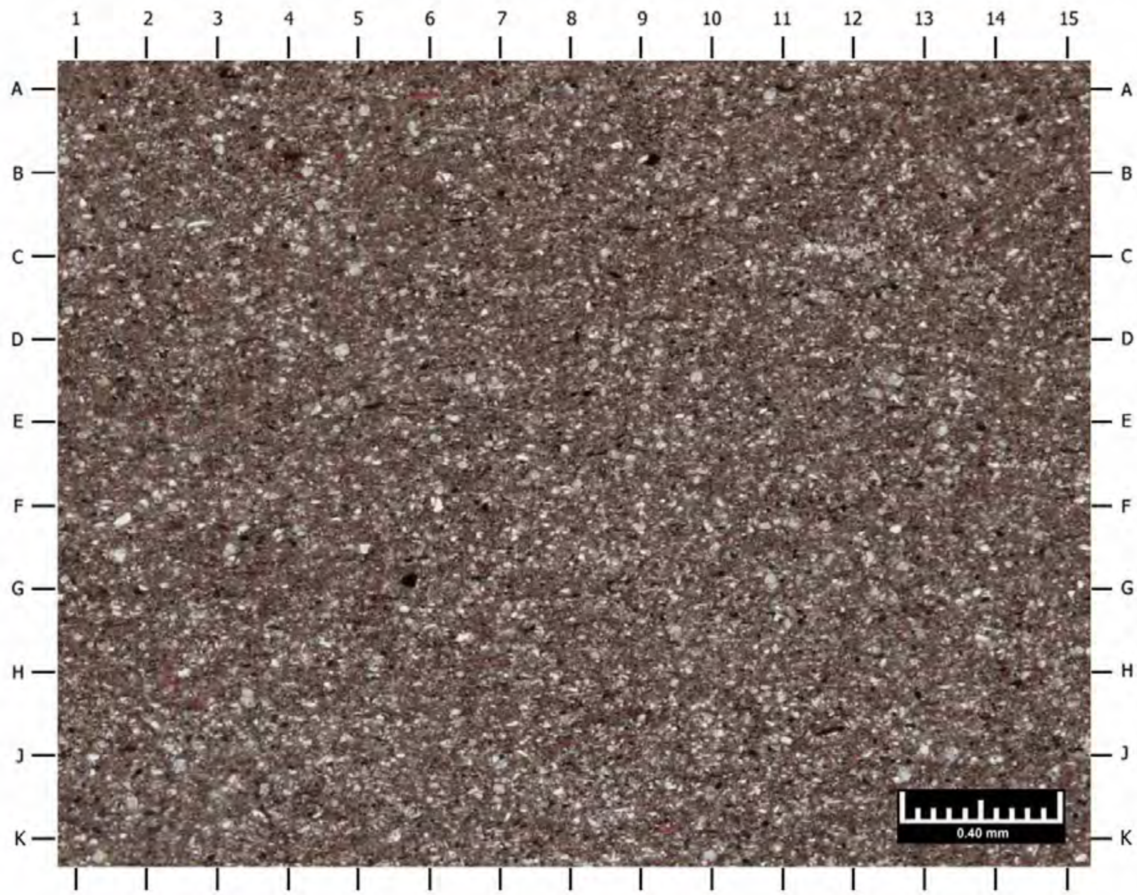
A) A silty, argillaceous mudstone comprised of quartz silt (F6.1, FG12.5, FG1.7), undifferentiated, calcareous fragments (stained red; H2.3, A6, B4.7), authigenic dolomite (DE12.5, DE9.7, BC 4.5), and authigenic pyrite (B9.1, G5.8, AB1.3) within an argillaceous matrix (D5; XRD indicates the clay composition of this sample to be chlorite: 11%; kaolinite: 2%; illite: 27%; mixed illite/smectite: 2%).

Magnification: A: 50X

PLATE 43B

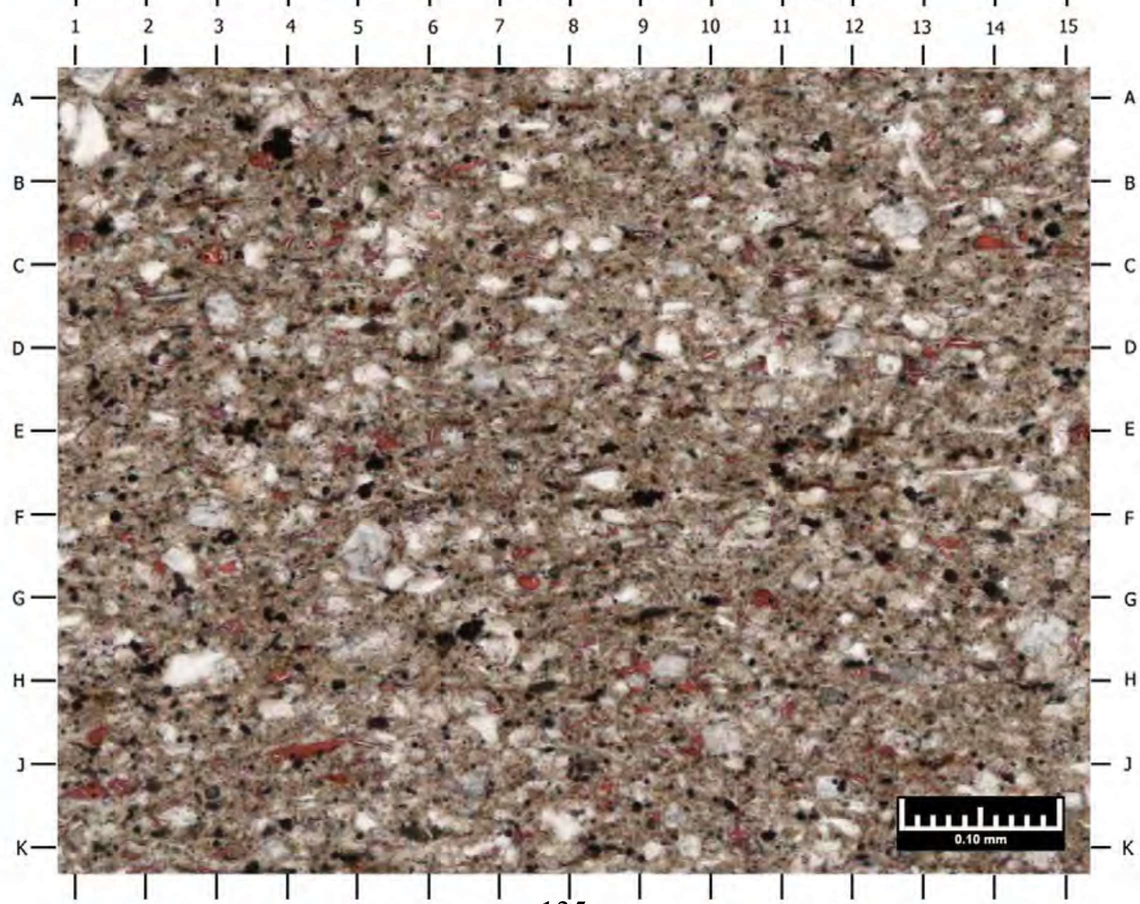
B) High magnification view of area near G7 in photo A illustrates quartz silt (H3, AB1, EF8.5), undifferentiated, calcareous fragments (stained red; E15, H9, G10.6), muscovite (GH13, CD2), authigenic dolomite (HJ10.2, BC12.5, FG5), and authigenic pyrite (AB4, GH6.5, F9) within an argillaceous matrix (EF6.5).

Magnification: B: 200X



A

50X



B

200X

Kentucky Geological Survey
Marvin Blan No. 1
Hancock County, Kentucky
Conventional Core

Weatherford File Number: HH-43701

SAMPLE DEPTH: 2821.90 FEET
SAMPLE NUMBER: 2-22 P

PLATE 44A

A) A calcareous, silty, argillaceous mudstone comprised of quartz silt (FG3, G2, G9.2), undifferentiated, calcareous fragments (stained red; F10, B2.9, B8), authigenic dolomite (F8, F8.2, FG4.1), and authigenic pyrite (CD9.9, AB5.7, A9) within an ar gillaceous matrix (C4; XRD indicates the clay composition of this sample to be chlorite: 11%; kaolinite: 2%; illite: 32%; mixed illite/smectite: 2%). The bottom half of this photograph depicts a calcareous, dolomite rich lamination while the top half of the photograph illustrates an argillaceous lamination.

Magnification: A: 50X

PLATE 44B

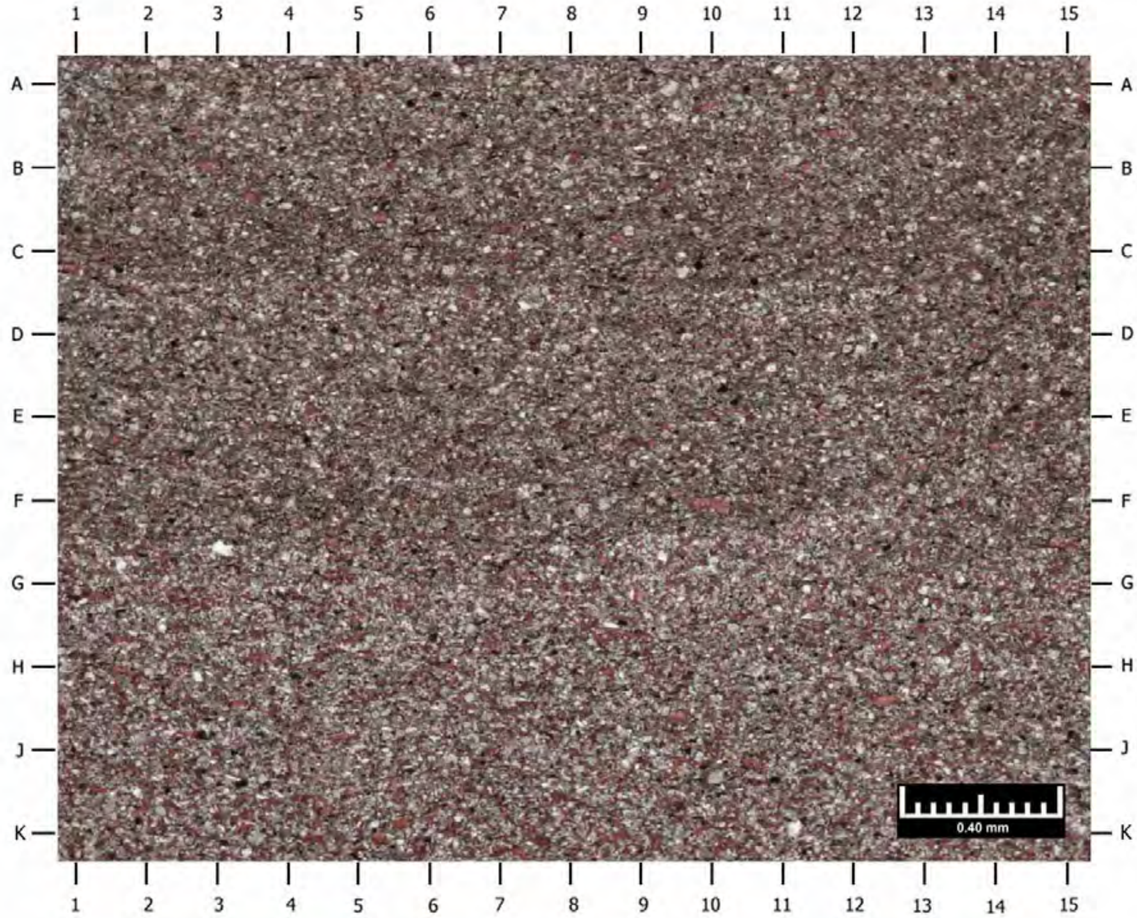
B) High magnification view of area near F9 in photo A illustrates quartz silt (H7, H15, JK15), undifferentiated, calcareous fragments (stained red; EF10, AB1, A12), a heavy mineral (HJ14.8), authigenic dolomite (EF2.3, EF3.8, GH9.6), and authigenic pyrite (BC1.5, EF7.5, FG13.5) within an argillaceous matrix (B6).

Magnification: B: 200X

Kentucky Geological Survey
Marvin Blan No. 1
Hancock County, KY
Conventional Core

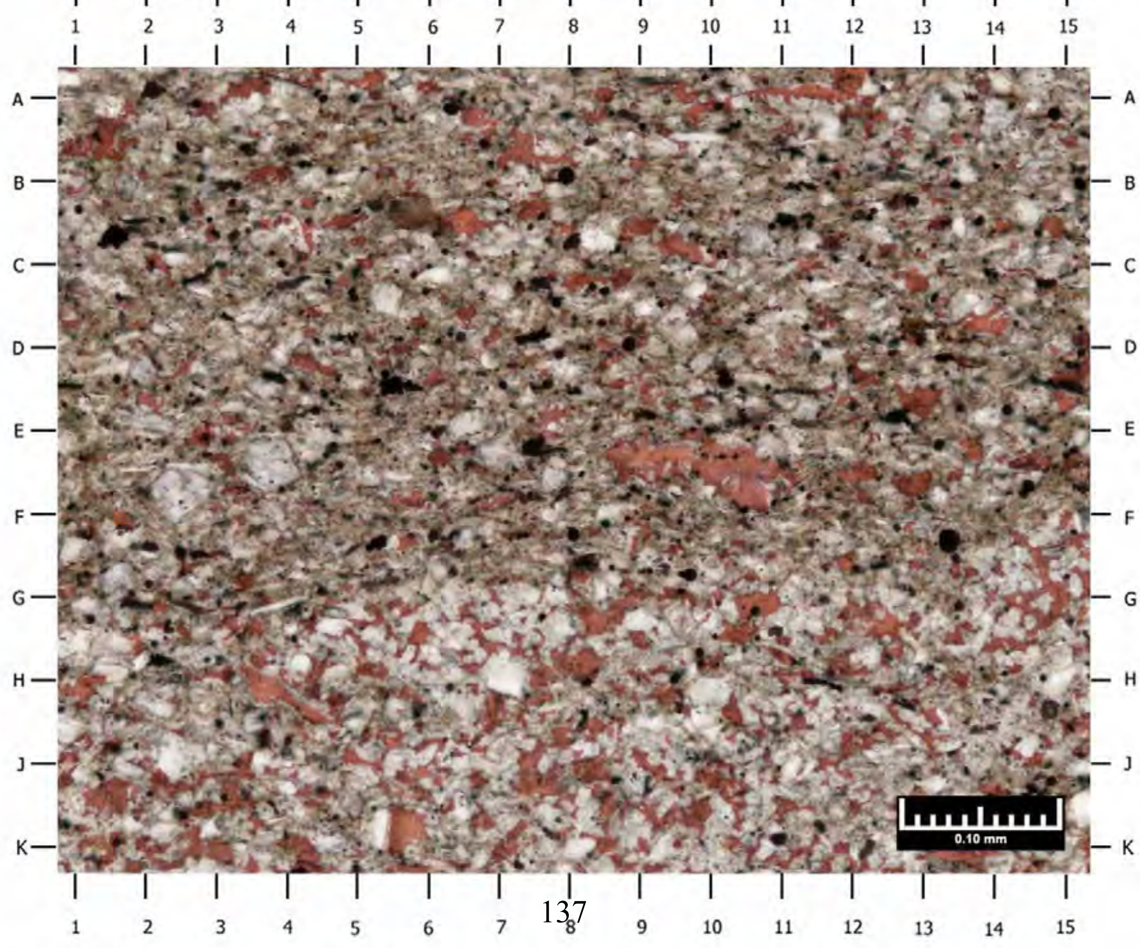
2821.90'
Plate 44

Weatherford
LABORATORIES



A

50X



B

200X

SAMPLE DEPTH: 2824.90 FEET
SAMPLE NUMBER: 2-25 P

PLATE 45A

A) A silty, argillaceous mudstone comprised of quartz silt (BC7.8, FG10.1), undifferentiated, calcareous fragments (stained red; CD7-10, C4-5, FG1), muscovite (GH10, EF15), authigenic dolomite (CD11, B6.5, AB7.5), and authigenic pyrite (CD8.5, E3, K6) within an argillaceous matrix (H6; XRD indicates the clay composition of this sample to be chlorite: 11%; kaolinite: 2%; illite: 30%; mixed illite/smectite: 2%). The area of this photograph from AG1-15 demonstrates a calcareous, dolomite rich lamination while are of the photograph from HK1-15 illustrates an argillaceous lamination.

Magnification: A: 50X

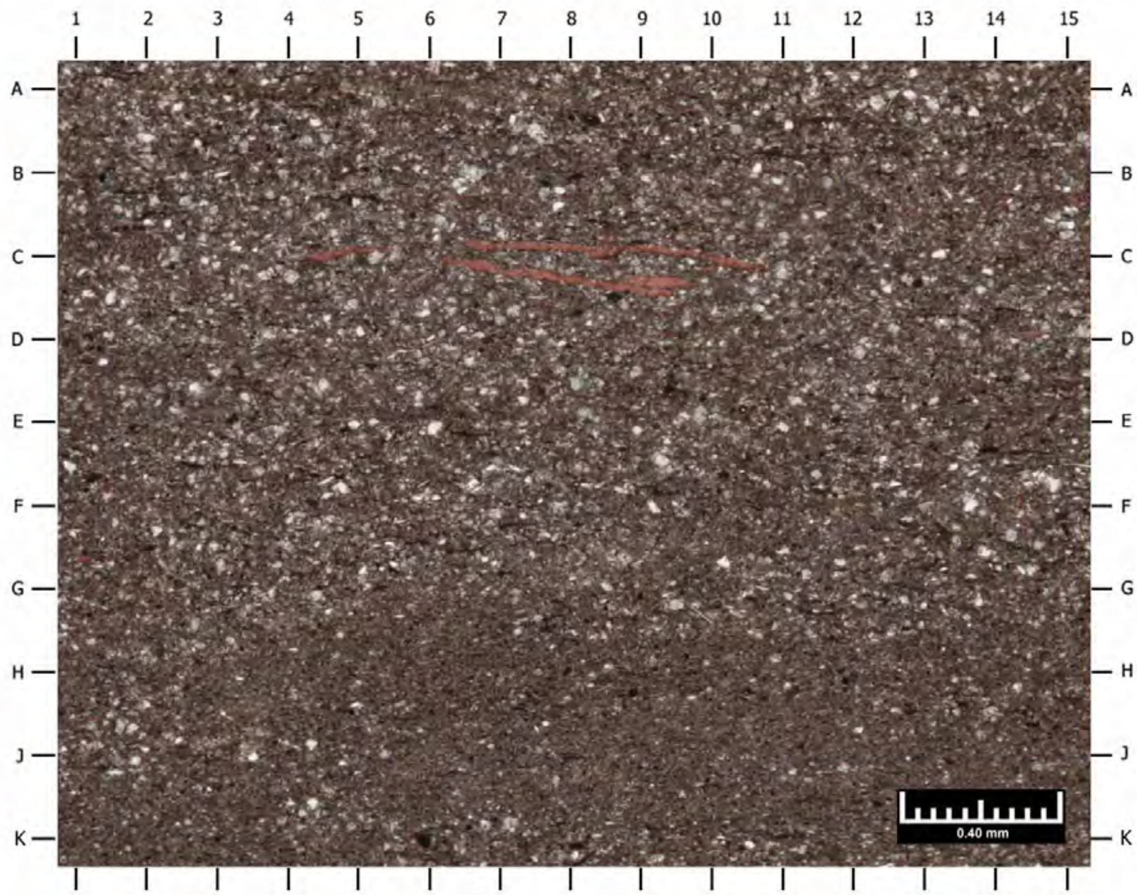
PLATE 45B

B) High magnification view of area near F8 in photo A illustrates quartz silt (D11, GH12, BC5), undifferentiated, calcareous fragments (stained red; F9, AB1, DE12), authigenic dolomite (EF13, A11), authigenic ferroan dolomite (stained blue; C15, B8, E3), and authigenic pyrite (B13, BC15, HJ8) within an argillaceous matrix (D6.5).

Magnification: B: 200X

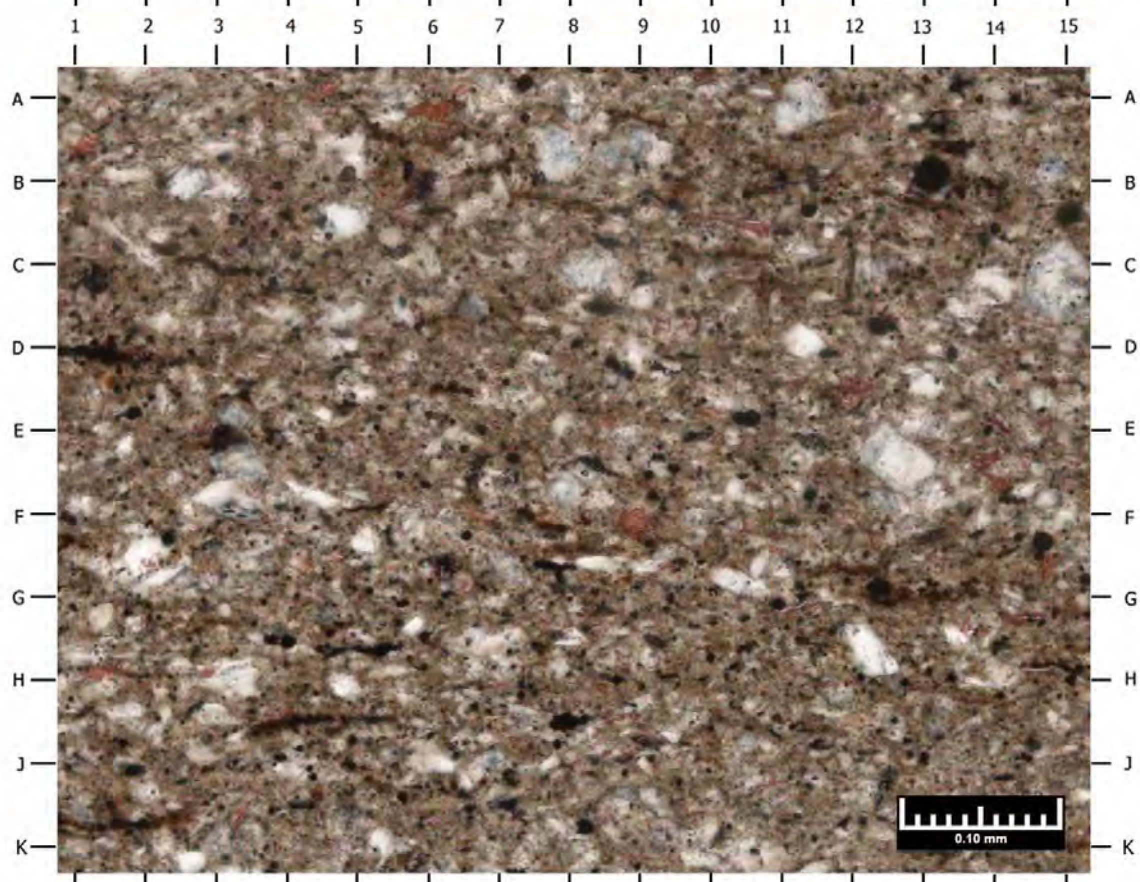
Kentucky Geological Survey
Marvin Blan No. 1
Hancock County, KY
Conventional Core

2824.90'
Plate 45



A

50X



B

200X

Kentucky Geological Survey **Weatherford File Number: HH-43701**
Marvin Blan No. 1
Hancock County, Kentucky
Conventional Core

SAMPLE DEPTH: 2827.90 FEET
SAMPLE NUMBER: 2-28 P

PLATE 46A

A) A silty, argillaceous mudstone comprised of quartz silt (JK5.8, J10.9, JK9.6), undifferentiated, calcareous fragments (stained red; GH11, HJ12.1, J12), plagioclase (H12.9; twinning visible in cross polars), authigenic dolomite (D2.2, HJ7.5, J12.6), and authigenic pyrite (EF2.7, C7, JK2.2) within an argillaceous matrix (C4; XRD indicates the clay composition of this sample to be chlorite: 11%; kaolinite: 2%; illite: 26%; mixed illite/smectite: 2%). The area of this photograph from K1-JK15 demonstrates a calcareous, silty, dolomite rich lamination.

Magnification: A: 50X

PLATE 46B

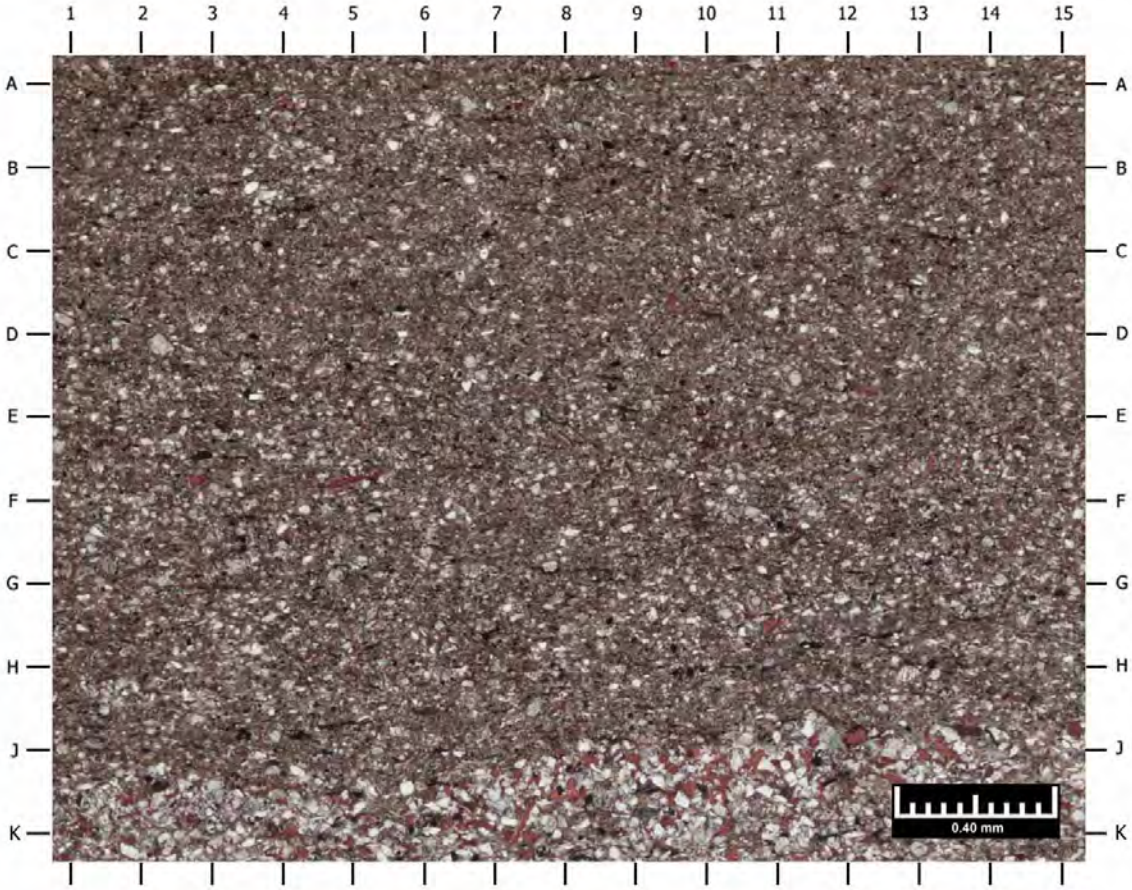
B) High magnification view of area near H8 in photo A depicts quartz silt (H7.5, JK11.7, E10.2), undifferentiated, calcareous fragments (stained red; JK2.3, K6.8, HJ10.2), muscovite (J1-2), authigenic dolomite (DE9.3, JK8.2, K10), and authigenic pyrite (B9, DE13.2, C2) within an argillaceous matrix (DE4).

Magnification: B: 200X

Kentucky Geological Survey
Marvin Blan No. 1
Hancock County, KY
Conventional Core

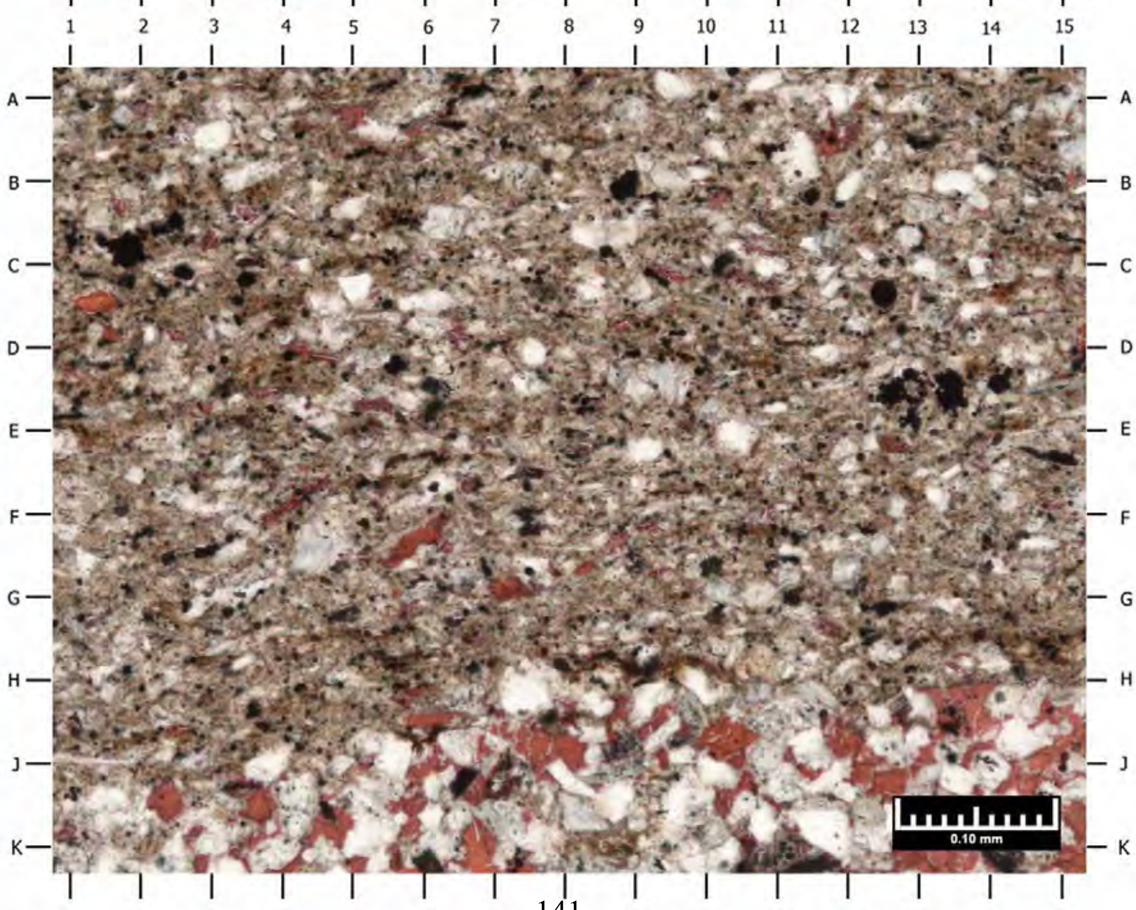
2827.90'
Plate 46

Weatherford® LABORATORIES



A

50X



B

200X

SAMPLE DEPTH: 2830.85 FEET
SAMPLE NUMBER: 2-31 P

PLATE 47A

A) A silty, argillaceous mudstone comprised of quartz silt (B3.1, CD12), undifferentiated, calcareous fragments (stained red; B1, B10, EF13.8), plagioclase (B3.2; twinning visible in cross polars), muscovite (HJ5, AB6), authigenic dolomite (CD13.2, CD12.1, GH4.2), and authigenic pyrite (CD3.5) within an argillaceous matrix (FG6; XRD indicates the clay composition of this sample to be chlorite: 10%; kaolinite: 2%; illite: 24%; mixed illite/smectite: 1%). The area of this photograph from A-E1-15 demonstrates a calcareous, dolomite rich lamination while the area of the photograph from E-K1-15 illustrates an argillaceous lamination. A probable burrow disrupts the calcareous, dolomite rich lamination from B8-D15.

Magnification: A: 50X

PLATE 48B

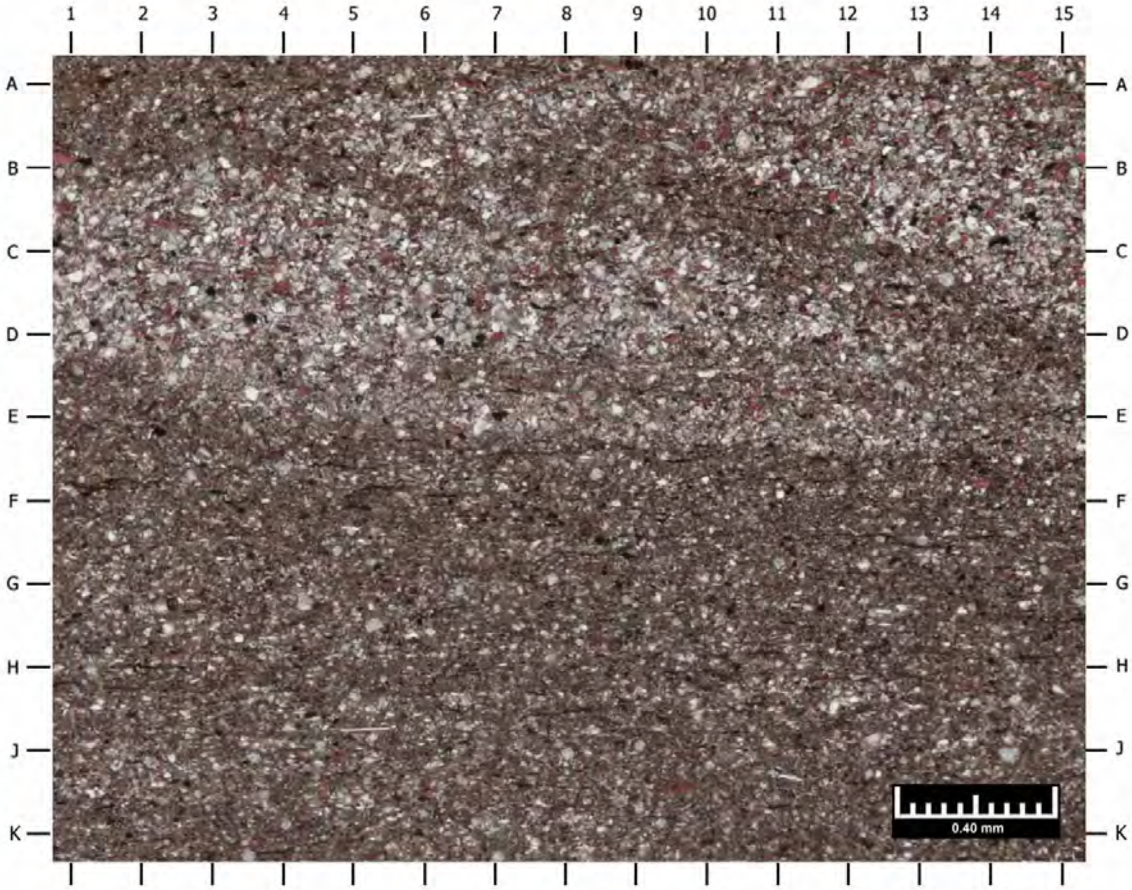
B) High magnification view of area near D9 in photo A illustrates quartz silt (EF13.6, B11, GH8.6), undifferentiated, calcareous fragments (stained red; D1.6, D10, A11.8), authigenic ferroan dolomite (stained blue; FG13.2, FG7, HJ3), and authigenic pyrite (GH2, K10.2, C14.5) within an argillaceous matrix (F4.5).

Magnification: B: 200X

Kentucky Geological Survey
Marvin Blan No. 1
Hancock County, KY
Conventional Core

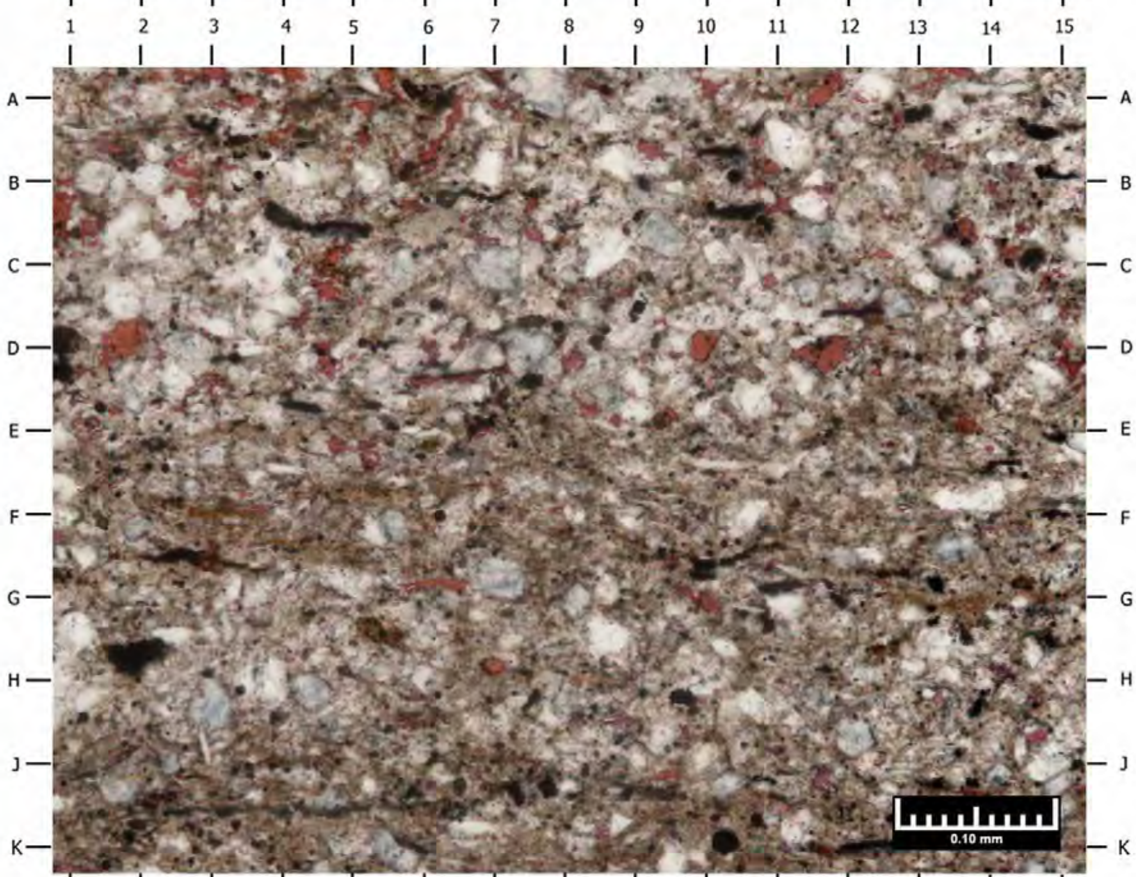
2830.85'
Plate 47

Weatherford
LABORATORIES



A

50X



B

200X

THIN SECTION MODAL ANALYSIS

Kentucky Geological Survey
Marvin Blan No. 1
Conventional Core
Class V CO2 Test Well, Hancock County, Kentucky

Weatherford File No.: HH-43701 **Analyst: Brad Walls**

DEPTH:	**2800.85**	**2803.85**	**2806.90**	**2809.80**
Sample Number	**2-1P**	**2-4 P**	**2-7 P**	**2-10 P**
Grain Size Avg. (mm):	**0.015mm**	**0.025mm**	**0.025mm**	**0.015mm**
Grain Size Range (mm):	**<0.01mm-0.1mm**	**<0.01mm-1.8mm**	**<0.01mm-1.3mm**	**<0.01mm-4.4mm**
Fabric:	**Massive**	**Massive**	**Massive**	**Laminated**
Rock Name:	**Calcareous, Argillaceous Mudstone**	**Argillaceous, Lime Mudstone**	**Calcareous, Silty, Argillaceous Mudstone**	**Silty, Argillaceous Mudstone**
FRAMEWORK GRAINS				
Quartz	**18.3**	**18.7**	**28.0**	**10.7**
Monocrystalline	18.3	18.7	28.0	10.7
Replacement Minerals	**18.7**	**19.3**	**32.0**	**31.0**
Dolomite	12.0	16.3	25.7	20.7
Ferroan Dolomite	Tr	0.0	1.0	1.3
Pyrite	6.7	3.0	5.3	9.0
Acessory Minerals	**2.0**	**0.0**	**0.6**	**0.6**
Muscovite	1.7	0.0	0.3	0.6
Undiff. Heavy Minerals	0.0	0.0	0.0	0.0
Sphalerite	0.3	Tr	0.3	0.0
Plagioclase	Tr	Tr	Tr	Tr
Apatite	0.0	0.0	0.0	0.0
Allochems (Undifferentiated)	**20.0**	**44.7**	**16.7**	**4.7**
Calcareous Fragments	20.0	44.7	16.7	4.7
Authigenic Clay	**41.0**	**17.3**	**22.7**	**53.0**
Clay (Undifferentiated)	41.0	17.3	22.7	53.0
TOTALS:	**100.0**	**100.0**	**100.0**	**100.0**

<u>**THIN SECTION MODAL ANALYSIS**</u>

Kentucky Geological Survey
Marvin Blan No. 1
Conventional Core
Class V CO2 Test Well, Hancock County, Kentucky

Weatherford File No.: HH-43701 **Analyst: Brad Walls**

DEPTH:	**2812.80**	**2815.90**	**2818.80**	**2821.90**
Sample Number	**2-13 P**	**2-16 P**	**2-19 P**	**2-22 P**
Grain Size Avg. (mm):	**0.015mm**	**<0.01mm**	**0.015mm**	**0.01mm**
Grain Size Range (mm):	**<0.01mm-0.05mm**	**<0.01mm-0.8mm**	**<0.01mm-0.08mm**	**<0.01mm-0.9mm**
Fabric:	**Laminated**	**Laminated**	**Laminated**	**Laminated**
Rock Name:	**Silty, Argillaceous Mudstone**	**Calcareous, Silty, Argillaceous Mudstone**	**Silty, Argillaceous Mudstone**	**Calcareous, Silty, Argillaceous Mudstone**
FRAMEWORK GRAINS				
Quartz	**14.7**	**16.7**	**20.4**	**15.3**
Monocrystalline	14.7	16.7	20.4	15.3
Replacement Minerals	**29.0**	**23.0**	**27.7**	**32.4**
Dolomite	19.3	18.3	15.7	14.7
Ferroan Dolomite	2.7	0.0	1.0	2.3
Pyrite	7.0	4.7	11.0	15.4
Acessory Minerals	**1.7**	**1.3**	**0.3**	**1.3**
Muscovite	0.7	1.3	Tr	0.3
Undiff. Heavy Minerals	0.0	0.0	0.0	0.0
Sphalerite	0.0	Tr	Tr	0.0
Plagioclase	0.3	Tr	0.3	Tr
Apatite	0.7	0.0	0.0	1.0
Allochems (Undifferentiated)	**4.3**	**25.7**	**6.3**	**9.0**
Calcareous Fragments	4.3	25.7	6.3	9.0
Authigenic Clay	**50.3**	**33.3**	**45.3**	**42.0**
Clay (Undifferentiated)	50.3	33.3	45.3	42.0
TOTALS:	**100.0**	**100.0**	**100.0**	**100.0**

THIN SECTION MODAL ANALYSIS

Kentucky Geological Survey
Marvin Blan No. 1
Conventional Core
Class V CO2 Test Well, Hancock County, Kentucky

Weatherford File No.: HH-43701 **Analyst: Brad Walls**

DEPTH:	**2824.90**	**2827.90**	**2830.85**
Sample Number	**2-25 P**	**2-28 P**	**2-31 P**
Grain Size Avg. (mm):	**0.015mm**	**0.02mm**	**0.015mm**
Grain Size Range (mm):	**<0.01mm-0.5mm**	**<0.01mm-0.5mm**	**<0.01mm-0.1mm**
Fabric:	**Laminated**	**Laminated**	**Laminated**
Rock Name:	**Silty, Argillaceous Mudstone**	**Silty, Argillaceous Mudstone**	**Silty, Argillaceous Mudstone**
FRAMEWORK GRAINS			
Quartz	**19.0**	**14.7**	**20.0**
Monocrystalline	19.0	14.7	20.0
Replacement Minerals	**27.3**	**29.0**	**24.7**
Dolomite	13.7	15.4	11.3
Ferroan Dolomite	1.3	1.3	2.0
Pyrite	12.3	12.3	11.4
Acessory Minerals	**2.3**	**0.3**	**1.0**
Muscovite	1.3	Tr	0.7
Undiff. Heavy Minerals	0.3	0.3	0.0
Sphalerite	0.7	Tr	0.3
Plagioclase	Tr	Tr	Tr
Apatite	Tr	0.0	Tr
Allochems (Undifferentiated)	**9.7**	**4.0**	**9.0**
Calcareous Fragments	9.7	4.0	9.0
Authigenic Clay	**41.7**	**52.0**	**45.3**
Clay (Undifferentiated)	41.7	52.0	45.3
TOTALS:	**100.0**	**100.0**	**100.0**

Well: Marvin Blan No. 1 Class V CO2 Test Well Field, Hancock County, KY USA													Analyst: Brad Walls											
			Constituents																			Shale Rock Properties		
Formation / Unit	Sample Depth (ft)	Lithology	Laminations	Quartz Total	Monocrystalline Quartz	Replacement Minerals (Sample Total)	Replacement Minerals (Laminations Total)	Dolomite	Ferroan Dolomite	Pyrite	Accessory Minerals (Sample Total)	Accessory Minerals (Laminations Total)	Muscovite	Heavy Minerals (Undifferentiated)	Sphalerite	Plagioclase	Apatite	Allochems (Undifferentiated)	Calcareous Fragments	Authigenic Clay	Clay (Undifferentiated)	Porosity (A-R Gas filled) (% of BV)	Permeability (A-R Press Decay, mD)	Dry Grain Density (gm/cc)
Highbridge Group / Black River Limestone	2800.85	Calcareous, argillaceous mudstone	Massive	18.3	18.3	18.7	NA	12.0	0.0	6.7	2.0	NA	1.7	0.0	0.3	0.0	0.0	20.0	20.0	41.0	41.0	0.20	3.29E-07	2.76
	2803.85	Argillaceous, calcareous mudstone	Massive	18.7	18.7	19.3	NA	16.3	0.0	3.0	0.0	NA	0.0	0.0	0.0	0.0	0.0	44.7	44.7	17.3	17.3	0.20	5.77E-06	2.76
	2806.90	Calcareous, silty, argillaceous mudstone	Massive	28.0	28.0	32.0	NA	25.7	1.0	5.3	0.7	NA	0.3	0.0	0.3	0.0	0.0	16.7	16.7	22.7	22.7	0.40	1.08E-06	2.77
	2809.80	Silty, argillaceous mudstone	Argillaceous	10.7	1.7	31.0	12.0	5.7	1.0	5.3	0.7	0.3	0.3	0.0	0.0	0.0	0.0	4.7	1.3	53.0	39.0	0.60	5.28E-05	2.78
			Calcareous / Dolomitic		9.0		19.0	15.0	0.3	3.7		0.3	0.3	0.0	0.0	0.0	0.0		3.3		14.0			
	2812.80	Silty, argillaceous mudstone	Argillaceous	14.7	7.7	29.0	17.3	10.0	2.7	4.7	1.7	1.0	0.3	0.0	0.0	0.0	0.7	4.3	2.3	50.3	41.0	0.60	4.52E-05	2.78
			Calcareous / Dolomitic		7.0		11.7	9.3	0.0	2.3		0.7	0.3	0.0	0.0	0.3	0.0		2.0		9.3			
	2815.90	Calcareous, silty, argillaceous mudstone	Argillaceous	16.7	1.7	23.0	6.3	4.3	0.0	2.0	1.3	1.0	1.0	0.0	0.0	0.0	0.0	25.7	3.7	33.3	22.0	0.60	4.26E-05	2.77
			Calcareous / Dolomitic		15.0		16.7	14.0	0.0	2.7		0.3	0.3	0.0	0.0	0.0	0.0		22.0		11.3			
	2818.80	Silty, argillaceous mudstone	Argillaceous	20.3	8.7	27.7	14.0	5.3	0.7	8.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	6.3	1.7	45.3	39.0	0.80	6.42E-06	2.78
			Calcareous / Dolomitic		11.7		13.7	10.3	0.3	3.0		0.3	0.0	0.0	0.0	0.3	0.0		4.7		6.3			
	2821.90	Calcareous, silty, argillaceous mudstone	Argillaceous	15.3	9.3	32.3	20.3	7.0	2.0	11.3	1.3	1.0	0.0	0.0	0.0	0.0	1.0	9.0	2.0	42.0	38.0	0.30	5.45E-06	2.78
			Calcareous / Dolomitic		6.0		12.0	7.7	0.3	4.0		0.3	0.3	0.0	0.0	0.0	0.0		7.0		4.0			
	2824.90	Silty, argillaceous mudstone	Argillaceous	19.0	10.7	27.3	14.3	6.0	1.3	7.0	2.3	1.7	1.0	0.3	0.3	0.0	0.0	9.7	4.7	41.7	32.3	0.20	1.37E-05	2.76
			Calcareous / Dolomitic		8.3		13.0	7.7	0.0	5.3		0.7	0.3	0.0	0.3	0.0	0.0		5.0		9.3			
	2827.90	Silty, argillaceous mudstone	Argillaceous	14.7	10.0	29.0	23.3	12.3	1.0	10.0	0.3	0.3	0.0	0.3	0.0	0.0	0.0	4.0	2.3	52.0	49.3	0.20	5.21E-06	2.76
			Calcareous / Dolomitic		4.7		5.7	3.0	0.3	2.3		0.0	0.0	0.0	0.0	0.0	0.0		1.7		2.7			
	2830.85	Silty, argillaceous mudstone	Argillaceous	20.0	10.0	24.7	15.0	4.0	2.0	9.0	1.0	1.0	0.7	0.0	0.3	0.0	0.0	9.0	4.3	45.3	39.3	0.10	5.99E-07	2.77
			Calcareous / Dolomitic		10.0		9.7	7.3	0.0	2.3		0.0	0.0	0.0	0.0	0.0	0.0		4.7		6.0			

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APPENDIX C:

XRD TABLES

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Weatherford LABORATORIES

WEATHERFORD LABORATORIES
X-RAY DIFFRACTION
(WEIGHT %)

Client: Kentucky Geological Survey
Well: Marvin Blan No. 1
Area: Hancock County, KY
Sample Type: Conventional Core

File No: HH-43701
Date: 10/16/09
Analyst: G. Walker

Plug	Sample	CLAYS				CARBONATES			OTHER MINERALS						TOTALS		
Number	Depth (ft)	Chlorite	Kaolinite	Illite	Mx I/S*	Calcite	Fe-Dol	Siderite	Quartz	K-spar	Plag.	Pyrite	Apatite	Barite	Clays	Carb.	Other
2-1 P	2800.85	9	1	23	1	22	2	Tr	25	2	8	3	4	0	34	24	42
2-4 P	2803.85	7	1	17	1	37	3	Tr	19	4	5	3	3	0	26	40	34
2-7 P	2806.90	8	1	20	1	19	9	Tr	24	3	8	4	3	0	30	28	42
2-10 P	2809.80	10	2	28	2	8	6	Tr	27	3	6	4	4	0	42	14	44
2-13 P	2812.80	12	2	32	2	7	4	Tr	24	3	5	5	4	0	48	11	41
2-16 P	2815.90	10	1	22	1	23	3	Tr	24	3	6	4	3	0	34	26	40
2-19 P	2818.80	11	2	28	2	8	3	Tr	28	3	7	4	4	0	43	11	46
2-22 P	2821.90	11	2	33	2	7	4	Tr	26	3	6	3	3	0	48	11	41
2-25 P	2824.90	11	2	31	2	8	3	Tr	27	3	7	3	3	0	46	11	43
2-28 P	2827.90	11	2	27	2	8	4	Tr	28	3	7	4	4	0	42	12	46
2-31 P	2830.85	10	2	25	1	11	4	Tr	30	3	8	3	3	0	38	15	47
	AVERAGE	10	2	26	1	14	4	Tr	26	3	7	4	3	0	39	18	43

* Ordered interstratified mixed-layer illite/smectite; Approximately 10-15% expandable interlayers

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Appendix 1D

Total Organic Carbon

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Weatherford LABORATORIES

TOTAL ORGANIC CARBON

Company: KENTUCKY GEOLOGICAL SURVEY **Project #: HH-43701/09-1570-A**

Client ID	Well Name	Lab ID	Sample Type	Depth	Prep	TOC Wt. %	Verified	Comments
2-1GC	Marvin Blan No. 1	UI000011	CORE	2800.85 ft	NOPR	0.60	TOC	
2-4GC	Marvin Blan No. 1	UI000012	CORE	2803.85 ft	NOPR	0.33	TOC	
2-7GC	Marvin Blan No. 1	UI000013	CORE	2806.90 ft	NOPR	0.37	TOC	
2-10GC	Marvin Blan No. 1	UI000014	CORE	2809.80 ft	NOPR	0.37	TOC	
2-13GC	Marvin Blan No. 1	UI000015	CORE	2812.80 ft	NOPR	0.66	TOC	
2-16GC	Marvin Blan No. 1	UI000016	CORE	2815.90 ft	NOPR	0.34	TOC	
2-19GC	Marvin Blan No. 1	UI000017	CORE	2818.80 ft	NOPR	0.66	TOC	
2-22GC	Marvin Blan No. 1	UI000018	CORE	2821.90 ft	NOPR	0.55	TOC	
2-25GC	Marvin Blan No. 1	UI000019	CORE	2824.90 ft	NOPR	0.68	TOC	
2-28GC	Marvin Blan No. 1	UI000020	CORE	2827.90 ft	NOPR	0.93	TOC	
2-31GC	Marvin Blan No. 1	UI000021	CORE	2830.85 ft	NOPR	0.83	TOC	

Notes:
NOPR - Normal Preparation EXT - Extracted Rock

Geochemical Services Group, 143 Vision Park Blvd., Shenandoah, Texas 77384 • Phone: 281-681-2200 • Fax: 281-681-0326 • Email: geocheminfo@weatherfordlabs.com

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Appendix 1E

Shale Rock Properties:
Summary of Routine Crushed Core Analyses Results

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Weatherford LABORATORIES

SHALE ROCK PROPERTIES
SUMMARY OF ROUTINE CRUSHED CORE ANALYSES RESULTS

As-Received and Vacuum Dried at 212°F

Kentucky Geological Survey — HH-43701
Marvin Blan No.1 — 10-29-03
Hancock County KY, USA

Sample ID	Top Depth, feet	Bottom Depth, feet	A-R Bulk Density, gm/cc	A-R Gas Filled Porosity, % of BV	A-R Press Decay Permeability, md	Dry Bulk Density, gm/cc	Dry Grain Density, gm/cc	Dry Helium Porosity, % of BV
2-1 SRP	2800.85	2800.95	2.66	0.2	3.29E-07	2.61	2.76	5.7
2-4 SRP	2803.85	2803.95	2.69	0.2	5.77E-06	2.65	2.76	3.7
2-7 SRP	2806.90	2807.00	2.69	0.4	1.08E-06	2.65	2.77	4.2
2-10 SRP	2809.80	2809.90	2.66	0.6	5.28E-05	2.61	2.78	6.1
2-13 SRP	2812.80	2812.95	2.65	0.6	4.52E-05	2.59	2.78	6.8
2-16 SRP	2815.90	2816.00	2.66	0.6	4.26E-05	2.60	2.77	6.0
2-19 SRP	2818.80	2818.90	2.64	0.8	6.42E-06	2.58	2.78	7.0
2-22 SRP	2821.90	2822.00	2.66	0.3	5.45E-06	2.60	2.78	6.4
2-25 SRP	2824.90	2825.00	2.65	0.2	1.37E-05	2.59	2.76	6.3
2-28 SRP	2827.90	2828.00	2.65	0.2	5.21E-06	2.60	2.76	5.9
2-31 SRP	2830.85	2830.95	2.66	0.1	5.99E-07	2.60	2.77	6.1
Average values:			2.66	0.4	1.63E-05	2.61	2.77	5.8

As-received bulk volumes and bulk densities were determined on intact bulk sample material.

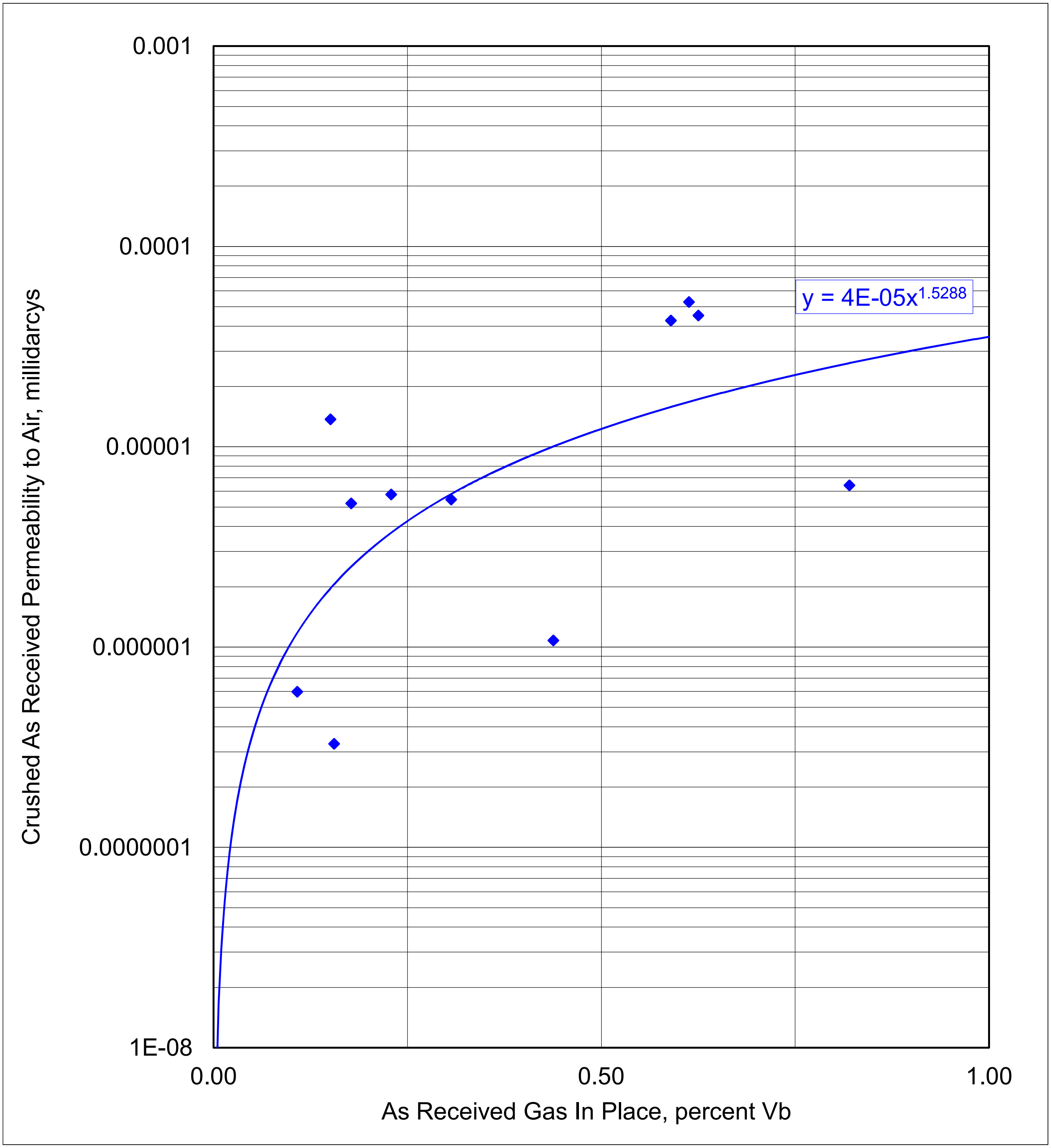
The bulk material was crushed and all other analysis reported herein were conducted on the crushed material.

PERMEABILITY VERSUS PERCENT GAS IN PLACE

As Received Crushed Preparation

Kentucky Geological Survey
Marvin Blan No.1
Hancock County KY, USA

HH-43701
10-29-03



Appendix 1F

Rock Mechanics Final Report

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Weatherford LABORATORIES

ROCK MECHANICS TESTING & ANALYSES
MARVIN BLAN NO. 1
HANCOCK COUNTY, KY
KENTUCKY GEOLOGICAL SURVEY

ROCK MECHANICS FINAL REPORT

(Unconfined Compressive Tests)

(Triaxial Compressive Tests)

(Acoustic Velocities)

WFT Labs HH-43701

Performed by:

Weatherford Laboratories
8845 Fallbrook Drive
Houston, TX 77064

Ohmyoung Kwon, Ph.D.

Report Issued:

September 29, 2009

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Procedures for Unconfined and Triaxial Compressive Strength Test

The general procedures for unconfined and triaxial compressive test are summarized in the following:

1) A right cylindrical plug is cut from the sample core and their ends ground parallel according to International Society for Rock Mechanics (ISRM) and American Society for Testing and Materials (ASTM) standards. A length to diameter ratio of 2:1 is recommended to obtain representative mechanical properties of the sample, which is also recommended by ASTM and ISRM. Physical dimensions of the specimen are recorded and the specimen is saturated with desired fluid if needed.

2) The specimen is then placed between two platens and a heat-shrink jacket is placed over the specimen.

3) Axial strain and radial strain devices are mounted in the endcaps and on the lateral surface of the specimen, respectively.

4) The specimen assembly is placed into the pressure vessel and the pressure vessel is filled with hydraulic oil. Unconfined test is conducted without filling the vessel.

5) Confining pressure is increased to the desired hydrostatic testing pressure. Unconfined test is conducted under zero confining pressure.

6) Measure ultrasonic velocities at the hydrostatic confining pressure.

7) Specimen assembly is brought into the contact with a loading piston that allows application of axial load.

8) Increase axial load at a constant rate until the specimen fails for unconfined test or differential stress reaches about 3000 psi or 10,000 psi for triaxial compressive test while confining pressure is held constant.

9) Reduce axial stress to the initial hydrostatic condition after sample fails or reaches a desired differential stress level.

10) Reduce confining pressure to zero and disassemble sample.

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SUMMARY OF TRIAXIAL COMPRESSIVE TESTS

Kentucky Geological Survey **Hancock County, KY**
Marvin Blan No. 1

Sample No.	Depth (ft)	Confining Pressure (psi)	Compressive Strength (psi)	Static Young's Modulus ($x10^6$ psi)	Static Poisson's Ratio
2-5VRM-A	2804.45	800	-	4.40	0.12
2-5VRM-B	2804.45	0	17264	4.36	0.22
3-4VRM-A*	3338.14	1000	-	5.43	0.27
3-4VRM-B	3338.14	0	7216	2.88	0.16
3-30VRM-A*	3364.47	1000	-	6.14	0.31
3-30VRM-B	3364.47	0	7910	2.74	0.12

* differential stress was applied to about 10,000 psi and then unloaded

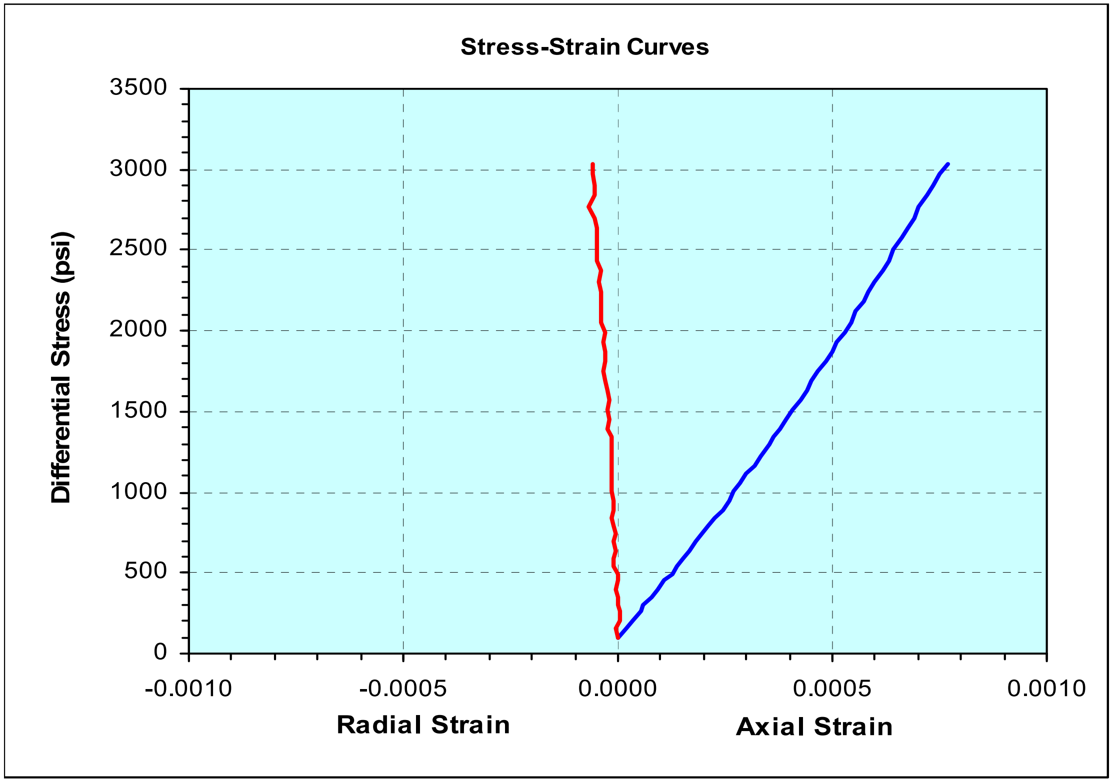
SUMMARY OF ULTRASONIC VELOCITIES AND DYNAMIC ELASTIC PARAMETERS

Kentucky Geological Survey **Hancock County, KY**
Marvin Blan No. 1

Sample No.	Depth (ft)	Confining Pressure (psi)	Bulk Density (g/cc)	Ultrasonic Wave Velocity*				Dynamic Elastic Parameter			
				Compressional		Shear		Young's Modulus ($x10^6$ psi)	Poisson's Ratio	Bulk Modulus ($x10^6$ psi)	Shear Modulus ($x10^6$ psi)
				ft/sec	μsec/ft	ft/sec	μsec/ft				
2-5VRM-A	2804.45	800	2.70	18637	53.66	10776	92.80	10.55	0.25	7.00	4.22
3-4VRM-A	3338.14	1000	2.70	20463	48.87	10619	94.17	10.78	0.32	9.75	4.10
3-30VRM-A	3364.47	1000	2.69	20396	49.03	10348	96.63	10.31	0.33	9.92	3.89

* ultrasonic velocities measured after applying 2000 psi differential stress

Result of Triaxial Compressive Test



Company	KGS
Project Title	Marvin Blan 1
WFT Project No.	HH-43701
Date	Sep., 2009

Sample No.	2-5VRM-A
Depth (ft)	2804.45
Saturation State	as-is
Confining Pressure (psi)	800
Bulk Density (g/cc)	2.70
Compressive Strength (psi)	-
Young's Modulus ($x10^6$ psi)	4.40
Poisson's Ratio	0.12

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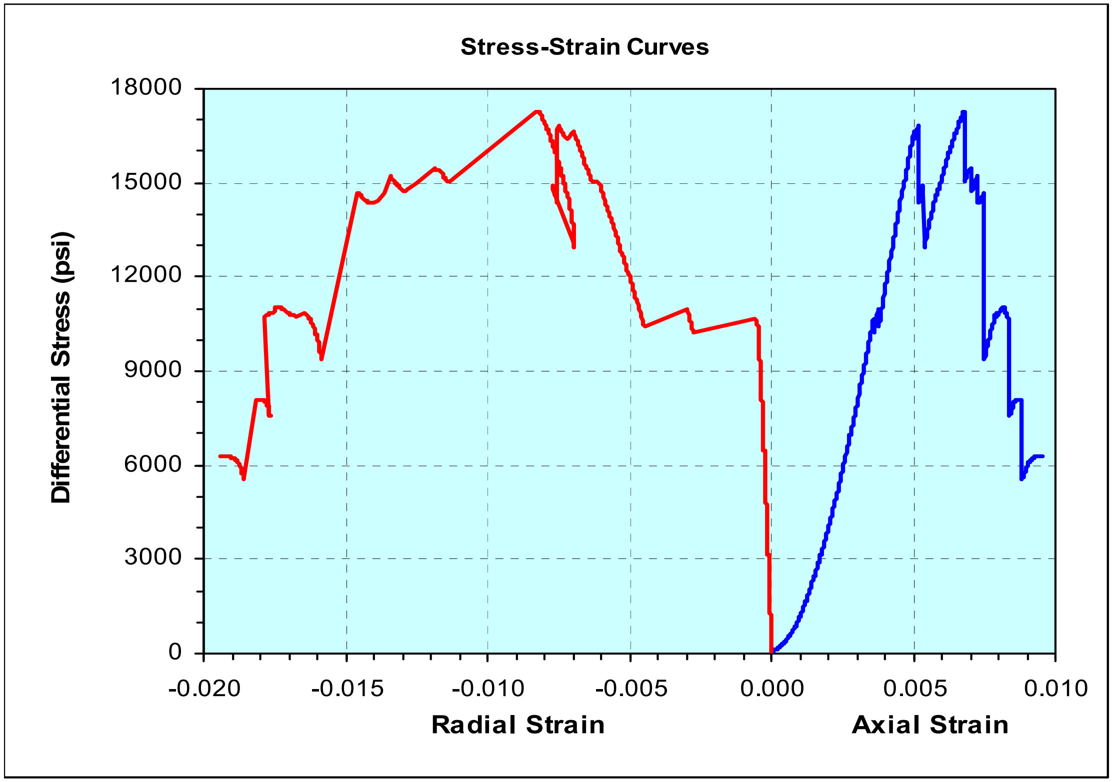
Result of Unconfined Compressive Test



Company	KGS
Project Title	Marvin Blan 1
WFT Project No.	HH-43701
Date	Sep., 2009

Sample No.	2-5VRM-B
Depth (ft)	2804.45
Saturation State	as-is
Confining Pressure (psi)	0
Bulk Density (g/cc)	2.70
Compressive Strength (psi)	17264
Young's Modulus ($x10^6$ psi)	4.36
Poisson's Ratio	0.22

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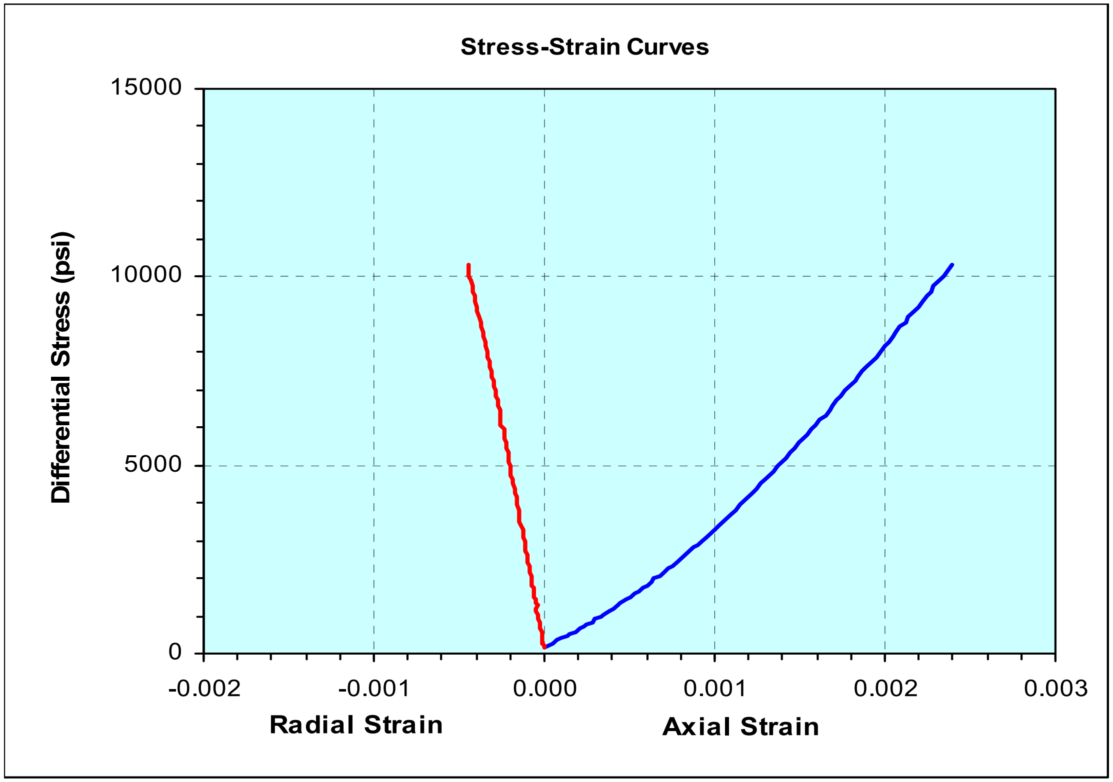
Result of Triaxial Compressive Test



Company	KGS
Project Title	Marvin Blan 1
WFT Project No.	HH-43701
Date	August, 2009

Sample No.	3-4VRM-A
Depth (ft)	3338.14
Saturation State	2% KCl
Confining Pressure (psi)	1000
Bulk Density* (g/cc)	2.70
Compressive Strength (psi)	-
Young's Modulus ($x10^6$ psi)	5.43
Poisson's Ratio	0.27

* saturated

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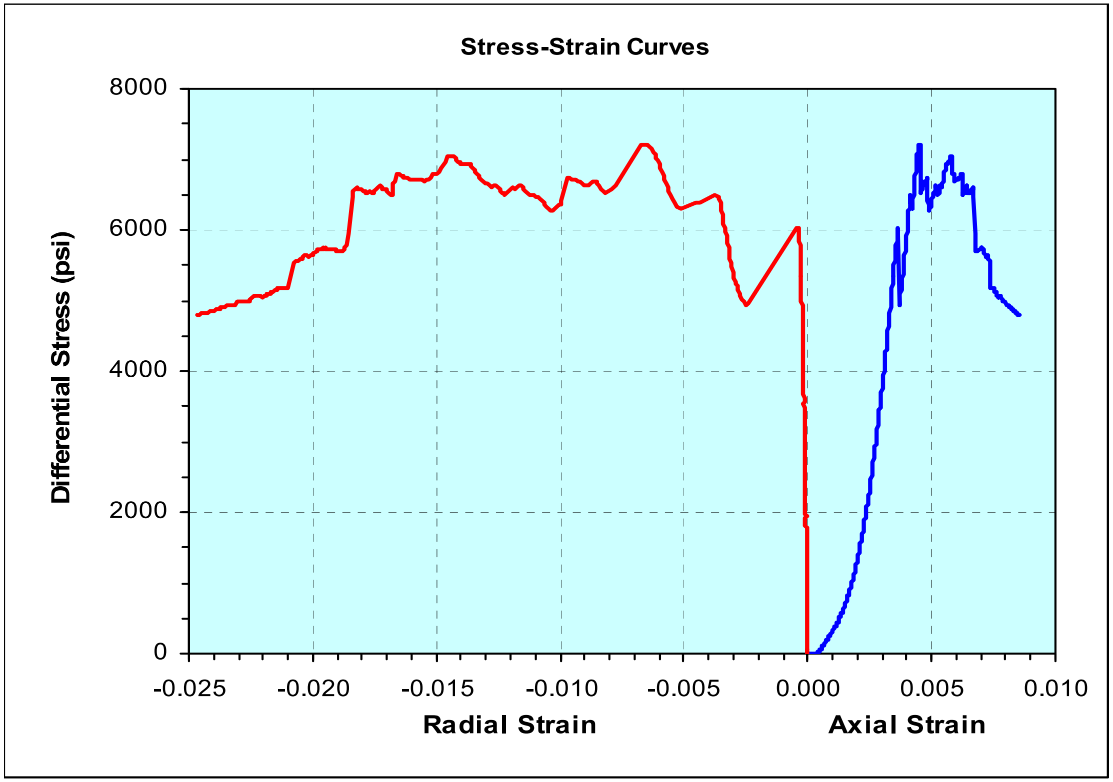
Result of Unconfined Compressive Test



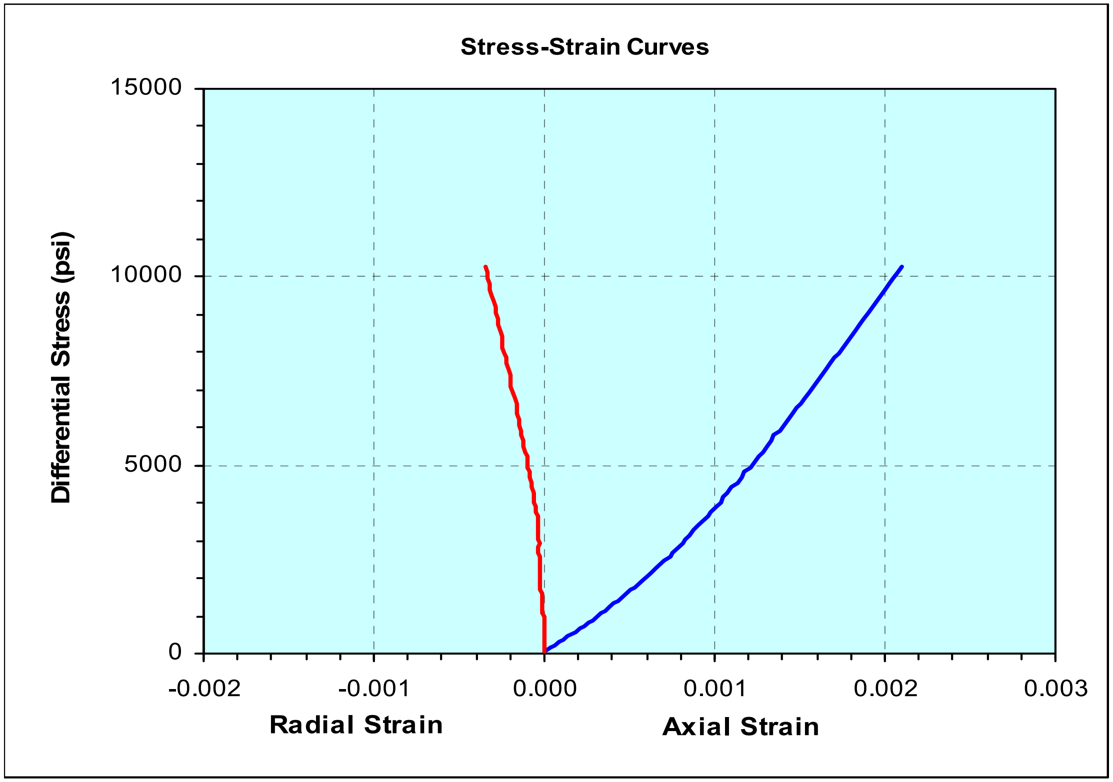
Company	KGS
Project Title	Marvin Blan 1
WFT Project No.	HH-43701
Date	August, 2009

Sample No.	3-4VRM-B
Depth (ft)	3338.14
Saturation State	2% KCl
Confining Pressure (psi)	0
Bulk Density* (g/cc)	2.70
Compressive Strength (psi)	7216
Young's Modulus ($x10^6$ psi)	2.88
Poisson's Ratio	0.16

* saturated

Weatherford LABORATORIES

Result of Triaxial Compressive Test



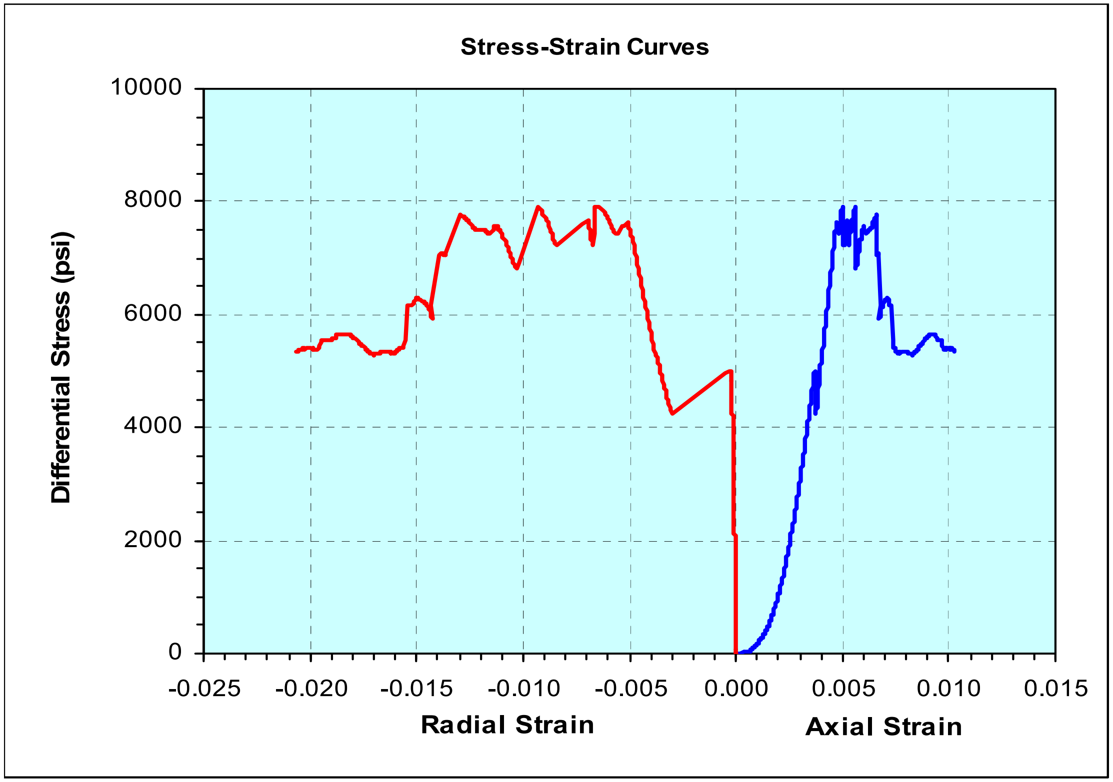
Company	KGS
Project Title	Marvin Blan 1
WFT Project No.	HH-43701
Date	August, 2009

Sample No.	3-30VRM-A
Depth (ft)	3364.47
Saturation State	2% KCl
Confining Pressure (psi)	1000
Bulk Density* (g/cc)	2.69
Compressive Strength (psi)	-
Young's Modulus ($x10^6$ psi)	6.14
Poisson's Ratio	0.31

* saturated

Weatherford LABORATORIES

Result of Unconfined Compressive Test



Company	KGS
Project Title	Marvin Blan 1
WFT Project No.	HH-43701
Date	August, 2009

Sample No.	3-30VRM-B
Depth (ft)	3364.47
Saturation State	2% KCl
Confining Pressure (psi)	0
Bulk Density* (g/cc)	2.70
Compressive Strength (psi)	7910
Young's Modulus (x10^6 psi)	2.74
Poisson's Ratio	0.12

* saturated

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Appendix 1G

Vapor Desorption Capillary Pressure

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VAPOR DESORPTION CAPILLARY PRESSURE

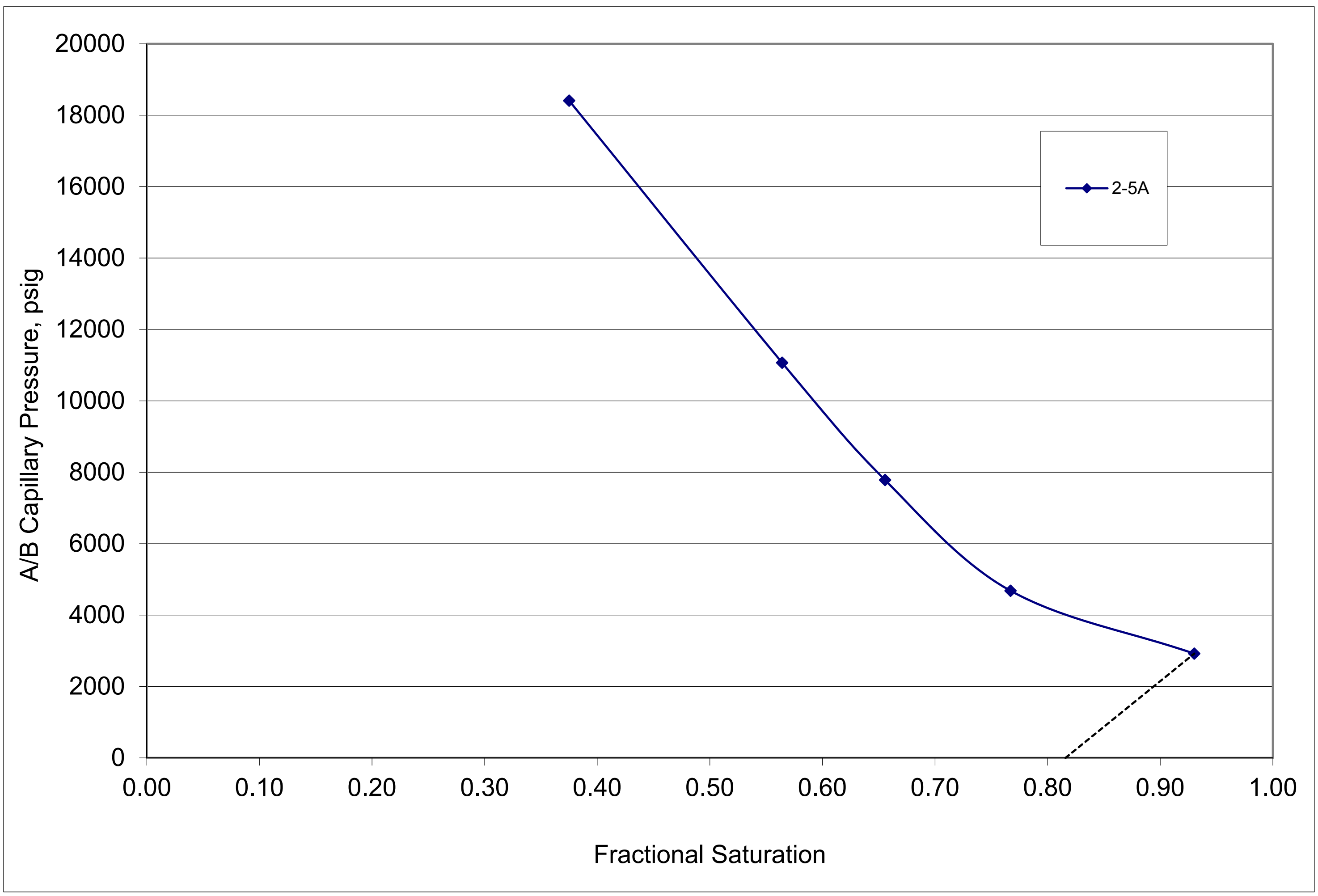
Test Temperature: 30°C

Kentucky Geological Survey
Marvin Blan No.1
Hancock County KY, USA

HH-43701
7-14-10

Sample ID	2-5A
Depth, feet	2804.45
	2804.50
Porosty, percent:	3.3
Grain Density, g/cc	2.749

	Relative Humidity, %	A/B Capillary Pressure, psig	Pore Throat Diameter, microns	Brine Saturation, fractional *
AR Swi		0		0.816
	87	2921	0.0140	0.930
	77	4681	0.0088	0.767
	69	7784	0.0053	0.656
	59	11068	0.0037	0.564
HD @ 60C	45	18408	0.0022	0.375



* Weight based saturation calculations based on an A/B system.

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Appendix 2

Project Engineering and Operations Reports

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Appendix 2A

Phase 2 Engineering and Operations Reports

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Kentucky Geological Survey
Marvin Blan #1
Phase II Testing Procedure
August 13, 2010
CO_2 Injection

Step	Est. Time (hr)	Day	Operations	Start Time	End Time	Task Description
			Daylight	8/20/10 7:00	8/20/10 13:00	Begin moving 14 frac tanks on location. Manifold 13 of the frac tanks and begin filling with freshwater.
			Daylight	8/20/10 13:00	8/23/10 0:00	Continue moving frac tanks on location and filling frac tanks with freshwater.
1	10	1.0	Daylight	8/23/10 7:00	8/23/10 17:00	Rig and equipment mobilization
2	6	2.0	Daylight	8/24/10 7:00	8/24/10 13:00	Rig up workover rig and unload BOP's and rental equipment. Receive 200 bbl of 9.0 lb/gal brine in a frac tank for kill fluid.
3	6	2.3	Daylight	8/24/10 13:00	8/24/10 19:00	Check well for pressure. Remove dry hole tree and install BOP.
4	4	3.0	Daylight	8/25/10 7:00	8/25/10 11:00	Pressure test BOPs and choke manifold.
5	6	3.2	Daylight	8/25/10 11:00	8/25/10 17:00	Pick up bridge plug retrieving tool and trip in well to bridge plug at ~3,640 ft. Engage, open valve, and check of pressure. Assume no pressure on well. If necessary, pump fluid to kill well.
6	4	4.0	Daylight	8/26/10 7:00	8/26/10 11:00	Release bridge plug and pull out of well with bridge plug and memory gauges without filling wellbore with water. Recover the two memory tools from the perforated pup joint below the bridge plug. Download bottom hole pressure and temperature data from the two memory tools.

7	7	4.2	Daylight	8/26/10 11:00	8/26/10 18:00	Rig up logging unit to run a gamma ray-ccl-differential temperature survey from surface to total depth, 8,126 ft. Pull out of the well with the logging tools.
8	5	5.0	Daylight	8/27/10 7:00	8/27/10 12:00	Trip in well open ended with the 3-1/2" workstring to 5,920 ft.
9	2	5.2	Daylight	8/27/10 12:00	8/27/10 14:00	Break circulation with 20 bbl of fresh water. Circulate a 150 ft balanced cement plug (~60 ft^3) from 5,920 ft to 5,770 ft. Pull out of the well with 310 ft of workstring and position the end of the pipe at 5,610 ft.
10	4	5.3	Daylight	8/27/10 14:00	8/27/10 18:00	Allow the cement to cure for 4 hours. Lower the workstring down and tag the top of the cement plug.
11	4	6.0	24 hr	8/28/10 7:00	8/28/10 11:00	Position the end of the workstring at 3,300 ft. Flush the wellbore with 8,000 gal of freshwater with 1 gal Bio-31/1,000 gal (equivalent to 2% KCl). Pull out of the well with the 3-1/2" workstring.
12	4	6.2	24 hr	8/28/10 11:00	8/28/10 15:00	Pick up an open hole isolation tool (OHIT) with the cementing sliding sleeve in the open positon and the botton plugged with a shear out sub. Install a backoff sub with a left hand thread approximately 93 feet above the above the OHIT. Install a memory pressure gauge in the annulus on the outside of the 3-1/2" workstring with a Cannon clamp approximately 155 ft above the OHIT. Lower the OHIT in the well on the 3-1/2" workstring and position the OHIT with the lower cement basket at ~5,345 ft.

13	2	6.3	24 hr	8/28/10 15:00	8/28/10 17:00	Rig up to cement and break circulation pumping fresh water down the 3-1/2" workstring and circulating throught the sliding sleeve in the OHIT. Mix and pump ~16.5 ft^3 down the 3-1/2" and install the closing dart for the sliding sleeve. Displace the cement and closing dart with 46.5 bbl of water. Land the closing dart and shift the sleeve closed. Pressure up and shear the isolation disk out of the bottom of the tool. Flush the tubing with 20 bbl of water.
14	10	6.4	24 hr	8/28/10 17:00	8/29/10 3:00	Wait on the cement to set up.
15	4	6.8	24 hr	8/29/10 3:00	8/29/10 7:00	Rig up logging unit to run a gamma ray-ccl-differential temperature survey from surface to the plugged back total depth, ~5,820 ft. Pullout of the well with the logging tools.
16	4	7.0	24 hr	8/29/10 7:00	8/29/10 11:00	Rig up wireline unit with bottom hole pressure tools and wellhead pressure control equipment. Lower bottom hole pressure tools in the well on the wireline and position in the well approximately 20 ft below the bottom of the OHIT at ~5,365 ft. Collect a minimum of one hour of static bottom hole pressure and temperature data.
17	9	7.2	24 hr	8/29/10 11:00	8/29/10 20:00	**Testing Interval from ~5,345 ft to ~5,820 ft.** Perform a constrant rate injection test at 10 bpm for approximately 8.5 hours while monitoring and recording the BHP and BHT with the SRO.
18	12	7.5	24 hr	8/29/10 20:00	8/30/10 8:00	Suspend injection and monitor the pressure falloff for approximately 12 hours.

19	16	8.0	24 hr	8/30/10 8:00	8/31/10 0:00	Remove the bottom hole pressure tools from the well and install differential temperature tools on the wireline. Run temperature decay logs at 13 hrs, 18 hrs, and 24 hrs. Remove the wireline and logging tools from the well. Rig down the logging unit.
20	3	8.7	24 hr	8/31/10 0:00	8/31/10 3:00	Pump an isolation plug down the 3-1/2" workstring and land the plug in the OHIT. Pick up on the tubing to the neutral position and screw out of the backoff sub at ~5,242 ft. Rig up cementing unit. Mix and pump a 50 ft balanced cement plug (19 ft^3) in the well from ~5,242 ft to ~5,192 ft. Position the end of the tubing at ~5,210 ft and reverse circulate the well clean.
21	4	8.8	24 hr	8/31/10 3:00	8/31/10 7:00	Pull out of the well with the 3-1/2" workstring and the memory pressure gauge. Remove the memory pressure gauge and download the data.
22	4	9.0	24 hr	8/31/10 7:00	8/31/10 11:00	Pick up the second OHIT with the cementing sliding sleeve in the open positon and the botton plugged with a shear out sub. Install a backoff sub with a left hand thread approximately 93 feet above the OHIT. Lower the OHIT in the well on the 3-1/2" workstring and position the OHIT with the lower cement basket at ~4,970 ft.

23	2	9.2	24 hr	8/31/10 11:00	8/31/10 13:00	Rig up to cement and break circulation pumping fresh water down the 3-1/2" workstring and circulating throught the sliding sleeve in the OHIT. Mix and pump ~22.5 ft^3 down the 3-1/2" and install the closing dart for the sliding sleeve. Displace the cement and closing dart with 43.2 bbl of water. Land the closing dart and shift the sleeve closed. Pressure up and shear the isolation disk out of the bottom of the tool. Flush the tubing with 20 bbl of water.
24	10	9.2	24 hr	8/31/10 13:00	8/31/10 23:00	Wait on the cement to set up. Spot and rig up air compressors for the air injection.
25	3	9.7	24 hr	8/31/10 23:00	9/1/10 2:00	Pick up on the tubing to the neutral position and screw out of the backoff sub at ~4,870 ft. Pull out of the well with the releasing tool and tubing.
26	4	9.8	24 hr	9/1/10 2:00	9/1/10 6:00	Rig up to install 1.66" tubing, geophones, and cables.
27	10	10.0	Daylight	9/1/10 6:00	9/1/10 16:00	Install the 1.66" tubing with the geophones in the well while clanmping the cable to the tubing.
28	24	11.0	Daylight	9/2/10 6:00	9/3/10 18:00	Collect VSP data - Assume data collected during two 12 hour shifts, working days.
29	10	13.0	24 hr	9/4/10 6:00	9/4/10 16:00	Pull out of the well and lay down the 1.66 tubing and geophones pods while spooling up the cable.
30	4	13.4	24 hr	9/4/10 16:00	9/4/10 20:00	Pick up 5-1/2" packer with tandem memory gauges below and above the packer and lower in the well on the 3-1/2" tubing. Set the packer in the 5-1/2" isolation tool at ~4,950 ft.

31	4	13.5	24 hr	9/4/10 20:00	9/5/10 0:00	Rig up logging unit to run a gamma ray-ccl-differential temperature survey from surface to the plugged back total depth, ~5,210 ft. Pullout of the well with the logging tools.
32	4	13.7	24 hr	9/5/10 0:00	9/5/10 4:00	Rig up wireline unit with bottom hole pressure tools and wellhead pressure control equipment. Lower bottom hole pressure tools in the well on the wireline and position in the well approximately 20 ft below the bottom of the OHIT at ~4,990 ft. Collect a minimum of one hour of static bottom hole pressure and temperature data.
33	1.5	13.9	24 hr	9/5/10 4:00	9/5/10 5:30	**Testing on Interval from ~4,970 ft to ~5,210 ft.** Perform a constant rate injection test at 10 bpm for approximately 1.5 hours while monitoring and recording the BHP and BHT with the SRO.
34	2	13.9	24 hr	9/5/10 5:30	9/5/10 7:30	Suspend injection and monitor the pressure falloff for approximately 2 hours.
35	24	14.0	24 hr	9/5/10 7:30	9/6/10 7:30	Perform a constant injection test with 380 tons of CO_2 for approximately 24 hours.
36	8.5	15.0	24 hr	9/6/10 7:30	9/6/10 16:00	Perform a constant rate injection test at 10 bpm for approximately 8.5 hours while monitoring and recording the BHP and BHT with the SRO.
37	12	15.4	24 hr	9/6/10 16:00	9/7/10 4:00	Suspend injection and monitor the pressure falloff for approximately 12 hours.
38	16	15.9	24 hr	9/7/10 4:00	9/7/10 20:00	Remove the bottom hole pressure tools from the well and install differential temperature tools on the wireline. Run temperature decay logs at 13 hrs, 18 hrs, and 24 hrs. Remove the wireline and logging tools from the well. Rig down the logging unit.

39	4	16.5	24 hr	9/7/10 20:00	9/8/10 0:00	Release the packer and remove the tubing and packer from the well. Lay down the packer and recover the data from two sets of memory tools.
40	6	16.7	24 hr	9/8/10 0:00	9/8/10 6:00	Rig up to install 1.66" tubing, geophones, and cables.
41	10	17.0	Daylight	9/8/10 6:00	9/8/10 16:00	Install the 1.66" tubing with the geophones in the well while clanmping the cable to the tubing.
42	24	18.0	Daylight	9/9/10 6:00	9/10/10 18:00	Collect VSP data - Assume data collected during two 12 hour shifts, working days.
43	10	20.0	Daylight	9/11/10 6:00	9/11/10 16:00	Pull out of the well and lay down the 1.66 tubing and geophones pods while spooling up the cable.
44	3	20.4	24 hr	9/11/10 16:00	9/11/10 19:00	Trip in the well with an isolation plug for the 5-1/2" casing. Land the plug in the 5-1/2" isolation tool.
45	3	20.5	24 hr	9/11/10 19:00	9/11/10 22:00	Rig up to cement and break circulation pumping fresh water down the 3-1/2" workstring. Mix and pump a 50 ft balanced cement plug in the well from ~4,870 ft to ~4,820 ft. Position the end of the tubing at ~4,840 ft and reverse circulate the well clean.
46	4	20.6	24 hr	9/11/10 22:00	9/12/10 2:00	Pull out of the well with the 3-1/2" workstring.

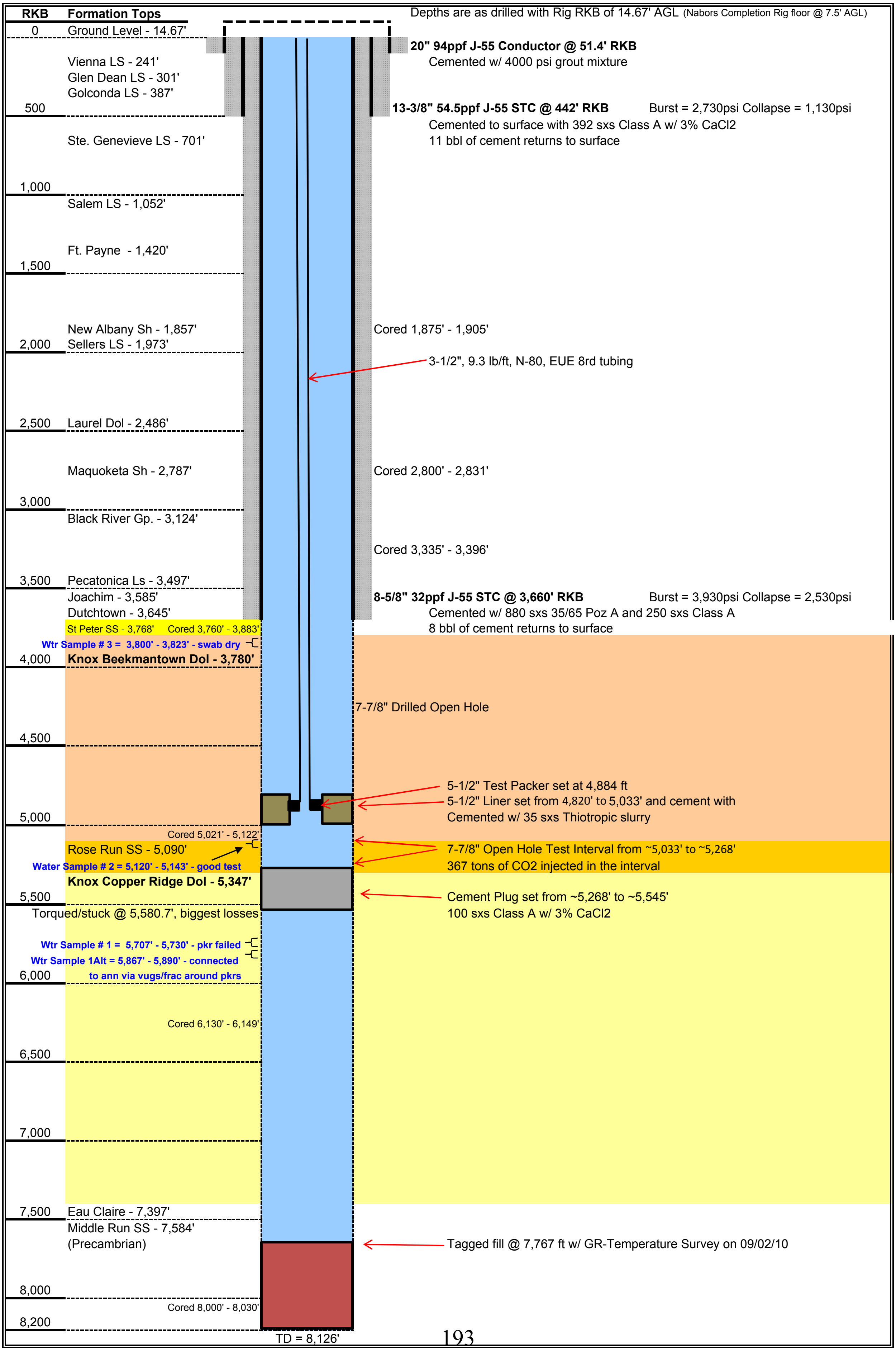
47	4	20.8	24 hr	9/12/10 2:00	9/12/10 6:00	Pick up the third OHIT with the cementing sliding sleeve in the open positon and the botton plugged with a shear out sub. Install a backoff sub with a left hand thread approximately 93 feet above the OHIT. Install a memory pressure gauge in the annulus on the outside of the 3-1/2" workstring with a Cannon clamp approximately 155 ft above the OHIT. Lower the OHIT in the well on the 3-1/2" workstring and position the OHIT with the lower cement basket at ~3,870 ft.
48	2	21.0	24 hr	9/12/10 6:00	9/12/10 8:00	Rig up to cement and break circulation pumping fresh water down the 3-1/2" workstring and circulating throught the sliding sleeve in the OHIT. Mix and pump ~18.5 ft^3 down the 3-1/2" and install the closing dart for the sliding sleeve. Displace the cement and closing dart with 33.7 bbl of water. Land the closing dart and shift the sleeve closed. Pressure up and shear the isolation disk out of the bottom of the tool. Flush the tubing with 20 bbl of water.
49	10	21.0	24 hr	9/12/10 8:00	9/12/10 18:00	Wait on the cement to set up.
50	4	21.5	24 hr	9/12/10 18:00	9/12/10 22:00	Rig up logging unit to run a gamma ray-ccl-differential temperature survey from surface to the plugged back total depth, ~4,840 ft. Pullout of the well with the logging tools.

51	4	21.6	24 hr	9/12/10 22:00	9/13/10 2:00	**Testing on Interval from ~3,870 ft to ~4,840 ft.** Rig up wirline unit with bottom hole pressure tools and wellhead pressure control equipment. Lower bottom hole pressure tools in the well on the wireline and position in the well approximately 20 ft below the bottom of the OHIT at ~3,890 ft. Collect a minimum of one hour of static bottom hole pressure and temperature data.
52	8.5	21.8	24 hr	9/13/10 2:00	9/13/10 10:30	Perform a constant rate injection test at 10 bpm for approximately 8.5 hours while monitoring and recording the BHP and BHT with the SRO.
53	12	22.1	24 hr	9/13/10 10:30	9/13/10 22:30	Suspend injection and monitor the pressure falloff for approximately 12 hours.
54	16	22.6	24 hr	9/13/10 22:30	9/14/10 14:30	Remove the bottom hole pressure tools from the well and install differential temperature tools on the wireline. Run temperature decay logs at 13 hrs, 18 hrs, and 24 hrs. Remove the wireline and logging tools from the well. Rig down the logging unit.
55	4	23.3	24 hr	9/14/10 14:30	9/14/10 18:30	Pump an isolation plug down the 3-1/2" workstring and land the plug in the OHIT. Pick up on the tubing to the neutral position and screw out of the backoff sub at ~3,770 ft. Rig up cementing unit. Mix and pump a 210 ft balanced cement plug in the well from ~3,770 ft to ~3,560 ft (78.0 ft^3 or 583 gallons). Position the end of the tubing at ~3,500 ft and reverse circulate the well clean.
56	3	23.5	24 hr	9/14/10 18:30	9/14/10 21:30	Pull out of the well while laying down the 3-1/2" tubing. Position the end of the tubing ~425 ft.

57	2	23.6	24 hr	9/14/10 21:30	9/14/10 23:30	Rig up cementing company and circulate a cement plug in the 8-5/8" casing from 425 ft to surface (145.4 ft^3 or 1,088 gallons).
58	3	23.7	24 hr	9/14/10 23:30	9/15/10 2:30	Pull out of well and lay down the remaining joints of the 3-1/2" workstring. Wash up BOPs to remove cement from the equipment. Nipple down the BOPs.
59	4	23.8	24 hr	9/15/10 2:30	9/15/10 6:30	Dig out the cellar around the wellhead and cut off the casing 4 ft below ground level. Weld a plate on the 8-5/8" casing stub.
60	12	24.0	Daylight	9/15/10 6:30	9/15/10 18:30	Rig down and release the workover rig and rental equipment.
61	12	25.0	Daylight	9/16/10 6:30	9/16/10 18:30	Equipment Demobilization. Clean up location and release the frac tanks.
		25.5				

Est. Total Hours **433.5** **26** **Estimated Days of Field Operations**

KGS Marvin Blan # 1 Well
Wellbore Schematic for the Injection Test Interval



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DAILY OPERATIONS REPORT

Operator: Kentucky Geological Survey
Contact: Rick Bowersox, Lexington Office
Dave Williams, Henderson Office
Well: Marvin Blan #1
Project: Phase 2 CO_2 Injection Testing
Date: August 30, 2010 – September 30, 2010
By: Bill Armstrong, Sandia Technologies, LLC
Rig: CC Forbes #77

August 30, 2010
CC Forbes Rig #77 and crew arrived on location at 11:30 AM. The rig was positioned on the well location. Adjustments were made to the rig and the derrick was raised. The wellhead valve on the dry hole tree was opened to check the well for pressure. The shut-in well pressure was 0 psi. The catwalk and pipe racks were unloaded and positioned on location. Operations were suspended for the night at 4:30 PM. Two leaks in the freshwater supply line were located and repaired by GN Excavating. The delivery of the frac tanks for freshwater storage was continued by Eastern Services with eleven frac tanks on location. Eastern began delivering and manifolding the frac tanks on Thursday, August 26th. The filling of the frac tanks with freshwater was begun on August 27th at 6:30 PM. No Accidents, no spills.

August 31, 2010
Field operations were resumed at 7:00 a.m. A prejob safety meeting was conducted with the CC Forbes and Sandia personnel. The dry hole tree consisting of a 2-1/16" 5M x 11" 5M adapter flange and 2-1116" 5M flanged gate valve was removed from the well. Three loads of rental equipment consisting of the pressure control equipment, 180 joints of 3-1/2" EUE 8rd tubing, and various subs were delivered to location and offloaded. The 11 ", 5M double ram blowout preventer (BOP) was installed on the well. The BOP closing unit (accumulator) was positioned and the hydraulic hoses from the accumulator to the BOP were installed. The BOP rams were function tested. The tubing handling tools and tongs were rigged up. An 8 ft x 40 ft office trailer was delivered to location, set up, and connected to electrical power provided by a rental generator. Five drums of double strength BIO-31 KCl substitute were delivered to location. Wireless internet service for the field office was installed by Norlight. The 8-5/8" casing and the wellhead pressure control equipment were filled with water and the BOP blind rams were closed. The BOP blind rams, the 8-5/8" casing, and the retrievable bridge plug at -3,630 ft were successfully pressure tested to a low pressure of275 psig and a high pressure of 2,270 psig. The test pressure was bled off the well. Two leaking BOP hydraulic connections were repaired. The location was cleaned up and the field operations were suspended for the night at 5:30 p.m. No Accidents, no spills.

September 1, 2010
Field operations were resumed at 7:00 a.m. A prejob safety meeting was conducted with the CC Forbes, TEAM Completion Services, and Sandia personnel. A 4" fluid return line was installed from the wellhead to a frac tank. The bridge plug retrieving tool was picked up with a 7.26" OD skirted guide. The bridge plug retrieving tool was lowered in the well on the 3-112", 9.30 Iblft, N-80, EUE 8rd tubing string to 3,578 ft while piping the tubing up from the pipe racks. A 3-1/2" safety valve was installed on the tubing and the 3-112" BOP pipe rams were closed on the tubing. The BOP pipe rams, 8-5/8" casing, and the retrievable bridge plug were successfully pressure tested to a low pressure of 310 psia and high pressure of 2,327 psia. The pressure was bled of the well and the pipe rams were open. The tubing string and bridge plug retrieving tool were lowered down and the top of the bridge plug was located at 3,626 ft. The string was picked up approximately I ft. The pipe rams were closed and circulation was established, reversing up the tubing. The circulating of the well was stopped and the pipe rams were opened. The string was slacked off and the retrievable bridge plug assembly was latched with the retrieving tool. The isolation valve above the bridge plug was opened to check for pressure below the tool. No indication of flow or increase pressure was detected after opening the down hole isolation valve. The bridge plug was released. The 3-112" tubing, retrieving tool, and the 8-5/8" retrievable bridge plug assembly were removed from the well. The tandem 1-1/4" OD memory pressure gauges were removed from the 2-7/8" perforated pup joint below the bridge plug. The bridge plug and retrieving tools were broken apart and loaded on TEAM's truck. TEAM's representative and tools were released. The location was cleaned up and the field operations were suspended for the night at 9:00 p.m. The pressure and temperature data were down loaded from the tandem memory tools. 375.1 days of data were recovered from each memory tool (~540,000 readings from each). No Accidents, no spills.

September 2, 2010
Field operations were resumed at 9:00 a.m. Checked well for pressure, well on slight vacuum. Waiting on Schlumberger logging crew to perform base temperature survey. Continuing to fill 12 frac tanks with fresh water, approximately 3,600 bbl (151 ,200 gallons) in the tanks at 11 :00 a.m. The Schlumberger logging unit and crew arrived on location at 3:30 p.m. A prejob safety meeting was conducted with the CC Forbes, Schlumberger, and Sandia personnel. Schlumberger's logging unit was rigged up to run a Differential Temperature Survey with gamma ran and casing collar locator. The Differential Temperature Survey was run from surface to 7,797 ft with a logging speed of 30 ft/min. The fluid level in the well was located at 105 ft. The electric line and logging tools were removed from the well. Schlumberger laid down the logging tools and secured their equipment. The well was isolated by closing the BOP blind rams. Field operations were suspended for the night at 11 :00 p.m. No Accidents, no spills.

September 3,2010
Field operations were resumed at 7:00 a.m. A prejob safety meeting was conducted with the CC Forbes, Schlumberger, and Sandia personnel. The logging unit was rigged up to run Schlumberger's electric line rotary coring tool. The rotary coring assembly was lowered in the well on the electric

line. A gamma ray depth correlation strip was run and the tool was depth correlated to the Weatherford's June 15,2009 Photo Density, Compensated Neutron, Array Induction log. Schlumberger began cutting the first rotary core at 5,235 ft. The rotary coring tool stopped functioning while cutting the first core. The electric line and rotary coring tool were removed from the welL Schlumberger was unable to repair the problem with the first tool assembly. The backup set of tools were picked up and tested on surface. The second set of tools also would not function properly. A third set of rotary coring tools were located and ordered from Bossier City, Louisiana. The well was isolated by closing the BOP blind rams and the location was cleaned up. Field operations were suspended for the night at 5:30 p.m. No Accidents, no spills.

September 4, 2010

Field operations were resumed at 9:00 a.m. A prejob safety meeting was conducted with the CC Forbes and Sandia personnel. A rerun 7·7/8" bit, 8-5/8" casing scraper, and bit sub were picked up on the first joint of 3-1/2" tubing. The bit and scraper were lowered in the well on the tubing to 3,634 ft. The 3-1/2" tubing and scraper assembly were removed from the welL The bit, scraper, and bit sub were laid down. A 2% KCl equivalent strength solution was mixed with a KCI substitute in eleven 500 bbl frac tanks. Began waiting on the delivery of Schlumberger's second set of rotary coring tools at 3:00 p.m. A prejob safety meeting was conducted for the rotary coring operations with the CC Forbes, Schlumberger, and Sandia personnel. Schlumberger's logging unit was rigged backup for running the rotary coring tools. The coring specialist and the second set of rotary coring tools arrived on location at 5: 1 0 p.m. The rotary sidewall coring tools were picked up and tested on surface. The rotary coring assembly was lowered in the well on the electric line. A gamma ray depth correlation strip was run from 5,325 ft to 5,190 ft and the coring tools were depth correlated to the Weatherford's June 15,2009 Photo Density, Compensated Neutron, Array Induction log. Schlumberger began cutting the first rotary core at 7: 1 0 p.m. The cutting of the 20^{th} core was finished at 9:30 p.m. The electric line and rotary coring tools were removed from the well. The cores were recovered, inspected, and pictures were taken of each core plug. 20 core plugs were recovered, 100% recovery. Schlumberger's logging unit and rotary coring trailer were rigged down and released. The well was isolated by closing the BOP blind rams and the location was cleaned up. Field operations were suspended for the night at 11 :45 p.m. No Accidents, no spills.

Observations

Rotary Sidewall Core Depths: 5235', 5227', 5219', 5213', 5207',5201', 5195',5187',5178', 5175', 5168',5165', 5155',5147',5139',5124',5116',5107',5098', and 5089'; 100% recovery.

September 5, 2010

Field operations were resumed at 7:00 a.m. A prejob safety meeting was conducted with the CC Forbes and Sandia personnel. A 2-7/8" EUE 8rd mule shoe and 2-7/8" EUE 8rd pin x 3 -112" EUE 8rd box crossover sub were picked up on the first joint of tubing. The 2-7/8" mule shoe was lowered in the well on the 3-1/2" tubing to 3,097 ft. An additional 63 joints of tubing were picked up from the pipe racks and installed in the string to position the end of tubing at 5,576 ft. Franklin Well

Services' cementing crew and equipment arrived on location at 12:30 p.m. A prejob safety meeting was conducted for the cementing operations with CC Forbes, Franklin, and Sandia personnel. The cementing equipment and lines were rigged up and the high pressure surface lines were pressure tested to 1,000 psig. Approximately 50 bbl of water were pumped down the tubing at 3.8 bbllmin and partial returns to the surface were established. The cementing lines and safety valve were removed from the tubing. One joint of tubing was removed and the end of the tubing was positioned at 5,545 ft. The safety valve and cementing line were installed on the tubing. Approximately 20 bbl of freshwater with 2% KCI equivalent was pumped down the tubing and a 100 sack Class "A" cement with 2% CaCh (21 bbl of slurry) were mixed and pumped down the tubing. The cement was displaced down the tubing with 43 bbl of freshwater with 2% KCl equivalent. The cementing line and the 3-112" safety valve were removed from the tubing. Ten joints of 3-112" tubing were pulled out of the well and laid down on the pipe racks. Then 10 stands (20 joints) of 3-112" tubing were pulled out of the well and stood back in the derrick. The cementing equipment was washed up on location. Franklin's cementing crew and equipment were released. The well was isolated by closing the BOP pipe rams and the location was cleaned up. Field operations were suspended for the night at 4:00 p.m. No Accidents, no spills.

Observations
100 sacks Class "A" balanced plug properties: 15.6 lb/gal, 1.18 fe/sx, 5.2 gal water/sx, 21 bbl slurry volume; 22 bbl of slurry were metered during job.

September 6, 2010
Field operations were resumed at 7:00 a.m. A prejob safety meeting was conducted with the CC Forbes and Sandia personnel. The 2-7/8" mule shoe and 3-1/2" tubing string were lowered in the well to 5,640 ft without tagging the top of cement in the open hole wellbore. Rick Bowersox with the KGS was informed of the failure to locate the cement plug in the wellbore at a depth of 5,640 ft. Options were discussed and a decision was made to add sand to the wellbore and then attempt to place a second balanced cement plug in the open hole interval. The end of the tubing string was positioned at 5,545 ft. The delivery of 12,000 Ib of masonry sand was scheduled. Rigged up to add sand to the wellbore by slurrying with freshwater. GN Excavating delivered 12,000 Ib of masonry sand to location at 12:30 p.m. Approximately 44 ft^3 of sand were slurried with freshwater down the tubing with end of the tubing at 5,545 ft. Four joints of tubing were removed from the well to position the end of the tubing at 5,422 ft. An additional 61 ft^3 of sand were slurried down the tubing with freshwater. The sand was flushed out of the tubing with 50 bbl of freshwater with 3% KCI equivalent. The end ofthe tubing was lowered down to 5,640 ft without tagging the sand. The end of the tubing was positioned at 5,545 ft and an additional 18 ft3 of sand were slurried down the tubing with freshwater, estimated total sand volume of 123 ft^3. Franklin Well Services' cementing crew and equipment arrived on location at 8:00 p.m. A prejob safety meeting was conducted for the cementing operations with CC Forbes, Franklin, and Sandia personnel. The cementing equipment and lines were rigged up and the pump discharge line to the well was pressure tested to 1,000 psig. The sand in the tubing was flushed out with 48 bbl of freshwater with 3% KC1 with a rate 1.3 bbl/min with the end of the tubing at 5,545 ft. A 100 sack Class "A" cement slurry with 3% CaCh,

5 lb/sx Kol-seal, and 118 lb/sx Pol-e-flake (21 bbl of slurry) was mixed and pumped down the tubing. The cement was displaced down with 43 bbl of freshwater with 2% KCl equivalent. The cementing line and the safety valve were removed from the tubing. Then 15 stands (3 0 joints) of 3-1/2" tubing were pulled out of the well and stood back in the derrick. The cementing equipment was washed up on location. Franklin's cementing crew and equipment were released. The well was isolated by closing the BOP pipe rams and the location was cleaned up. Field operations were suspended for the night at 22:30 p.m. No Accidents, no spills.

Observations
100 sack Class "A" cement with 3% CaCl, 5 lb/sx Kol-seal, and 118 lb/sx Pol-e-flake balanced plug properties: 15.6 lb/gal, 1.18 ft^3/sx, 5.2 gal waterlsx, 21 bbl slurry volume; 23 bbl of slurry were metered during job.

September 7, 2010
Field operations were resumed at 8:00 a.m. A prejob safety meeting was conducted with the CC Forbes and Sandia personnel. The 2-7/8" mule shoe and 3-1/2" tubing string were lowered in the well and the top of firm cement was locate at 5,268 ft. The 3-1/2" tubing and mule shoe were removed from the well and 25 joints of tubing were laid down during the process. The 5-1/2" casing handling tools were rigged up and the specialty equipment for the 5-1/2" isolation tool were measured. The 5-1/2" isolation tool (5-1/2" liner) was picked up and lowered in the well on the 3-1/2" tubing to 3,465 ft. Praxair delivered two CO_2 storage vessels to location. The well was isolated by closing the BOP pipe rams and installing a safety valve on the tubing. The location was cleaned up and the field operations were suspended for the night at 4:45 p.m. No Accidents, no spills.

Observations
The 5-1/2" Isolation Tool consisted of the following from bottom to top: 5-1/2" LTC box up shear-out plug, 0.75 ft; 1 jt 5-1/2", 15.5 lb/ft, J-55, LTC casing, 41.90 ft with 4 cement baskets and 2 centralizers; 5-1/2" LTC sliding sleeve with ports in the open position, 1.83 ft; 1 jt 5-1/2", 15.5 lb/ft, J-55, LTC casing, 41.83 ft with 1 cement basket and 1 centralizer on the coupling; 1 jt 5-1/2",15.5 Ib/ft, J-55, LTC casing, 41.92 ft; 1 jt 5-1/2",15.5 lb/ft, J-55, LTC casing, 42.10 ft with 1 centralizer on the coupling; 1 jt 5-1/2", 15.5 Ib/ft, J-55, LTC casing, 41.85 ft; 5-1/2" LTC pin x 3-1/2" Disconnect Sub with left-handed threads, 1.16 ft. Total Liner length = 213.34 ft. No Accidents, no spills.

September 8, 2010
Field operations were resumed at 7:00 a.m. A prejob safety meeting was conducted with CC Forbes and Sandia personnel. The 5-1/2" isolation tool (5-1/2" liner) was lowered in the well on the 3-1/2" tubing and positioned with the bottom at 5,033 ft, sliding sleeve at 4,990 ft, and disconnect sub at 4,821 ft. Franklin's cementing crew and equipment arrived on 8:30 a.m. A prejob safety meeting was conducted for the cementing operations with CC Forbes, Franklin, and Sandia personnel. The cementing equipment and lines were rigged up and the pump discharge line to the well was pressure

tested to 2,200 psig. The tubing and liner were displaced with 118 bbl of freshwater with 3% KCl equivalent (2.5 tubing and liner volumes) with rates from 2 to 3.5 bbl/min. Returns to surface were established after pumping approximately 50 bbl. A 35 sacks of Thixotropic cement slurry were mixed and 7.4 bbl of slurry were pumped down the tubing. The cementing lines were removed and the top cementing dart was installed in the 3-1/2" tubing. The cementing lines were installed. The dart and cement were displaced with 46 bbl of freshwater with 3% KCl equivalent without landing the dart in the sliding sleeve. An additional 4 bbl of freshwater with 3% KCl equivalent were pumped without landing the plug, 9% over the calculated volume. A decision was made to rig down the cementing lines and to remove the tubing and liner from the wel1. The cementing lines and valves were removed from the well. The 3-1/2" tubing and 5-1/2" liner were removed from the well. The 5-1/2" casing and liner equipment were laid down on the pipe racks. The cementing dart was located in the top of the sliding sleeve. The dart nose failed to line up with the seat in the sliding sleeve. The cementing baskets were damaged during the removal of the equipment, but all five cementing baskets were removed from the well. A 7-7/8" rerun bit and bit sub were picked up and lowered in the well on the 3-112" tubing. Firm cement was located in the well at 4,884 ft. Eleven joints of tubing were removed from the well to position the bit at a depth of 4,542 ft. The well was isolated by closing the BOP pipe rams and installing a safety valve on the tubing. The location was cleaned up and the field operations were suspended for the night at 8:00 p.m. No Accidents, no spills.

Observations

- The cementing dart nose failed to line up with the seat in the sliding sleeve. The dart nose missed the seat or opening in the sliding sleeve. Additional fins will be added to the dart to improve the alignment and centering of the dart in the 5-1/2" liner.
- Sandia is also investigating the option of modifying the seat in the sliding sleeve to include a tapered entry guide for the dart.
- Praxair delivered three 60 ton CO2 storage vessels to location during the day. There are five storage vessels on location.

September 9, 2010

Field operations were resumed at 7:00 a.m. Armstrong Tool's service man, power swivel, and duplex pump arrived on location. A prejob safety meeting was conducted with CC Forbes, Armstrong Tool, and Sandia personnel. The 7-7/8" rerun bit and 3-1/2" tubing were lowered back in the well to 4,880 ft. A double studded adapter, crossover spool, and stripper head were installed on the well. The swivel and hoses were rigged up to reverse circulate with the bit at 4,880 ft. An attempt was made to circulate the well while pumping down the tubing-casing annulus without establishing returns up the tubing while pumping at 3 bpm. The pumping was stopped and the hoses were rigged up to pump down the tubing and returning up the annulus. Reamed and washed cement from 4,884 ft to 4,910 ft without establishing returns to surface and plugged the drill bit with solids. Attempts to unplug the bit were unsuccessful. The power swivel was rigged down. The tubing and bit were removed from the well. Armstrong's pump was rigged down and released. A Franklin's pump truck was ordered to provide the pumping services for the cleanout of the well. The stripper head and crossover spool were removed from the well. The bit was removed from the bits sub and a small amount of solids were removed from the partially plugged bit. The crossover spool and stripper head were installed back on the well. The bid and tubing were lowered back in the well. The power swivel and Franklin's pump truck were rigged up to reverse circulate the well with the bit at 4,854 ft. Washed and reamed down through soft cement from 4,854 ft to 4,930 ft while reverse circulating. The stripper rubber failed with the bit at 4,930 ft. The stripper rubber would not hold the pressure required for reverse circulating the well. The hoses were switched to circulate the well while pumping down the tubing. Resumed washing and reaming through soft cement from 4,930 ft to 4,970 ft. Washed and ream down with the bit from 4,970 ft to 5,265 ft while pumping 5 bbl per minute without any resistance. The well was circulated for 30 minutes with the bit at 5,265 ft. The power swivel was rigged down and 8 stands of tubing were removed from the well to position the bit at 4,760 ft. Armstrong's stripper head, spool, and double studded adapter were stripped off the well. Armstrong's and Franklin's equipment and personnel were released. The well was isolated by closing the BOP pipe rams and installing a safety valve on the tubing. The location was cleaned up and the field operations were suspended for the night at 22:30 p.m. No Accidents, no spills.

Observations

- Reamed through soft cement from 4,854 ft to 4,970 ft.
- The wellbore appeared to be free of cement below 4,970 ft.

September 10, 2010

Field operations were resumed at 8:00 a.m. A prejob safety meeting was conducted with CC Forbes and Sandia personnel. A 7-7/8" bit was lowered in the well on the 3-112" tubing from 4,760 ft to 5,250 ft without tagging up. The 3-1/2" tubing and bit were removed from the well. The 5-1/2" casing handling tools were rigged up. The 5-1/2" isolation tool (5-1/2" liner) was picked up and lowered in the well on the 3-1/2" tubing. The 5-1/2" liner was positioned with the bottom of the blow-out plug at 5,033 ft, sliding sleeve from 4,991 ft to 4,989 ft, and the top of the left-hand disconnect sub at 4,820 ft. The cementing equipment was positioned on location and rigged up. The cementing pump discharge lines were pressure tested to 1,600 psig. The tubing and liner were flushed with 50 bbl of freshwater with 2% KCl equivalent at a rate of 3 bbl/min. A prejob safety meeting was conducted for the cementing operations with CC Forbes, Franklin, KGS, and Sandia personnel Thirty-five sacks of Thixotropic cement slurry were mixed and 7.1 bbl of cement were pumped down the tubing. The cementing lines were removed from the tubing and the cementing dart was installed in the 3-112" tubing. The cementing lines were connected back to the tubing. The dart and cement were displaced with 47.5 bbl of freshwater with 3% KCl equivalent with a final circulating pressure of 300 psig. The dart landed in the sliding sleeve port and the pressure increased to 1,200 psig to shift the sliding sleeve closed. The sliding sleeve seat and the plug in the blow-out plug were sheared and purged out of the liner. An additional 1 bbl of fluid was pumped to ensure that the seat and the plug were pushed out of the liner. The well was shut-in by closing the safety valve on the tubing. The cementing equipment was rigged down and released. The location was cleaned up and the field operations were suspended for the night at 7:30 p.m. No Accidents, no spills.

Observations

The 5-1/2" Isolation Tool consisted of the following from bottom to top: 5-1/2" LTC box up shear-out plug, 0.75 ft; 1 jt; 5-1/2", 15.5lb/ft, J-55, LTC casing, 41.90 ft with 4 cement baskets and 2 centralizers; 5-1/2" LTC sliding sleeve with ports in the open position, 1.83 ft; 1 jt 5-1/2", 15.5 lb/ft, J-55, LTC casing, 41.83 ft with 1 centralizer on the coupling; 1 jt 5-1/2", 15.51b/ft, J-55, LTC casing, 41.92 ft; 1 jt 5-1/2", 15.5 lb/ft, J-55, LTC casing, 42.10 ft with 1 centralizer on the coupling; 1 jt 5-112", 15.5lb/ft, J-55, LTC casing, 41.85 ft; 5-1/2" LTC pin x 3-1/2" Left-handed Disconnect Sub, 1.16 ft. Total Liner length 213.3 ft. Cement Slurry Properties: 14.21b/gal, 1.61 ftisx, and 7.9 gal waterlsx.

September 11, 2010

Field operations were resumed at 7:00 a.m. A prejob safety meeting was conducted with CC Forbes, Geolog, and Sandia personnel. Geolog's logging unit was rigged up to run a differential temperature survey. The logging tools were lowered in the well and a differential temperature survey was run from 3,500 ft to 5,254 ft with a logging speed of 30 ft/min. The logging tools were removed from the well. The fluid level was located at 42 ft. The logging unit was rigged down and released. An injection test was performed on the interval with a 4" centrifugal pump. An injection rate of 13 gal/min was calculated. The injection test results were reviewed with Rick Bowersox and a decision was made to acidize the interval with 15% hydrochloric acid. The tubing was released from the 5-1/2" liner by rotating the string in the clockwise direction approximately 12 turns. The 3-112" tubing and the left-hand disconnect sub were removed from the well. The 3-112" tubing was lowered in the well and positioned with the end of the tubing at 4,851 ft at 5: 15 p.m. Franklin's stimulation crew and equipment arrived at 8:00 p.m. The pump truck and acid transport were position on location and rigged up. The 3-1/2" tubing was lowered in the well from 4,851 ft. The end of the tubing set down at 5,060 ft, 194 ft above the depth reached with the temperature log tools. Several attempts were made to work the end of the tubing by the obstruction at 5,060 ft without success. A maximum weight of 20,000 lb was set down on the obstruction. The end of the tubing was positioned at 5,058 ft. A prejob safety meeting was conducted on the acid stimulation with CC Forbes, Franklin, and Sandia personnel. The well was acidized with 2,500 gallons of 15% hydrochloric acid according to the. following: 20 bbl of 15% HCl acid; 29 bbl ofFW with 2% KCl equivalent; 5 min soak period; 5 bbl of FW with 2% KCl equivalent; 5 min soak period; 5 bbl ofFW with 2% KCl equivalent; 5 min soak period; 6 bbl of FW with 2% KCl equivalent. Flushed tubing-casing annulus with 2% KCl equivalent. A joint of tubing was added to the string to lowered down and tagged the obstruction at 5,060 ft. Approximately 20,000 lb of string weight was set down without moving the obstruction. A joint of tubing was laid back down and the end of the tubing was positioned back at 5,058 ft. The remaining 39 bbl of 15% HCl acid was pumped down the tubing and displaced with 46 bbl of FW with 2% KCI equivalent. The acid treatment pumping rates during the displacement ranged from 0.5 bbl/min to 2 bbl/min. The end of the tubing was positioned at 4,540 ft by removing 8 stands (16 joints) from the well. The acid pump truck and transport were rigged down and released. The tubing-casing annulus was flushed with freshwater with 2% KCl equivalent for 30 minutes. The well was shut-in by closing BOP pipe rams and installing a safety valve on the tubing. The location was cleaned up and the field operations were suspended for the night at 1 :00 a.m. on September 12th. No Accidents, no spills.

Observations
Temperature Log Confirmed cement behind the 5-1/2" liner from 4,840 ft to 4,985 ft and some cement from 4,985 ft to ~5,030 ft.

September 12, 2010
Field operations were resumed at 8:00 a.m. A prejob safety meeting was conducted with CC Forbes and Sandia personnel. The end of the tubing was lowered in the well from ~4,540 ft to ~5,060 ft. The obstruction was located and 25,000 lb of string weight was set on the object without moving it. The 3-1/2" tubing was pulled out of the well. The 3-1/2" tubing handling tools were rigged down and the handling tools for SR2020's 1-1/4" tubing were rigged up. The extra joints of 3-1/2" tubing were moved off the pipe racks and the pipe rack spacing was adjusted for the 23 ft joints of 1-1/4" tubing. SR2020 finished positioning their equipment for the geophone installation. A prejob safety meeting was conducted for the installation of the 1-1/4" tubing, geophone pods, and geophones with CC Forbes, SR2020, and Sandia personnel. The 1-1/4" tubing was transferred to the pipe racks, inspected, and numbered. A sheave for the geophone cable was positioned on the underside of the tubing board. Several geophone pods were connected to the 1-1/4" tubing on the catwalk. The installation of the 1-1/4" tubing, geophone pods, and geophones was begun at 1:00 p.m. A geophone pod was installed on the bottom of each joint of tubing to position the geophones with a 25 ft spacing. A geophone was installed in each pod and the cable was clamped to the tubing on each joint with a centralizing guide during the installation. A total of 79 pods with geophones were picked up and installed in the well. SR2020 and Appalachian were working to resolve a communication problem between the vibe trucks and encoder box at the end of the day. The well was secured. The location was cleaned up and the field operations were suspended for the night at 8:00 p.m. No Accidents, no spills.

Observations
CO_2 Delivery: Total of 7 loads, 134.8 tons, delivered and transferred to vessels.

September 13, 2010
Field operations were resumed at 7:00 a.m. SR2020 and Appalachian's personnel resumed attempting to diagnose the communication problem between the vibe trucks and encoder. The CC Forbes crew arrived on location at 8:00 a.m. SR2020 and Appalachian's personnel were unable to correct the communication problem with the equipment on location. The location was cleaned up and the field operations were suspended for the night at 3 :00 p.m. Appalachian's management agreed to hotshot their encoder from Pennsylvania to the KGS Marvin Blan #1 location on Tuesday. Appalachian's encoder should arrive on location sometime Tuesday evening. No Accidents, no spills.

September 14, 2010
Field operations were resumed at 7:00 a.m. SR2020 and Appalachian's personnel resumed attempting to diagnose the communication problem between the vibe trucks and encoder. They were unable to resolve the communication problems. Operations were suspended at 8:00 a.m. while waiting on the arrival of the encoder. Appalachian Geophysical shipped their encoder by hotshot from Marienville, Pennsylvania at 6:15 a.m. CST. CC Forbes, SR2020, and Appalachian's crews arrived on location at 5:00 p.m. Appalachian encoder was also delivered to location at 5:00 p.m. The encoder was installed and the vibe trucks were communicating with the encoder by 5:15 p.m. SR2020 and Appalachian began testing the vibe trucks, encoder, and recorder in preparation for running the zero offset VSP survey at 5:30 p.m. Additional issues were encountered with the sweep data frequency and noise in the data. The crews were released and the operations were suspended for the night at 7:30 p.m. without resolving the sweep data problems. No Accidents, no spills.

Observations
13 loads of CO_2 delivered to location at 9:30 p.m. on September 14th, 250 tons.

September 15, 2010
Field operations were resumed at 7:00 a.m. SR2020 and Appalachian resumed testing the vibe trucks, encoder, and recorder. The zero offset VSP survey was conducted with the vibe trucks on the west edge of the well pad. A prejob safety meeting on the installation of the 1-1/4" tubing and geophones was conducted with personnel from CC Forbes, SR2020, and Sandia personnel. The installation of the 1-1/4" tubing and geophones in the well was resumed at 9:10 a.m. The installation of the 1-1/4" tubing, 80 geophone pods, and 80 geophones was finished at 11:30 a.m. The 80 geophones were set with ~25 ft spacing between each geophone with the bottom geophone (#1) at 3,641 ft and the top geophone (#80) at 1,668 ft. The water level was checked and determined to be at 98 ft. The geophones were coupled to the 8-5/8" casing by adding 80 psig of air pressure to the 1-1/4" tubing. SR2020 and Appalachian began running the VSP survey at 12:15 p.m. Initially three sweeps were performed per vibe point to check the quality of the data. After running several surveys, a decision was made to perform three sweeps on each vibe point. Operations were suspended for the night with 360 vibe points performed. The crews were released and exited the locations at 7:30 p.m. No Accidents, no spills.

Observations
13 loads of CO_2 delivered to location at 9:30 p.m. on September 14$^{th;}$ 250 tons.

September 16, 2010
Field operations were resumed at 6:00 a.m. A prejob safety meeting was conducted with SR2020 and Appalachian's personnel on the VSP survey. SR2020 and Appalachian resumed running the VSP survey at 6:40 a.m. with three sweeps on each vibe point. The before injection survey was finished at 6:30 p.m. The VSP survey included 926 vibe points (868 for the 3D survey and 58 for the two walkaway survey lines). A nitrogen cylinder, regulator, and supply line were connected to the 1-1/4"

tubing. The pressure on the 1-1/4" string was increased with the nitrogen until the disk on the bottom of the 1-1/4" string ruptured. The disk was ruptured to allow the water to drain out of the 1-1/4" tubing while removing the string from the well. Operations were suspended for the night with 7;00 p.m. and the crews exited the location. No Accidents, no spills.

Observations
17 loads (323 tons) of CO_2 delivered to location.

September 17, 2010
Field operations were resumed at 7:00 a.m. A prejob safety meeting was conducted with SR2020, CC Forbes, and Sandia's personnel on the removal of the geophone assembly. Seventy-two joints of the 1-1/4" tubing were removed from the well and laid down on the pipe racks while spooling the geophone cable onto the SR2020's drum. Then 80 joints of 1-1/4" tubing with one geophone pod per joint were removed and laid down on the racks while spooling the geophone cable and geophones onto the drum. SR2020's sheave was removed from the tubing board. The 1-1/4" bottom hole assembly was removed and laid down. SR2020's equipment was rigged down. The 1-1/4" handling tools were laid down and the 3-1/2" handing tools were picked up. A 11" 5M x 11" 3M double studded adapter and a 11" 3M x 7-1/16" 3M spool were installed on the well. A 4-3/8" OD concave mill and crossovers were picked up and made up on the first joint of 3-112" tubing. The mill was lowered in the well on the 3-1/2" tubing and set in the top of the 5-1/2" liner at 4,824 ft. The well was, isolated by closing the pipe rams. Operations were suspended for the night with 7:30 p.m. and the CC Forbes crew exited the location. No Accidents, no spills.

Observations
18 loads (350 tons) of CO2 delivered to location.

September 18, 2010
Field operations were resumed at 7:00 a.m. A prejob safety meeting was conducted with CC Forbes, Armstrong Tool, and Sandia's personnel on rigging up the stripper head and power swivel. A 4.375" mill and the tubing were lowered in the well. The obstruction was located at 5,060 ft. The stripper head was installed on the wellhead and the power swivel was rigged up. A safety meeting on the power swivel cleanout operations was held with CC Forbes, Armstrong Tool, Franklin, and Sandia's personnel. The milling on the obstruction at 5,060 ft while reverse circulating the well with a pump rate of 4 barrels per minute (bpm) was begun at 10:15 a.m. The obstruction was cleaned to a depth of 5,062.5 ft and the mill was washed and reamed to 5,076 ft without any resistance. The well was circulated for 10 minutes and circulation was stopped to pick up the next joint of tubing. The swivel was disconnected from the tubing with the well flowing up the tubing at 1:15 PM. When the connection was unscrewed from the tubing, three members of the CC Forbes crew were sprayed with the water flowing out of the well. The swivel was connected back to the tubing and circulation was reestablished. The well was circulated for approximately two hours while the crew members returned to town to shower and change clothes. A pressure relief valve on a Praxair CO2 storage vessel failed

around 3:00 p.m. According to the CC Forbes' rig operator who witnessed the failure, the pressure relief valve opened normally to vent the pressure. Then the pressure relief assembly, which was mounted on a 2" NPT tee and connected to a 2" NPT male connection on the tank, began spinning and unscrewed the assembly from the tank. The assembly was completely unscrewed from the tank fitting and fell to the ground. The tank was then vented the CO_2 through the 2" open line at a very high rate. Praxair was notified of the CO_2 pressure relief system failure. The wellbore cleanout operations were resumed at 4:15 p.m. The mill was reamed and washed down from 5,076 ft to 5,135 ft without any resistance. The mill was worked through a second obstruction from 5,135 ft to 5,140 ft. The mill was reamed and washed down from 5,140 ft to 5,267 ft without any resistance. The well was reverse circulated to remove wellbore solids for 30 minutes at 4 bpm with the mill at 5,267 ft. A prejob safety for the stimulation of the well with 15% hydrochloric acid was held with CC Forbes, Armstrong Tool, Franklin, and Sandia's personnel. The power swivel was rigged down and the pump truck was rigged up to acidize the well while pumping down the 3-1/2" tubing. The mill was positioned at 5,236 ft. An attempted was made to circulate the well with water, but the mill was plugged with solids. The mill was cleared by switching the pump lines to reverse circulate the well. The acid treatment of the well with 2,000 gallons of 15% HCl acid was begun at 11 :00 p.m. with the mill at 5,236 ft. The interval was treated with 20 bbl of 15% HCl acid and the acid was displaced with 47 bbl of freshwater with 2% KCl equivalent. The mill was positioned at 5,076 ft and the interval was treated with the remaining 27.6 bbl of 15% HCl acid and acid was displaced into the formation with 75 bbl of freshwater with 2% KCl equivalent. Twelve joints of tubing were removed from the well to position the mill above the 5-112" liner at a depth of 4,700 ft. Operations were suspended for the night at 2:00 a.m. and the crews exited the location. No Accidents, no spills.

Observations
Approximately 57 tons of CO_2 were lost when the pressure relief system failed on the storage vessel.

September 19, 2010
Field operations were resumed at 10:00 a.m. A prejob safety meeting was conducted with CC Forbes and Sandia's personnel on the removal of the stripper head and pulling out of the well with the tubing. The stripper head was removed from the well. The 3-1/2" tubing and the 4.375" mill were pulled out of the well and the mill and crossovers were laid down. Armstrong Tool's spool and double studded adapter were removed from the well. Armstrong Tool's rental equipment was loaded onto the service representatives' truck and released. The testing bottom hole assembly was measured, assembled, and picked up. The bottom hole assembly consisted of a 2-7/8" mule shoe, crossover over guide, 2-7/8" pup joint with a gauge carrier and tandem memory gauges, 5-1/2" ArrowSet I-X packer, 2-7/8" pup joint, crossover, four joints of 3-1/2" tubing, and a 3-1/2" pup joint with a gauge carrier and tandem memory gauges. The test assembly was lowered in the well on the 3-1/2" tubing. The packer was set in the 5-1/2" liner at 4,884 ft with the bottom of the 2-7/8" mule shoe at 4,903 ft. The memory gauges below the packer were set at 4,891 ft and 4,893 ft and the memory gauges above the packer were positioned at 4,742 ft and 4,744 ft. A safety valve, pump-tee, wireline valve, and injection line valve were installed on the tubing. A prejob safety meeting was conducted with CC Forbes, Gulf Coast Well Analysis, and Sandia's personnel on the planned logging

operations. The logging unit was rigged up to run a Differential Temperature Survey. The CC Forbes crew was released for the night at 9:00 p.m. A Differential Temperature Survey was run from surface to 5,256 ft at a logging speed of 30 feet per minute. A gamma ray-casing collar locator log was then run from 5,256 ft to 3,600 ft. The logging tools were secured in the wire line lubricator for the night. Operations were suspended for the night at 2:30 a.m. and the crews exited the location. No Accidents, no spills.

September 19, 2010
Field operations were resumed at 7:00 a.m. A prejob safety meeting was conducted with CC Forbes, Schwartz, GCWA, and Sandia's personnel on the planned injection testing. The wireline pressure control equipment was removed from the well and the temperature tools were laid down. The bottom hole pressure tools were picked up and installed on the well with the pressure control equipment. Schwartz's pump truck and surface injection lines were rigged up for the planned injection test. The surface injection lines and the wire line pressure control equipment were successfully pressure tested to 2,400 psig. The surface readout pressure gauge (SRO) was lowered in the well on the electric line and a casing collar locator depth correlation strip was run. The electric line depth was corrected and the SRO gauge was set at a depth of 5,070 ft. The static bottom hole pressure and temperature at 11:55 a.m. were 2,189.29 psia and 103.56°F. Injection for the step-rate injection test was begun at noon with an initial rate of 2 bbl/min. The rate was increased to 4 bbllmin at 12:15 p.m. with a final bottom hole pressure of 2,443.0 psig at 2 bbl/min. The rate was increased to 6 bbl/min at 12:30 p.m. with a final bottom hole pressure of 2,703.7 psia at 4 bbl/min. The bottom hole pressure was 2,983.5 psia at 12:45 p.m. A decision made to maintain the injection rate of 6 bbl/min. The injection rate was reduced to 5 bbl/min at 1 :00 p.m. due to an engine overheating on the pump truck. The injection period was ended at 2:00 p.m. with 589 bbl of water injected and a final bottom hole pressure of 2,987 psi a at 5 bbl/min. The bottom hole pressure was monitor and recorded from 2:00 p.m. to 5:00 p.m. A prejob safety meeting was conducted with Praxair, GCWA, KGS, and Sandia's personnel on the CO_2 injection test. The bottom hole pressure at 5,070 ft was 2,237 psia at 5:00 p.m. The CO_2 injection was begun at 5:00 p.m. and the injection rate was stabilized at 3 bbl/min. The bottom hole pressure with 47 bbl of CO_2 injected was 2,550 psia with a surface injection pressure of ~ 1,000 psig. The injection rate was reduced to 2.5 bbl/min at 10:30 p.m. with 974 bbl injected. The final bottom hole pressure at the 3 bbl/min rate was 2,581.7 psia. The bottom pressure at midnight was 2,537.5 psia with an injection rate of 2.5 bbl/min. A total of 1,202 bbl (220 tons) of CO_2 was injected during the 7 hour period. No Accidents, no spills.

September 20, 2010
The injection of CO_2 was continued at a rate of2.5 bbl/min with a surface pressure of933 psig and a bottom hole pressure of 2,537.5 psia at 5,070 ft. The CO_2 injection period was ended at 5:10 a.m. with a final injecting surface pressure of 878 psig and bottom hole pressure of 2,538.5 psia. A cumulative CO_2 volume of 2,000 bbl (367 tons) was injected during the test. The CO_2 injection lines were rigged down and the water injection lines and the pump truck were rigged up. Injection for the constant rate test with freshwater with 2% KCl equivalent was begun at 5:41 p.m. with a rate of 6

bbl/min. The bottom hole pressure prior to beginning injection was 2,366.2 psia. The injection rate was reduced to 5 bbl/min at 6: 15 a.m. and held constant for the remainder of the test. The bottom hole pressure increased to 3,364.0 psia at 8:28 a.m. with 846 bbl of water injected. The bottom hole pressure gradually decreased during the remainder of the constant rate injection period. The injection period was ended at 5:25 p.m. with 3,676 bbl of water injected and a final injecting bottom hole pressure of 3,308.98 psia. The well was shut-in and the pressure falloff was monitored for the remainder of the night. Selective bottom hole pressure and temperature readings are presented below:

Time	**Pressure (psia)**	**Temperature (F)**
05:28	3,308.98	85.92
05:30	2,769.49	86.16
18:00	2,526.20	87.06
19:00	2,425.16	88.19
22:00	2,325.16	89.57
00:00	2,293.46	90.35

No Accidents, no spills.

September 21, 2010
The injection of CO_2 was continued at a rate of 2.5 bbl/min with a surface pressure of 933 psig and a bottom hole pressure of 2,537.5 psia at 5,070 ft. The CO_2 injection period was ended at 5:10 a.m. with a final injecting surface pressure of 878 psig and bottom hole pressure of 2,538.5 psia. A cumulative CO_2 volume of 2,000 bbl (367 tons) was injected during the test. The CO_2 injection lines were rigged down and the water injection lines and the pump truck were rigged up. Injection for the constant rate test with freshwater with 2% KCl equivalent was begun at 5:41 p.m. with a rate of 6 bbl/min. The bottom hole pressure prior to beginning injection was 2,366.2 psia. The injection rate was reduced to 5 bbl/min at 6: 15 a.m. and held constant for the remainder of the test. The bottom hole pressure increased to 3,364.0 psia at 8:28 a.m. with 846 bbl of water injected. The bottom hole pressure gradually decreased during the remainder of the constant rate injection period. The injection period was ended at 5:25 p.m. with 3,676 bbl of water injected and a final injecting bottom hole pressure of3,308.98 psia. The well was shut-in and the pressure falloff was monitored for the remainder of the night. Selective bottom hole pressure and temperature readings are presented below:

Time	**Pressure (psia)**	**Temperature (F)**
05:28	3,308.98	85.92
05:30	2,769.49	86.16
18:00	2,526.20	87.06
19:00	2,425.16	88.19
22:00	2,325.16	89.57
00:00	2,293.46	90.35

No Accidents, no spills.

September 22, 2010
The pressure falloff monitoring at 5,070 ft was continued until 6:00 a.m. Selective bottom hole pressure and temperature readings are presented below:

Time	Pressure (psia)	Temperature (F)
00:00	2,283.95	90.4
02:00	2,271.58	91.1
04:00	2,255.75	91.8
06:00	2,243.83	92.4

The electric line and bottom hole pressure tools were removed from the well while making pressure gradient stops at 4,000 ft, 3,000 ft, 2,000 ft, and 1,000 ft. The safety valve was closed and the wire line pressure control equipment with the logging tools were removed from the well. The bottom hole pressure tools were laid down and the differential temperature tools were connected to the electric line. A Differential Temperature Survey was run from surface to 5,254 ft at a logging speed of 30 ftlmin. The electric line and logging tools were removed from the well and the well was shut-in by closing the tubing safety valve. The shut-in wellhead tubing pressure was 31 psi a at 12:30 PM. The wireline pressure control equipment and logging tools removed from the well. The logging unit was rigged down. The 5-112" ArrowSet I-X packer was released and the 3-112" tubing and packer were removed from the well. The two sets of tandem memory gauges were removed from the bottom hole assembly. The packer bottom hole assembly was laid down. The pressure and temperature data from the four memory pressure gauges were downloaded. A 5-1/2" cast iron bridge plug (CIBP) with the setting tool was picked and lowered in the well on the 3-1/2" tubing. The CIBP was positioned at 4,885 ft and an attempt was made to set the tool. Multiple attempts were made to set the CIBP from 4,850 ft to 4,954 ft without setting the tool. Ten joints of tubing were removed from the well to position the CIBP at 4,640 ft. Operations were suspended for the night with 9:00 p.m. No Accidents, no spills.

September 23, 2010
A prejob safety meeting was conducted on the removal of the tubing and the 5-1/2" cast iron bridge plug from the well with CC Forbes and Sandia's personnel. The 3-1/2" tubing and the 5-1/2" CIBP were removed from the well. The CIBP was inspected and laid down. A 2-7/8" mule shoe and crosser were picked up and lowered in the well on the 3-1/2" tubing. The mule shoe was positioned in the top of the 5-1/2" liner at 4,824 ft. Franklin's cementing crew arrived on location and positioned their equipment. A prejob safety meeting was conducted for the cementing operations with CC Forbes, Franklin, and Sandia's personnel. The crews finished rigging up the cementing and return lines. The cement slurry was mixed with 75 sacks of Class "A" cement plus 3% CaCl (I5.61b/gal, 1.18 ft3/sx, and 5.2 gal waterlsx). The cement pumping consisted of circulating 10 bbl of freshwater, 17.1 bbl of cement slurry, and displacing the cement with 37 bbl of freshwater. A calculated balanced cement plug was spotted from 4,824 ft to 4,608 ft. The surface cementing line and valve were removed from the tubing and 16 stands (32 joints) of tubing were pulled out of the well to position the mule shoe at 3,826 ft. Operations were suspend for one hour while waiting on

the cement to set up. The 3-1/2" tubing and mule shoe were removed from the well. The rig was prepared for the installation of SR2020' s 1-1/4" tubing and geophones by changing the tubing handling tools. SR2020's sheave for the geophone cable was hung from the tubing board. The end of the geophone cable was strung through the sheave and tied off on the ground. The rig was leveled to center the traveling block over the well. The well was shut-in and operations were suspended for the night with 5:30 p.m. No Accidents, no spills.

Observations
The 5-1/2" CIBP was not damaged and was in good shape after removal from the well. The tool was still in the run or trip position and never shifted to the set position. The tool should have shifted to the set position when the tubing string was rotated to the right during the attempts to set the tool. Four spring steel stabilizer in the setting tool are designed to apply force to the 5-1/2" casing to prevent the setting tool from rotating when the tubing is turned to the right. The swivel section in the setting tool was stuck or frozen with debris or fine solids from the wellbore. The setting tool was rotating with the tubing which prevented the tool from shifting to the set position. The assembly was worked loose by hand during the inspection.

September 24, 2010
A prejob safety meeting was conducted on the installation ofthe 1-1/4" tubing and geophones with CC Forbes, SR2020, and Sandia's personnel. SR2020's 1-1/4" tubing, geophone pods, and geophones were installed in the well. The installation of the 1-1/4" tubing, 80 geophone pods, and 80 geophones was finished at 3:00 p.m. The 80 geophones were set with 25 ft spacing between each geophone with the bottom geophone (#1) at 3,641 ft and the top geophone (#80) at 1,668 ft. The water level was checked and determined to be at 92 ft referenced to RKB of 14.7 ft above ground level. The geophones were coupled to the 8-5/8" casing by adding 80 psig of air pressure to the 1-1/4" tubing. Appalachian's three vi be trucks were positioned in the field to begin the VSP survey. SR2020 was unable to load and run the data recording system. SR2020 spent the remainder of the day attempting to diagnose and resolve the data recording system problem. Operations were suspended for the night at 7:00 p.m. without resolving the problem with SR2020's data recording system. No Accidents, no spills.

September 25, 2010
Operations were resumed at 6:30 a.m. with SR2020 working to diagnose the data recording system problem. The 12 volt DC power supply on the system was replaced with three 12 volt car batteries without resolving the problem. The problem was located in the first geode box. The geode box was replaced and the data recording system began functioning normally. A call was placed to Appalachian's vibe crew to return to location at 9:30 a.m. Appalachian's crews arrived on location and the VSP survey was begun at 10: 1 0 a.m. Three sweeps were performed on each vibe point with each sweep consisting of a 12 second vibration and a 4 second pause. The survey was performed with three Appalachian vibe trucks. Operations were suspended for the night at 7:00 p.m. with approximately 50% of the points complete. No Accidents, no spills.

September 26, 2010
The VSP survey was resumed at 6:00 a.m. with three vibe trucks. Three sweeps were performed on each vibe point with each sweep consisting of a 12 second vibration and a 4 second pause. The post injection VSP survey was finished at 3:30 p.m. The survey consisted of 895 points (836 3D points and 59 walk-away points). Appalachian's crews and three vibe trucks were released. A nitrogen cylinder, regulator, and supply line were connected to the 1-1/4" tubing. The pressure on the 1-1/4" string was increased with the nitrogen until the equalization disk on the bottom of the string ruptured. A prejob safety meeting was conducted with CC Forbes, SR2020, and Sandia's personnel on the removal of the 1-1/4" tubing and geophones. The removal of the 1-1/4" tubing and geophones was begun, but the 1-1/4" tubing was slipping in the tubing slips. The slip segments were cleaned, but the tubing continued to slide through the slips. The slip segments were not biting the pipe. A decision was made to wait on the delivery of the new slip segments on Monday morning before removing the 1-1/4" tubing. Operations were suspended for the night at 5:00 p.m. No Accidents, no spills.

September 27, 2010
Operations were resumed at 10:00 a.m. when the replacement slip segments arrived. The new slip segments were installed in the 1-1/4" slips and the slips were successfully tested on the 1-1/4" pipe. A prejob safety meeting was conducted for the removal of the 1-1/4" tubing and the geophones with CC Forbes, SR2020, and Sandia's personnel. SR2020's 1-1/4" tubing and geophones were removed from the well while laying the tubing and geophone pods. The geophone cable and geophones were rolled up on the cable reel during the removal. SR2020's equipment was rigged down and loaded onto two trucks. SR2020's equipment and crews were released and left the locations at 6:45 p.m. A 2-7/8" mule shoe and crossover were picked up and lowered in the well on the 3-112" tubing. The top of cement plug, which was set on September 23rd, was tagged at a depth of 5,037 ft. Twenty-three stands (46 joints) of tubing were removed from the well and the mule shoe was positioned at 3,637 ft. Franklin's cementing crew arrived on location at 9:00 p.m. The cementing equipment was positioned on location and set up for the cementing. A prejob safety meeting was conducted for the cementing operations with CC Forbes, Franklin, KGS, and Sandia's personnel. A cement slurry was mixed with 100 sacks of Class "A" cement plus 3% CaCh (15.6Ib/gal, 1.18 ft3/sx, and 5.2 gal FW/sx). The cementing operations consisted of circulating 10 bbl of freshwater, 21 bbl of cement slurry, and displacing the cement with 25 bbl of freshwater. The calculated depths for the balanced cement plug were from 3,637 ft to 3,293 ft. The surface cementing valve and line were removed from the tubing and 12 stands (24 joints) oftubing were removed from the well to position the mule shoe at 2,879 ft. Franklin's cementing equipment was washed up and released. The well was shut-in and operations were suspended for the night at 11 :00 p.m. No Accidents, no spills.

September 28, 2010
Operations were resumed at 8:00 a:m. A prejob safety meeting was conducted for the removal of the 3-1/2" tubing with CC Forbes and Sandia's personnel. The 3-1/2" tubing was lowered in the well and the top of cement was located at 3,716 ft. Forty-four joints of 3-1/2" tubing were removed from

the well and were laid down on the pipe racks. The 3-112" tubing was lowered in the well and the mule shoe was positioned at 3,700 ft. The location cleaned up and organized while waiting on Schwartz's cementing crew. Schwartz's cementing crew arrived on location at 11:15 a.m. The cementing equipment was positioned on location and rigged up. A prejob safety meeting was conducted for the cementing operations with CC Forbes, Schwartz, KGS, and Sandia's personnel. A cement slurry was mixed with 100 sacks of Class "A" cement plus 3% CaCl (15.6 lb/gal, 1.18 ft^3/sx, and 5.2 gal FW/sx). The cementing operations consisted of circulating 10 bbl of freshwater, 21 bbl of cement slurry, and displacing the cement with 25 bbl of freshwater. The calculated depths for the balanced cement plug were from 3,700 ft to 3,363 ft. The surface cementing valve and line were removed from the tubing and 12 stands (24 joints) of tubing were removed from the well to position the mule shoe at 2,944 ft. Schwartz's cementing equipment was rigged down, washed up, and released. Operations were suspended while waiting on the cement to set up. The 3-1/2" tubing was lowered in the well and the top of the cement was located at 3,514 ft at 4:15 p.m. The 3-1/2" tubing was removed from the well while laying the tubing down on the pipe racks. The tubing began pulling wet after removing 8 joints from the well. The last 15 joints of the 3-1/2" tubing were plugged with cement. Finished laying down 112 joints of 3-1/2" tubing and the mule shoe joint. The well was secured and the CC Forbes crew exited the location at 8:00 p.m. A water blasting unit was called out and arrived on location at 9:30 p.m. The water blaster was rigged up and attempted to wash the cement out of the 15 joints of tubing. The water blaster was unable to clean the cement out the tubing. The water blaster was released and operations were suspended for the night at 11 :00 p.m. No Accidents, no spills.

September 29, 2010

Operations were resumed at 7 :00 a.m. A prejob safety meeting was conducted on returning the rental equipment with CC Forbes and Sandia's personnel. Three stands of 3-1/2" tubing were lowered in the well and removed from the well while laying the tubing down on the pipe racks. The 3-1/2" tubing and the rental tools were loaded onto two trucks. The 11 ", SM double ram blowout preventer was nippled down and removed from the well. The accumulator, double ram blowout preventer, and annular blowout preventer were loaded onto a third truck. The three loads of rental equipment were returned to Thomas Tools. A Western Kentucky Well Survey logging unit was positioned and rigged up to run a gamma ray-casing collar locator log. The logging tools were lowered in the well and depth corrected. The top of the cement plug in the well was located at 3,477 ft. The electric line and logging tools were removed from the well. The gamma ray casing collar locator tools were removed from the well. An 8-5/8" cast iron bridge plug and setting tool were installed on the electric line and lowered in the well. The CIBP was positioned and set with the center of the element at 800 ft. The electric line and setting tool were removed from the well. The Western Kentucky Well Survey logging unit was rigged down and released. The CC Forbes' workover rig was rigged down. The base beam, catwalk, two sets of pipe racks, and the support skid were loaded onto two trucks. Operations were suspended for the night at 8:00 p.m. No Accidents, no spills.

September 30, 2010

Operations were resumed at 7:00 a.m. The two loads of rig equipment were released and returned two CC Forbes. The CC Forbes' workover rig was released and left the location at 8:30 a.m. GN Excavation moved two excavators, one rubber tire backhoe, two bulldozers, and tree dump trucks onto the well locations. GN Excavation began removing the gravel from the well pad and transferring the gravel to an area to the north ofMr. Blan's barn. Approximately 60% ofthe gravel was removed from the location during the day. The rental casing head and casing spool were removed from the well by cutting the 13-3/8" casing and 8-5/8" casing. The rental casing head, casing spool, and an adapter flange with a 2-1/16" valve were prepared to be returned to the supplier by banding the equipment to a pallet. An 8-5/8" casing extension, an 8-5/8" weld-on 8-5/8" pin, and an 8-5/8" Larkin tubing head were installed on the well. No Accidents, no spills. Final Report.

This report was compiled and edited from daily emails dated August 30, 2010, to September 30, 2010, by J. Richard Bowersox, Kentucky Geological Survey, Lexington, Kentucky.

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LCO_2 Storage Tank Batch Analysis Report

Plant Location: Washington, IN 74204
Location Sample Taken From: Tank 1
Date Sample Taken: 9/19/2010
Sampled From (Vaporized Liquid): Vaporized Liquid
Cylinder Number if **Used:** na
Report Number (yymmdd-hhmm): 100919-1635
Batch **Number Sampled From:** 262wshclOcdl

Component (Formula/Abbreviation)	Phase Tested	Unit	Source Test Results	
Acetaldehyde (C_2H_40)	Vap orized Liquid	ppm/v	0.016	ppm/v
Ammonia (NH3))	Vap orized Liquid		< 0.250	ppm/v
Benzene (0_6H_6)	Vap orized Liquid		< 0.010	ppm/v
Carbon Dioxide (CO_2)	Vap orized Liquid	% CO_2	99.980	% CO_2
Carbon Monoxide (CO)	Vap orized Liquid	ppm/v	< 1.000	ppm/v
Dimethyl ether (C_2H_60)	Vap orized Liquid	ppm/v	N/A	ppm/v
Ethanol (C_2H_60)	Vap orized Liquid	ppm/v	N/A	ppm/v
Methanol (CH_4O)	Vap orized Liquid	ppm/v	N/A	ppm/v
Nitric oxide (NO)	Vap orized Liquid	ppm/v	< 0.500	ppm/v
Nitrogen Dioxide (NO_2)	Vap orized Liquid	ppm/v	< 0.500	ppm/v
Total Hydrocarbons (THC)	Vap orized Liquid	ppm/v	< 1.000	ppm/v
Total Sulfur (TS)	Vap orized Liquid	ppm/v	0.012	ppm/v
Water (H_2O)'	Vap orized Liquid	ppm/v	1.900	ppm/v
Odor	Vap orized Liquid	Foreign	None	
Taste	Vap orized Liquid	Foreign	None	
Color	Vaporized Liquid	Foreign	Normal	
Non Volatile Residue (NVR)	Snow from Liquid	Qualitative	None	

NA indicates not analyzed. All concentrations are in ppm (mole/mole) unless otherwise indicated. This analysis does not include parameters below the minimum detection limit. A component with a value below its minimum detection limit is reported as less than the detection limit or ND (not detected). LOD is for QA lab instruments.

Comments:

Reviewed By: Bruce Clendenen 9-19-10
Signature Date

2 B-I N DCO2-Q UA-2085-F

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Appendix 2B

Well Abandonment Reports

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KGS Marvin Blan #1

Hancock County, Kentucky

October 1, 2010

Casing and Cementing Program

Conductor

20" 94ppf J-55 Conductor @ 51.4' RKB
Cemented to surface with a 4,000 psi grout mixture

Surface Casing

13-3/8" 54.5ppf J-55 STC @ 442' RKB
Cemented to surface with 392 sacks Class A w/ 3% CaCl2
11 bbl of cement returns to surface

Protection Casing

8-5/8" 32ppf J-55 STC @ 3,660' RKB
Cemented w/ lead slurry of 880 sacks 35/65 Poz A and tail slurry of 250 sacks Class A
8 bbl of cement returns to surface

Abandonment of Open Hole Injection Interval

1st Cement Plug Balanced Cement Plug set from ~5,268' to ~5,545'
100 sacks of Class A cement with 3% $CaCl_2$
Top of cement plug tagged with tubing string

2nd Cement Plug Balanced Cement Plug set from ~5,037' to ~5,275'
75 sacks of Class A cement with 3% $CaCl_2$
Top of cement plug tagged with tubing string

3rd Cement Plug Balanced Cement Plug set from ~3,716' to ~3,942'
100 sacks of Class A cement with 3% $CaCl_2$
Top of cement plug tagged with tubing string

4th Cement Plug Balanced Cement Plug set from ~3,477' to ~3,716'
100 sacks of Class A cement with 3% $CaCl_2$
Top of cement plug tagged with tubing string and electric line

Mechanical Plug 8-5/8" Cast Iron Bridge Plug set with center of element at 800 ft
Set with electric line and verified by tagging top

5th Cement Plug Proposed Cement Plug
18 sack Class A Cement Plug set from ~740' to ~800'

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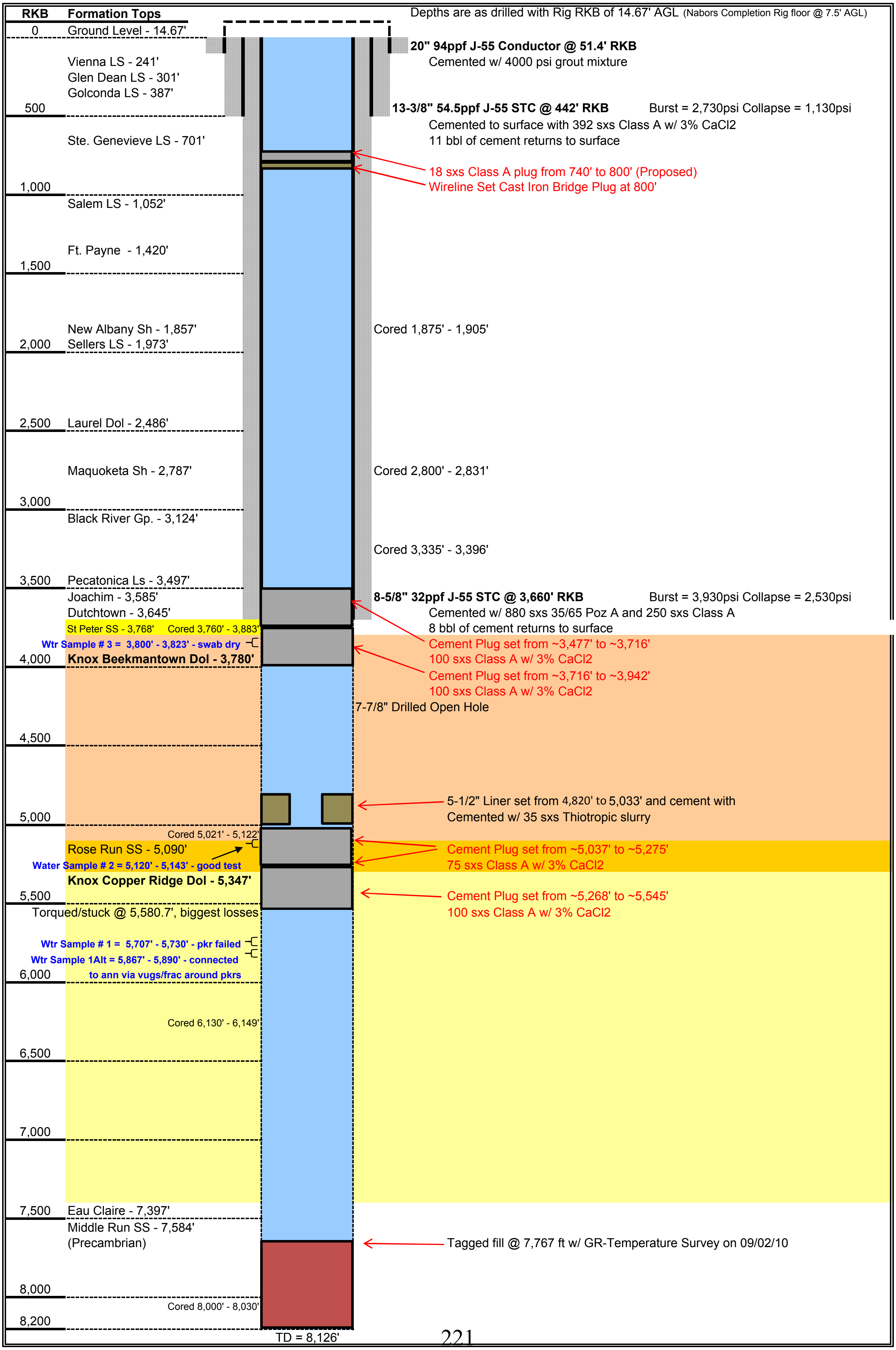
KGS Marvin Blan # 1 Well
Wellbore Schematic for the Abandonment



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UNIVERSITY OF KENTUCKY

Kentucky Geological Survey
Research
504 Rose Street
228 Mining & Mineral Resources Bldg.
Lexington, KY 40506-0107
Phone: (859) 257-5500
Fax: (859) 257-1147
www.uky.edu/kgs

November 8, 2011

Mr. George Ford
U.S. Environmental Protection Agency
Water Protection Division
Safe Drinking Water Branch
Ground Water & SDWA Enforcement Section
61 Forsyth Street, S.W.
Atlanta, GA 30303-8960

RE: UIC Permit Number KYV0049 – Injection Well Abandonment

Dear Mr. Ford:

On October 14, 2011, the Marvin Blan #1 well, the subject of this UIC permit, was plugged as required by Mr. Fred McManus' letter to me of August 19, 2011. A cement plug was placed in well at 1221–900 ft, exceeding the requirements stated in Mr. McManus' letter. The plugging was witnessed on behalf of the U.S. Environmental Protection Agency by Mr. Carl Weller, and by Mr. David A. Williams of the Kentucky Geological Survey. A copy of the plugging affidavit was filed with the Kentucky Division of Oil and Gas dated October 18, 2011 is enclosed, as well as a copy of the plugging affidavit dated September 29, 2010, for the plugs at 3477 ft and deeper.

With the well plugging requirement completed, I am requesting that the Marvin Blan #1 well be released from the requirements of the UIC permit so it can be transferred to a production company and converted to an oil and gas producing well above the top of the abandonment plug at 900 ft. Transfer of the well will be in accordance to regulations of the Kentucky Division of Oil and Gas.

If you have any questions in this matter, please contact me at (859) 323-0536, or by email at *j.r.bowersox@uky.edu*. Thank you for your assistance.

Sincerely,

J. Richard Bowersox, PhD
Senior Research Geologist
Kentucky Geological Survey

KGS

An Equal Opportunity University

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COMMONWEALTH OF KENTUCKY
DEPARTMENT OF MINES AND MINERALS
DIVISION OF OIL AND GAS
P.O. Box 2244
FRANKFORT, KY 40601 PHONE (502) 573-0147

AFFIDAVIT TO TIME AND MANNER OF PLUGGING AND FILLING WELL AS REQUIRED BY LAW

(TYPE OR PRINT IN INK)

NAME AND ADDRESS OF LAST OPERATOR: KENTUCKY GEOLOGICAL SURVEY- UNIVERSITY OF KENTUCKY

E-MAIL ADDRESS OF LAST OPERATOR: N/A

NAME AND ADDRESS OF ORIGINAL OPERATOR: N/A

E-MAIL ADDRESS OF ORIGINAL OPERATOR:

NAME AND ADDRESS OF COAL OPERATOR:

E-MAIL ADDRESS OF COAL OPERATOR:

PERMIT NO. 104925 ELEVATION 620 COUNTY HANCOCK TOTAL DEPTH 8126' PBTD - 800'

CARTER COORDINATES 2158 [x] FNL [ ] FSL 1683 [ ] FEL [x] FWL SEC 12 LETTER P NUMBER 34

FARM OWNER (LESSOR) MARVIN & BRENDA BLAN WELL NUMBER 1

AFFIDAVIT TO BE MADE IN TRIPLICATE, ONE COPY TO BE MAILED TO THE DEPARTMENT OF MINES AND MINERALS, ONE COPY TO BE RETAINED BY THE WELL OPERATOR AND THE THIRD TO BE MAILED BY REGISTERED MAIL TO EACH COAL OPERATOR NAMED AT THEIR RESPECTIVE ADDRESSES.

AFFIDAVIT

STATE OF KENTUCKY,

COUNTY OF ______________ } SS:

______________, OPERATOR OF THE ABOVE CAPTIONED WELL DOES HEREBY SWEAR THAT THE PLUGGING OF SAID WELL WAS COMPLETED ACCORDING TO INSTRUCTIONS FROM THE OIL AND GAS INSPECTOR AND ACCORDING TO CHAPTER 353 OF THE KENTUCKY REVISED STATUTES ON 9-29-2010 (PLUGGED DATE), RECORD OF WHICH IS LISTED BELOW OR SHOWN ON THE BACK OF THIS FORM.

	FROM	TO	WITH (PLUG DESCRIPTION)
PLUGGED:	5545'	5268'	100 sx "A" Cement w/3% CaCl2
PLUGGED:	5275'	5037'	75 sx "A" Cement w/3% CaCl2
PLUGGED:	3942'	3716'	100 sx "A" Cement w/3% CaCl2
PLUGGED:	3716'	3477'	100 sx "A" Cement w/3% CaCl2
PLUGGED:		800'	Cast Iron Bridge Plug
PLUGGED:			
PLUGGED:			
PLUGGED:			

INDICATE BELOW THE SIZE AND INTERVAL OF ALL CASING LEFT IN THE WELL AND IF AND WHERE IT WAS SHOT OFF:

CASING SIZE	INTERVAL	SHOT OFF AT	BOTTOM OF CASING AT
20"	0-51.4'		51.4'
13 3/8"	0-442'		442'
8 5/8"	0-3360'		3360'

IF CASING WAS NOT LEFT IN THE WELL, INDICATE THE BORE HOLE SIZE AND INTERVAL:

CASING SIZE ______________ INTERVAL ______________

CASING SIZE ______________ INTERVAL ______________

(OPTIONAL) SIGNATURE OF CONTRACTOR RESPONSIBLE FOR ABOVE PLUGGING ______________ TITLE ______________

[signature] Co-Principal Investigator

(REQUIRED) SIGNATURE OF OPERATOR RESPONSIBLE FOR ABOVE PLUGGING TITLE

SWORN TO AND SUBSCRIBED BEFORE ME THIS 18 DAY OF October, 20 11

[signature]
NOTARY PUBLIC

MY COMMISSION EXPIRES: 1-11-14

ALL BLANKS MUST BE COMPLETED. INCOMPLETE ADDIFAVITS WILL BE REJECTED.

FORM ED-38
(REV. 2/99)

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COMMONWEALTH OF KENTUCKY
DEPARTMENT OF MINES AND MINERALS
DIVISION OF OIL AND GAS
P.O. Box 2244
FRANKFORT, KY 40601 PHONE (502) 573-0147

AFFIDAVIT TO TIME AND MANNER OF PLUGGING AND FILLING WELL
AS REQUIRED BY LAW

R# 137114 GW

(TYPE OR PRINT IN INK)

University of Kentucky - Kentucky Geological Survey
NAME AND ADDRESS OF LAST OPERATOR

Williams @ UKy.edu
E-MAIL ADDRESS OF LAST OPERATOR

Ky. Geolo (Same)
NAME AND ADDRESS OF ORIGINAL OPERATOR

(Same)
E-MAIL ADDRESS OF ORIGINAL OPERATOR

NAME AND ADDRESS OF COAL OPERATOR

E-MAIL ADDRESS OF COAL OPERATOR

Kentucky Geological Survey
0137114025

PERMIT NO. 104925 ELEVATION 620 COUNTY HANCOCK TOTAL DEPTH P.B.T.D. 900'

CARTER COORDINATES 2758 ☑ FNL ☐ FSL 1683 ☐ FEL ☑ FWL SEC 12 LETTER P NUMBER 34

FARM OWNER (LESSOR) BLAN, MARVIN & BRENDA WELL NUMBER 1

AFFIDAVIT TO BE MADE IN TRIPLICATE, ONE COPY TO BE MAILED TO THE DEPARTMENT OF MINES AND MINERALS, ONE COPY TO BE RETAINED BY THE WELL OPERATOR AND THE THIRD TO BE MAILED BY REGISTERED MAIL TO EACH COAL OPERATOR NAMED AT THEIR RESPECTIVE ADDRESSES.

AFFIDAVIT

STATE OF KENTUCKY,

COUNTY OF ____________ } SS:

KENTUCKY GEOLOGICAL SURVEY, OPERATOR OF THE ABOVE CAPTIONED WELL DOES HEREBY SWEAR THAT THE PLUGGING OF SAID WELL WAS COMPLETED ACCORDING TO INSTRUCTIONS FROM THE OIL AND GAS INSPECTOR AND ACCORDING TO CHAPTER 353 OF THE KENTUCKY REVISED STATUTES ON PARTIAL PLUG 10/14/11 (PLUGGED DATE), RECORD OF WHICH IS LISTED BELOW OR SHOWN ON THE BACK OF THIS FORM.

	FROM	TO	WITH (PLUG DESCRIPTION)
PLUGGED:	1221'	900' (PARTIAL PLUG)	160 SX CLASS "A" CEMENT
PLUGGED:			
PLUGGED:			
PLUGGED:			
PLUGGED:			
PLUGGED:			
PLUGGED:			
PLUGGED:			

INDICATE BELOW THE SIZE AND INTERVAL OF ALL CASING LEFT IN THE WELL AND IF AND WHERE IT WAS SHOT OFF:

CASING SIZE	INTERVAL	SHOT OFF AT	BOTTOM OF CASING AT

IF CASING WAS NOT LEFT IN THE WELL, INDICATE THE BORE HOLE SIZE AND INTERVAL:

CASING SIZE	INTERVAL

(OPTIONAL) SIGNATURE OF CONTRACTOR RESPONSIBLE FOR ABOVE PLUGGING TITLE

[signature] Co-Principle Investigator
(REQUIRED) SIGNATURE OF OPERATOR RESPONSIBLE FOR ABOVE PLUGGING TITLE

SWORN TO AND SUBSCRIBED BEFORE ME THIS 18th DAY OF OCTOBER, 20 11

[signature]
~~NOTARY PUBLIC~~

MY COMMISSION EXPIRES: ____________

RECEIVED
OCT 21 2011
CONTINUED
DIVISION OF OIL & GAS

ALL BLANKS MUST BE COMPLETED. INCOMPLETE ADDIFAVITS WILL BE REJECTED.

FORM ED-38
(REV. 2/99)

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 4
ATLANTA FEDERAL CENTER
61 FORSYTH STREET
ATLANTA, GEORGIA 30303-8960

NOV 22 2011

Certified Mail
Return Receipt Requested

Dr. J. Richard Bowersox
Senior Research Geologist
Kentucky Geological Survey
504 Rose Street
228 Mining and Mineral Resources Building
Lexington, Kentucky 40506-0107

Dear Mr. Bowersox:

The U. S. Environmental Protection Agency, Region 4, has reviewed the records for setting of the final cement plug required for the plugging and abandonment of the Marvin Blan #1 injection well (KYV0049). This action completes the plugging and abandonment requirements for the subject well. The status of this well has been revised in our data base from active to plugged and abandoned. It is our understanding that the well will be converted to an oil production well.

Under the terms of the permit the Kentucky Geological Survey (KGS) is required to collect and analyze samples from four water supply wells and two springs for "two years" after injection well closure. Therefore, KGS must collect and analyze samples and submit the data to the EPA quarterly until October 18, 2013.

If you have any questions concerning the above, please call Mr. George Ford of my staff at (404) 562-9307.

Sincerely

Fred McManus
Chief
Ground Water & Safe Drinking Water Act
Enforcement Section

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Appendix 2C

Pressure Transient Analysis Reports

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September 21, 2011

Mr. Bill Armstrong
Mr. Phil Papadeas
Sandia Technologies, LLC
6731 Theall Road
Houston, TX 77066

Dear Sirs,

Please find attached the analysis of the 2009 and 2010 injection falloff tests conducted on the KGS Marvin Blan Well #1 located in Hancock County, Kentucky.

The table below provides a summary of the key findings for each test followed by a brief discussion of the analysis of the "long" falloff periods from each test.

		2009	**2010**
Test Date		Aug-2009	Sep-2010
Transmissibility	md-ft/cp	21,889	4,336
Permeability (to Water)	md	9.3	12.5
Skin	dim	-4.45	-2.45
Model		2-Phi	2-Phi
Omega	frac	0.1	0.7
Lambda		5.50E-06	3.00E-06
Boundary Type		2 - Perpendicular	None
Distance - left	ft	900	N/A
Distance - right	ft	900	N/A
Pi, at gauge depth	psia	1517.9	2061.5
Gauge Depth	ft		4893

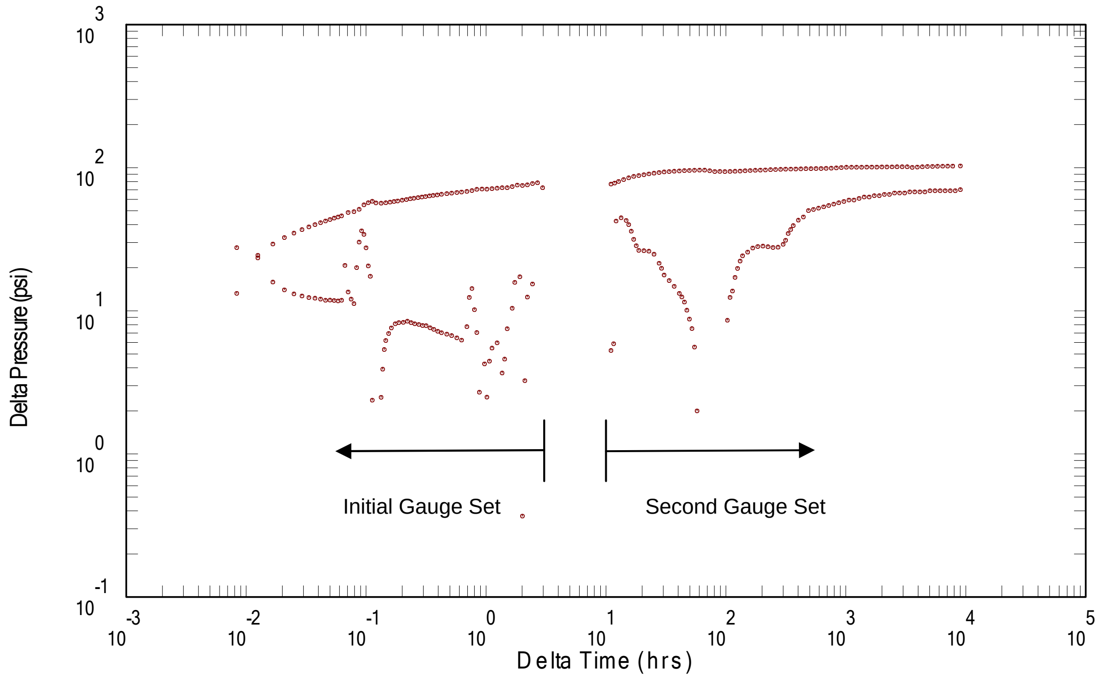
Reservoir Description Services

PO Box 442003
Houston, TX 77244
(281) 531-5850
www.RDSHouston.com

Discussion of Results - 2009 Injection Falloff Test

The analysis of the 2009 data is complicated somewhat due to the shift in the data and discontinuity caused by introducing 2 different gauge sets to record pressures during the falloff. The initial gauge set captures data up to 3 hours into the falloff and the second gauge set captures the long term falloff from 10 to 9000 hours.

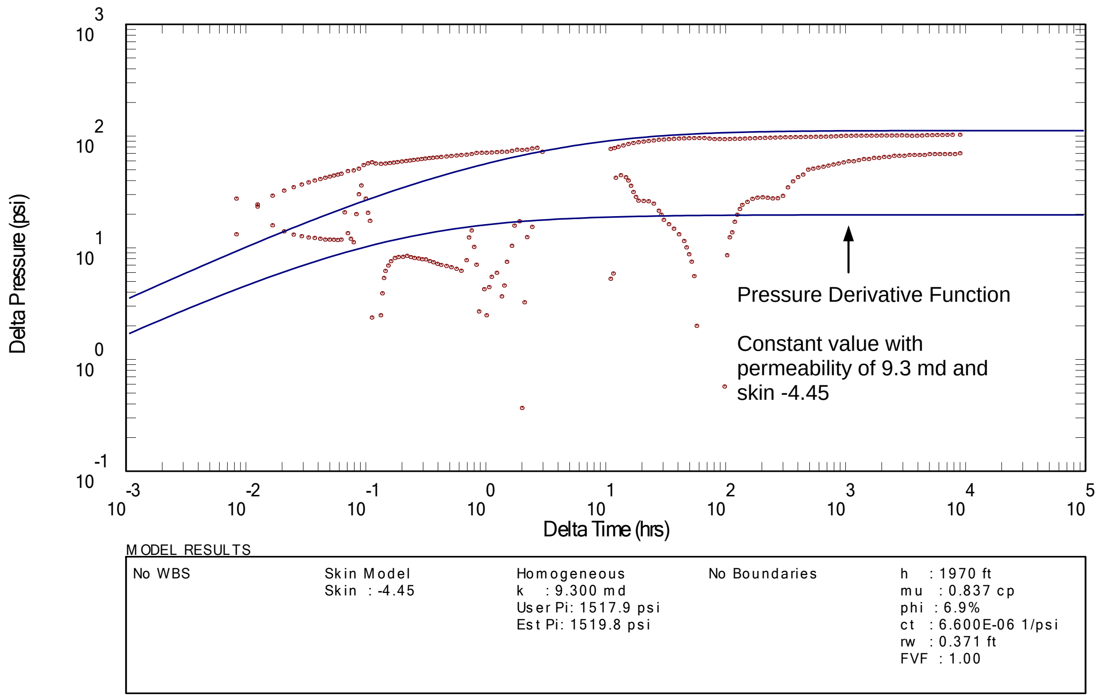
The disturbance created by changing the gauges affects the ability to see radial flow and the absolute difference in pressure has a minor impact on the estimated skin; the longer term data requires a slightly smaller skin to match the delta pressure on the log-log plot.



Homogeneous Model with Constant Skin

The log-log plot on the next page shows the 2009 injection falloff data with a homogeneous skin model as a point of reference to the final analysis.

The homogenous model uses permeability of 9.3 md and Skin of -4.45 and illustrates that there isn't a section of the "middle" time data that exhibits constant value in the pressure derivative function which is typical of radial flow. The homogeneous model helps to show the reservoir system is more complex than a simple homogeneous system.



Complex Reservoir Model

The data after 2000 hours shows the pressure derivative function trending toward a constant value which would indicate the presence of a straight line on the "semi-log" plot of the data. Had stabilization in the derivative function been observed early in the test it would normally be used be to estimate transmissibility (kh/u) and skin but seeing this behavior late in the test suggests the possible presence of intersecting no-flow boundaries.

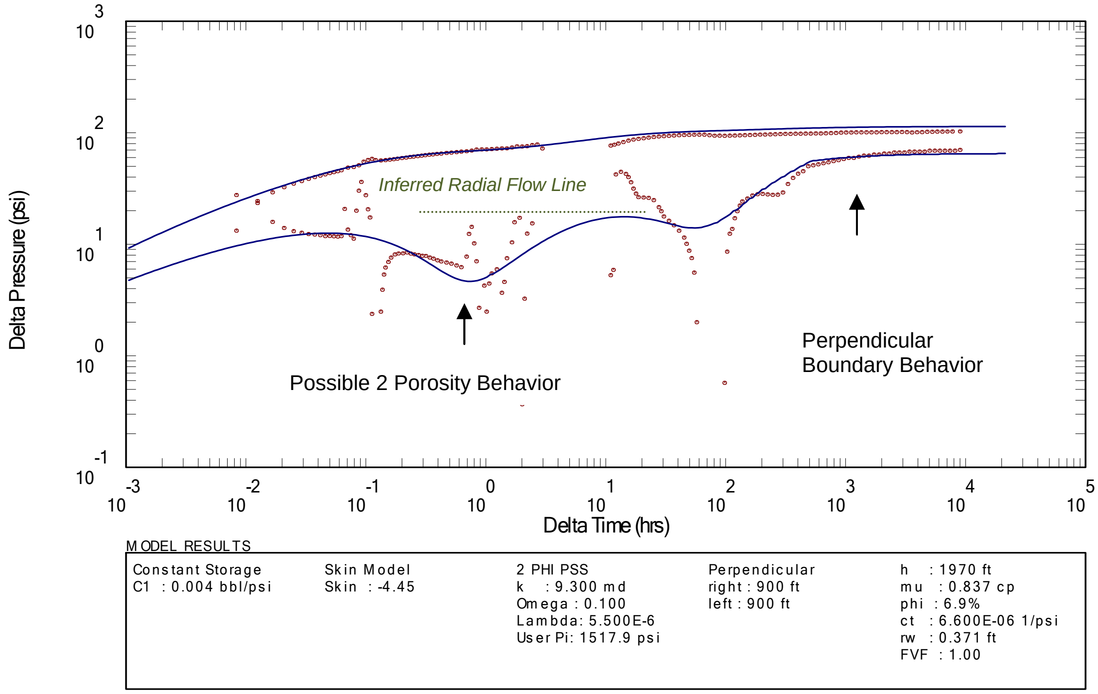
Working backward from the stabilization in the late time pressure derivative data helps determine permeability and skin. The plot on the next page shows a good match is achieved with permeability of 9.3 md, skin of -4.45 and perpendicular no-flow boundaries at 900 ft on either side of the well. The intersection boundaries cause the increase in the model derivative function that starts around 200 hours and finally stabilizes after 5000 hours.

The dashed line on the plot shows where radial flow would occur with the perpendicular boundaries however the data still suggests the presence of a system that can't be explained with late time boundaries alone.

A *two porosity* model seems to provide a better match of the data prior to 3 hours into the falloff than the homogeneous model with boundaries. Two porosity behavior is characterized by the "trough" in the pressure derivative function data which occurs because of flow from either reservoir layers and/or natural fractures. Even though the match is improved using the two-porosity model, it is beyond the scope of this analysis to suggest the two-porosity conditions actually exist in the reservoir.

In addition, there are several disturbances in the 2009 data around 0.1 and 100 hours which are most likely from operations or wellbore related and not reservoir induced (i.e. events such as closing valves at surface, fluid gradient change, etc).

The plot below shows the final analysis match using a two porosity model with perpendicular boundaries. The annotations indicate the portions of the test affected by possible no-flow boundaries and possible two-porosity behavior.



It is not suggested that this analysis is the only unique interpretation. The late time data could also be matched with an intersecting no-flow boundary model with angle between barriers less than 90 degrees. For instance, a model match with angle between boundaries of 60 degrees could be obtained in which case the permeability would be approximately 14 md.

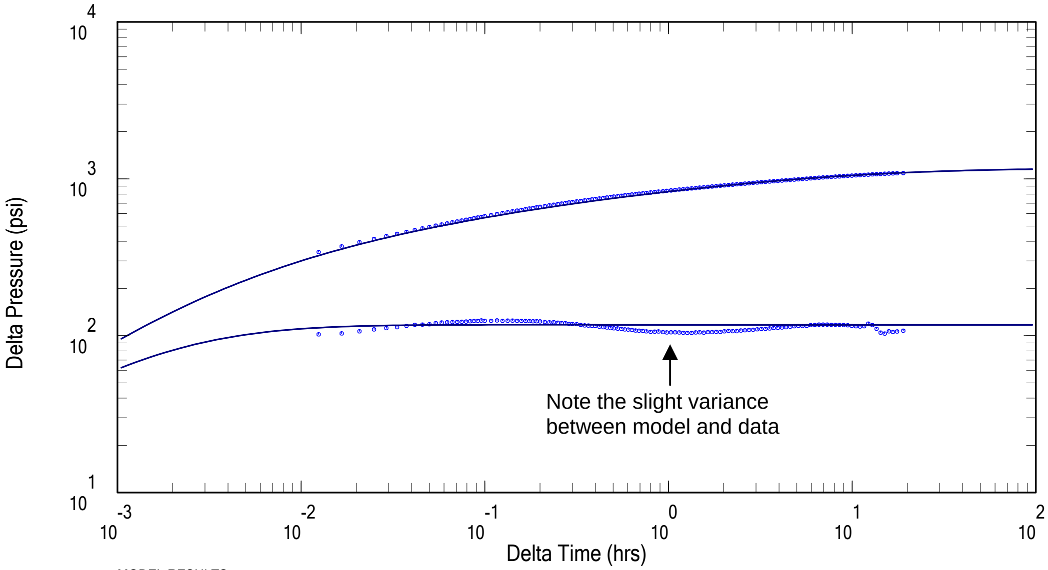
Another possible match would be with a radial composite model that would have a zone of higher transmissibility near the well and a decrease in transmissibility several hundred feet away from the well in all directions.

Discussion of Results - 2010 Injection Falloff Test

Homogeneous Model with Constant Skin

A homogenous model using permeability of 12.5 md and skin of -2.43 is shown below. The homogenous model provides a good match of the 2010 data but comparison of the model derivative function to the data derivative function highlights a slight variation from 0.7 to 3 hours into the falloff.

The slight decrease in the derivative function data is too minor to be caused by a no-flow boundary but can be matched once again with a two-porosity model as shown on the next page.

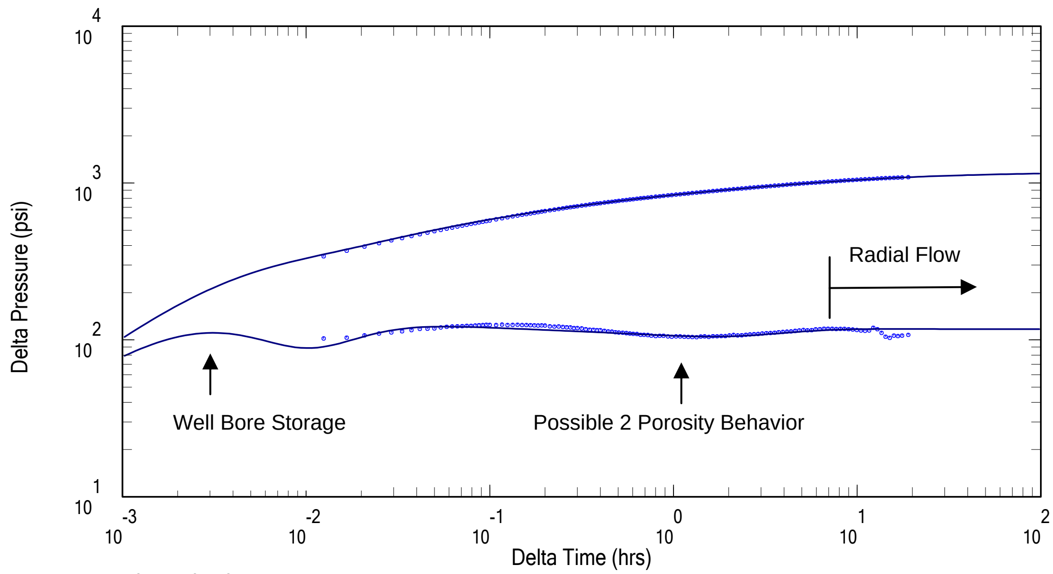


MODEL RESULTS

Constant Storage	Skin Model	Homogeneous	No Boundaries	h : 230 ft
C1 : 0.002 bbl/psi	Skin : -2.43	k : 12.500 md		mu : 0.663 cp
		Est Pi: 2056.7 psi		phi : 9.7%
				ct : 6.600E-06 1/psi
				rw : 0.328 ft
				FVF : 1.00

Complex Reservoir Model

The plot below shows the two porosity model used to match the falloff with excellent agreement. This match suggests radial flow occurs after 8 hours.



MODEL RESULTS

Exp Function	Skin Model	2 PHI SLABS	No Boundaries	h : 230 ft
C1 : 0.002 bbl/psi	Skin : -2.45	k : 12.500 md		mu : 0.663 cp
C2 : 0.004 bbl/psi		Omega : 0.700		phi : 9.7%
COD : 1.100		Lambda: 3.000E-6		ct : 6.600E-06 1/psi
		User Pi: 2061.5 psi		rw : 0.328 ft
				FVF : 1.00

Definition of Terms

Transmissibility (kh/u) equals permeability (k) times thickness (h) divided by viscosity (cp). The units for transmissibility are md-ft/cp. Transmissibility is derived from the radial flow portion of the data.

Permeability (k) is determined by dividing transmissibility by thickness (h) and multiplying by viscosity (u).

Skin (s), is a dimensionless term that accounts for the difference in the observed injection pressure at the time of shut-in to the theoretical pressure that would exist with the given transmissibility.

Pi is the reservoir pressure at the start of the rate history used in the analysis. Pi has units of psi.

Wellbore storage (C) defines the compressibility of the fluid in the wellbore times the storage volume. Wellbore storage (WBS) has units of bbl/psi. In the case of changing wellbore storage the model uses 2 storage values (initial and final) and a term to determine when the model transitions from the first storage to the final storage.

In a two porosity model Omega defines the ratio of the storativity of the higher perm but lower storage capacity system (i.e. fissures) to the storativity the total system (i.e. matrix + fissures). Omega is a fraction.

Storativity is a dimensionless value defined as (phi*ct*h)fissures divided by [(phi*ct*h)fissures+(phi*ct*h)matrix]

phi is porosity (fraction), ct is total compressibility (1/psi) and h is thickness.

Also in a two porosity model Lambda is a dimensionless term that defines how fluid moves from the higher permeability fissures into the lower permeability matrix.

A two porosity model can represent a naturally fractured reservoir but can also represent a layered system where injection goes from the well into a high permeability layer that then feeds a low permeability layer. Flow between the high and low permeability system is possible because of the surface area of contact.

Additional analysis plots for the 2009 and 2010 tests are attached.

Please let me know if you need any additional information.

Best regards,

Allen Klingensmith
Reservoir Description Services

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KGS Marvin Blan #1 Well
2009 Injection Falloff Tests

Long Term Build-up

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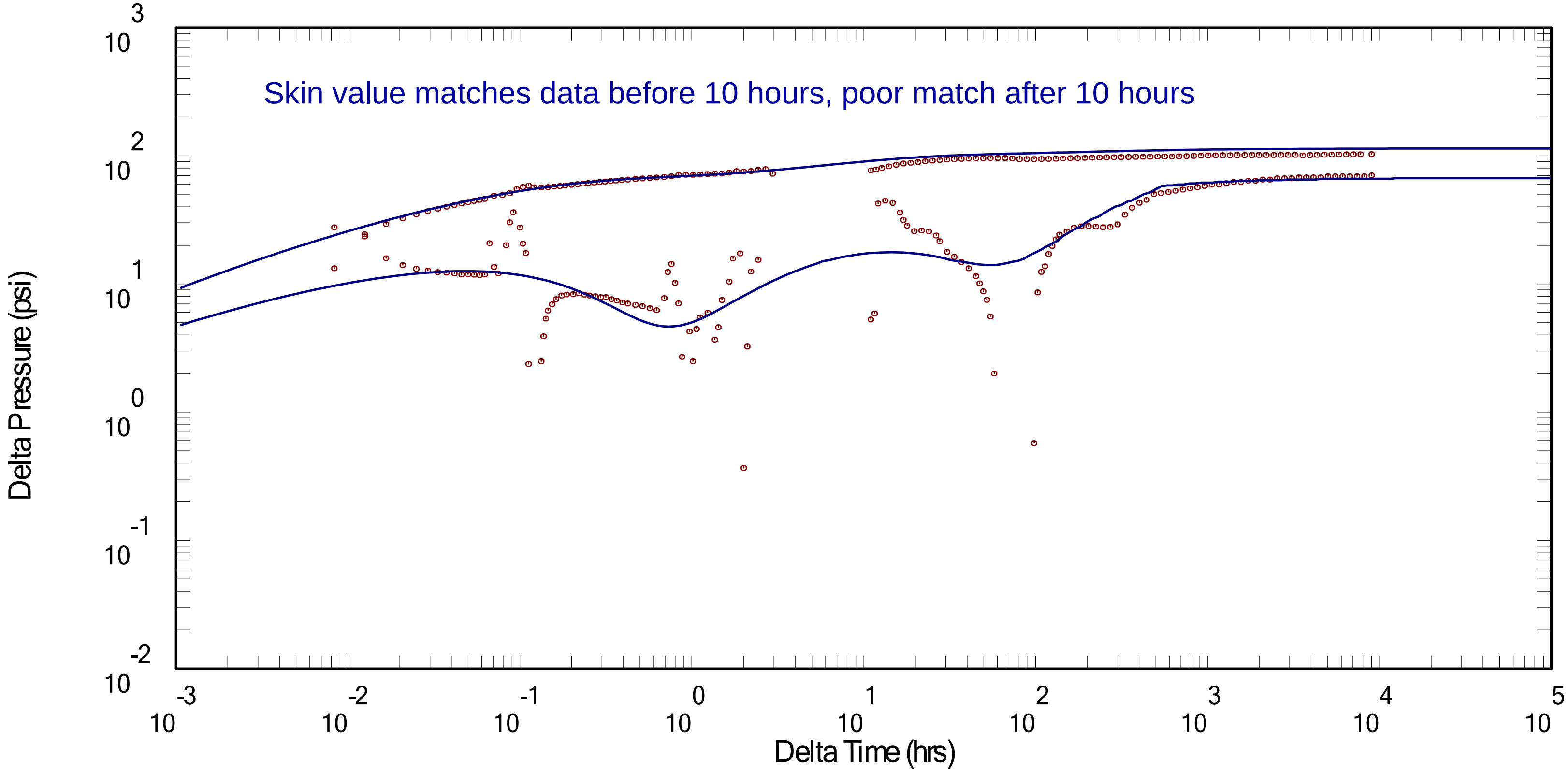
Log-log Plot

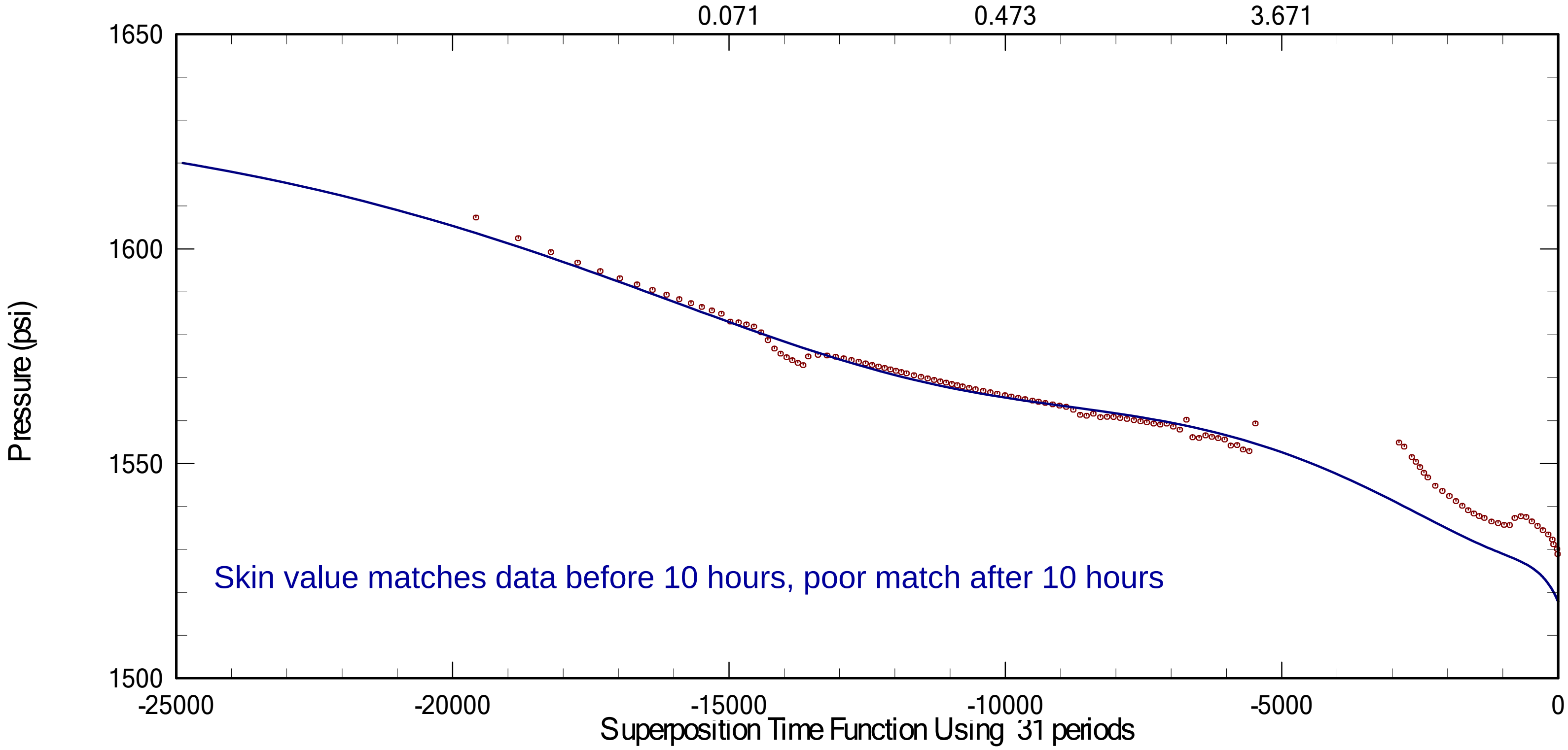
Two Porosity Model, Perp Boundaries, Skin - 4.45



MODEL RESULTS

Constant Storage C1 : 0.004 bbl/psi	Skin Model Skin : -4.45	2 PHI PSS k : 9.300 md Omega : 0.100 Lambda: 5.500E-6 Est Pi: 1517.9 psi	Perpendicular right : 900 ft left : 900 ft	h : 1970 ft mu : 0.837 cp phi : 6.9% ct : 6.600E-06 1/psi rw : 0.371 ft FVF : 1.00

Semi-log Plot
Two Porosity Model, Perp Boundaries, Skin - 4.45

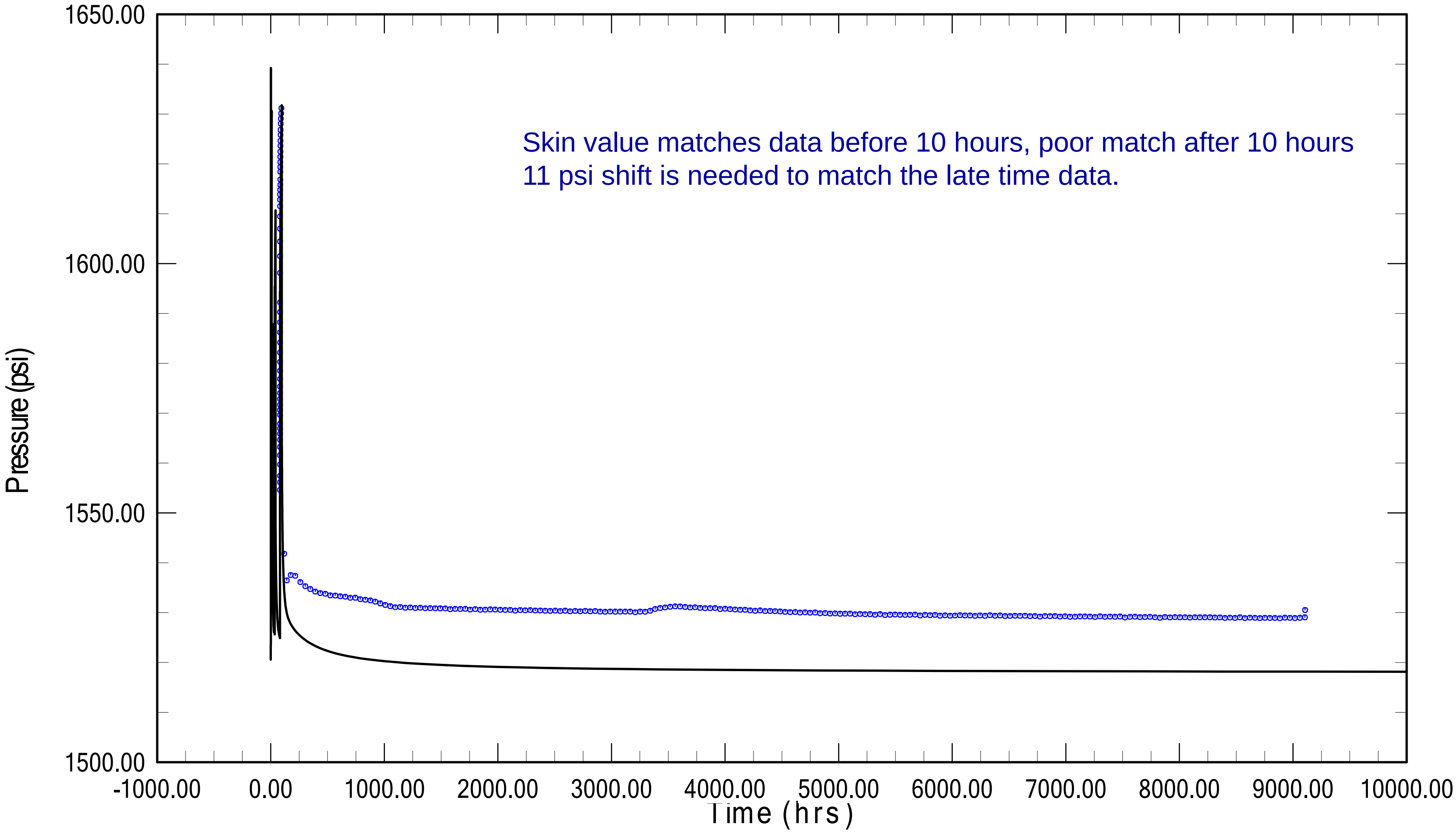


MODEL RESULTS

Constant Storage	Skin Model	2 PHI PSS	Perpendicular	h : 1970 ft
C1 : 0.004 bbl/psi	Skin : -4.45	k : 9.300 md	right : 900 ft	mu : 0.837 cp
		Omega : 0.100	left : 900 ft	phi : 6.9%
		Lambda: 5.500E-6		ct : 6.600E-06 1/psi
		Est Pi: 1517.9 psi		rw : 0.371 ft
				FVF : 1.00

Pressure History Simulation Plot

Two Porosity Model, Perp Boundaries, Skin - 4.45

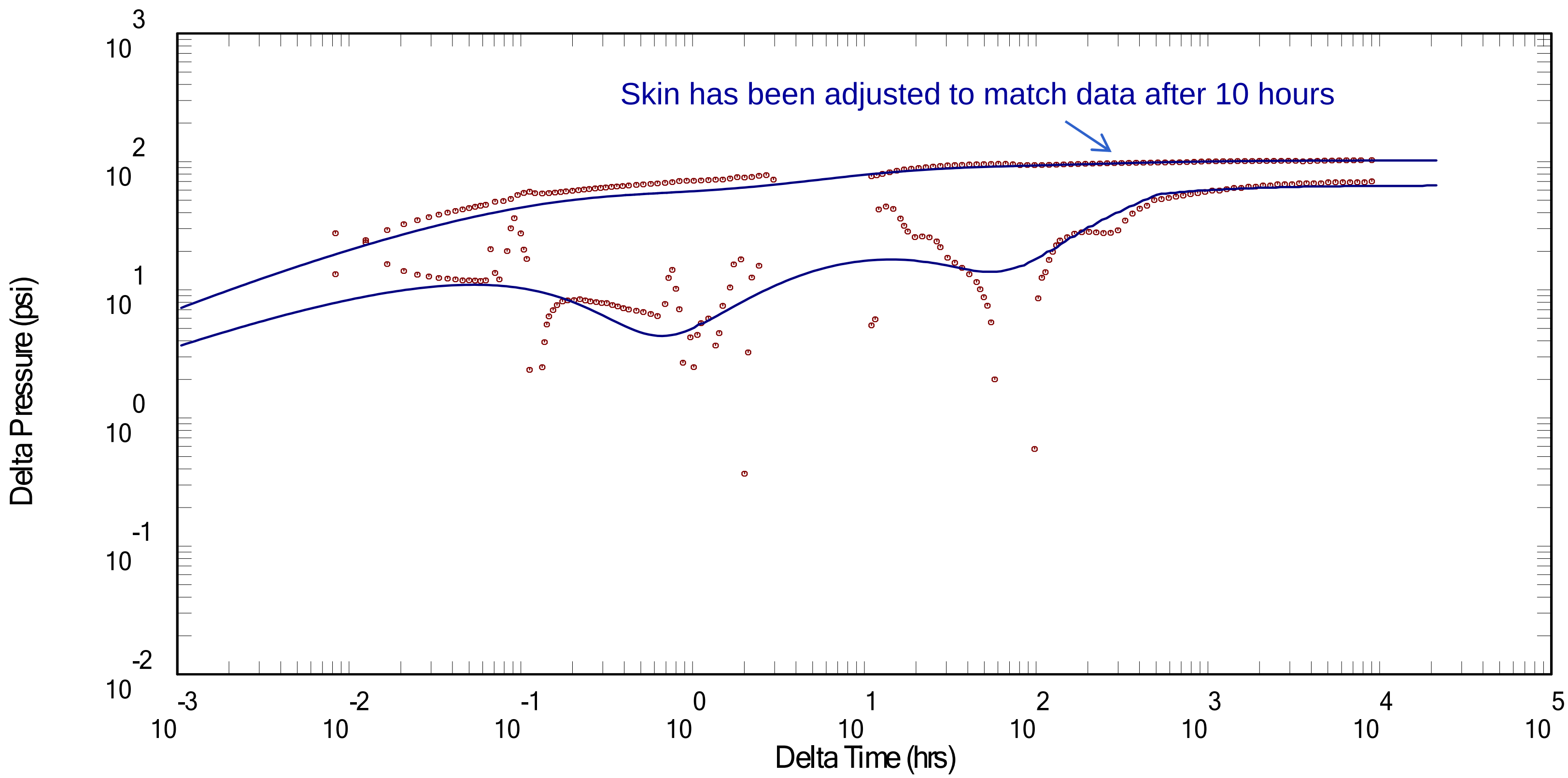


Pressure shift in late time data

- The analysis plots on the next page use the same results as the previous plots with the exception of skin and Pi. Skin has been decreased to -4.75 (from -4.45) to cause a shift in the data to match the long term shut-in data.
- Shifting the long term shut-in data by – 11.1 psi would have the same affect.

Log-log Plot

Two Porosity Model, Perp Boundaries, Skin – 4.75

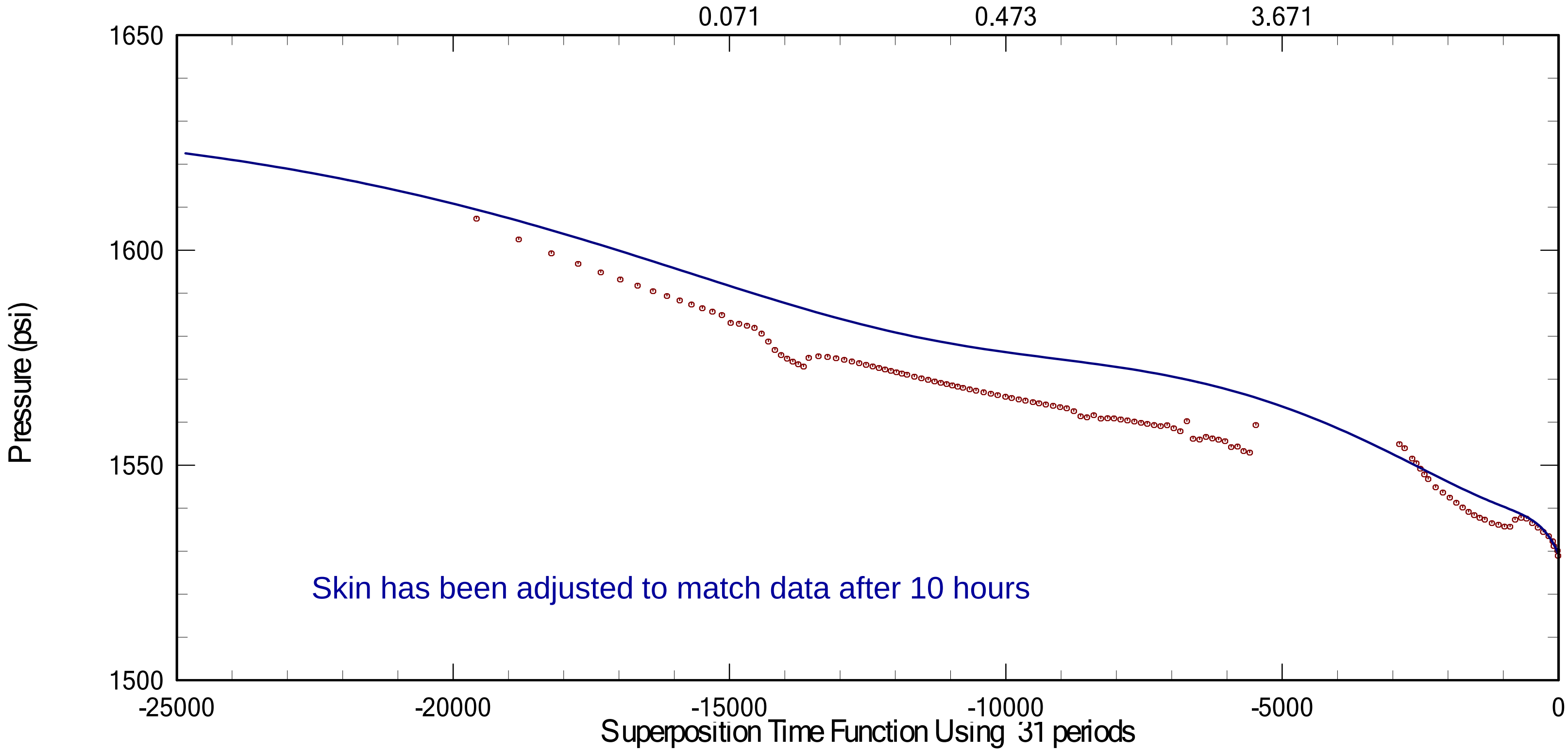


MODEL RESULTS

Constant Storage	Skin Model	2 PHI PSS	Perpendicular	h : 1970 ft
C1 : 0.004 bbl/psi	Skin : -4.75	k : 9.300 md	right : 900 ft	mu : 0.837 cp
		Omega : 0.100	left : 900 ft	phi : 6.9%
		Lambda: 5.500E-6		ct : 6.600E-06 1/psi
		User Pi: 1529.3 psi		rw : 0.371 ft
				FVF : 1.00

Semi-log Plot

Two Porosity Model, Perp Boundaries, Skin – 4.75

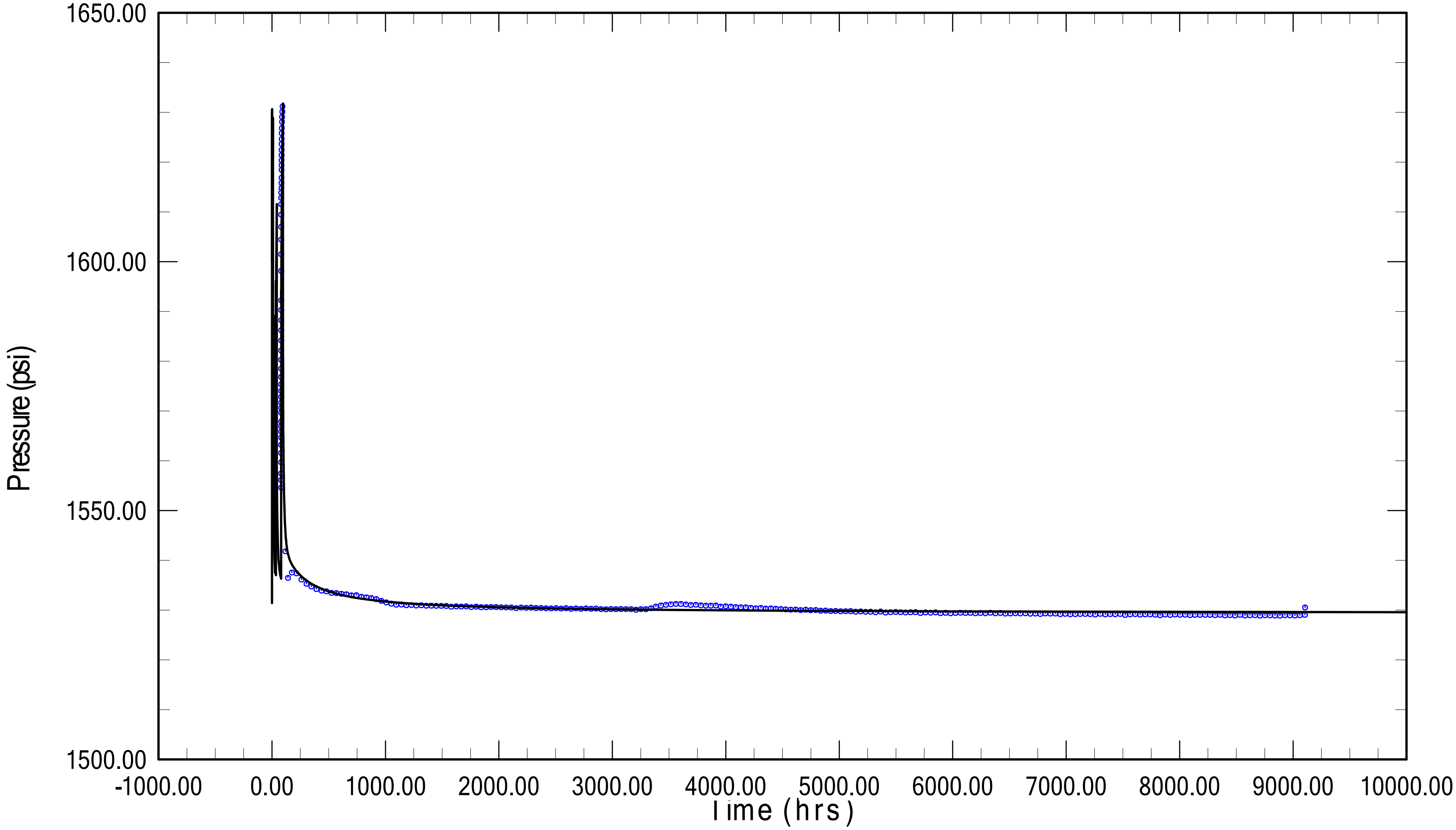


MODEL RESULTS

Constant Storage	Skin Model	2 PHI PSS	Perpendicular	h : 1970 ft
C1 : 0.004 bbl/psi	Skin : -4.75	k : 9.300 md	right : 900 ft	mu : 0.837 cp
		Omega : 0.100	left : 900 ft	phi : 6.9%
		Lambda: 5.500E-6		ct : 6.600E-06 1/psi
		User Pi: 1529.3 psi		rw : 0.371 ft
				FVF : 1.00

Pressure History Simulation Plot

Two Porosity Model, Perp Boundaries, Skin – 4.75



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KGS Marvin Blan #1 Well
2010 Injection Falloff Tests

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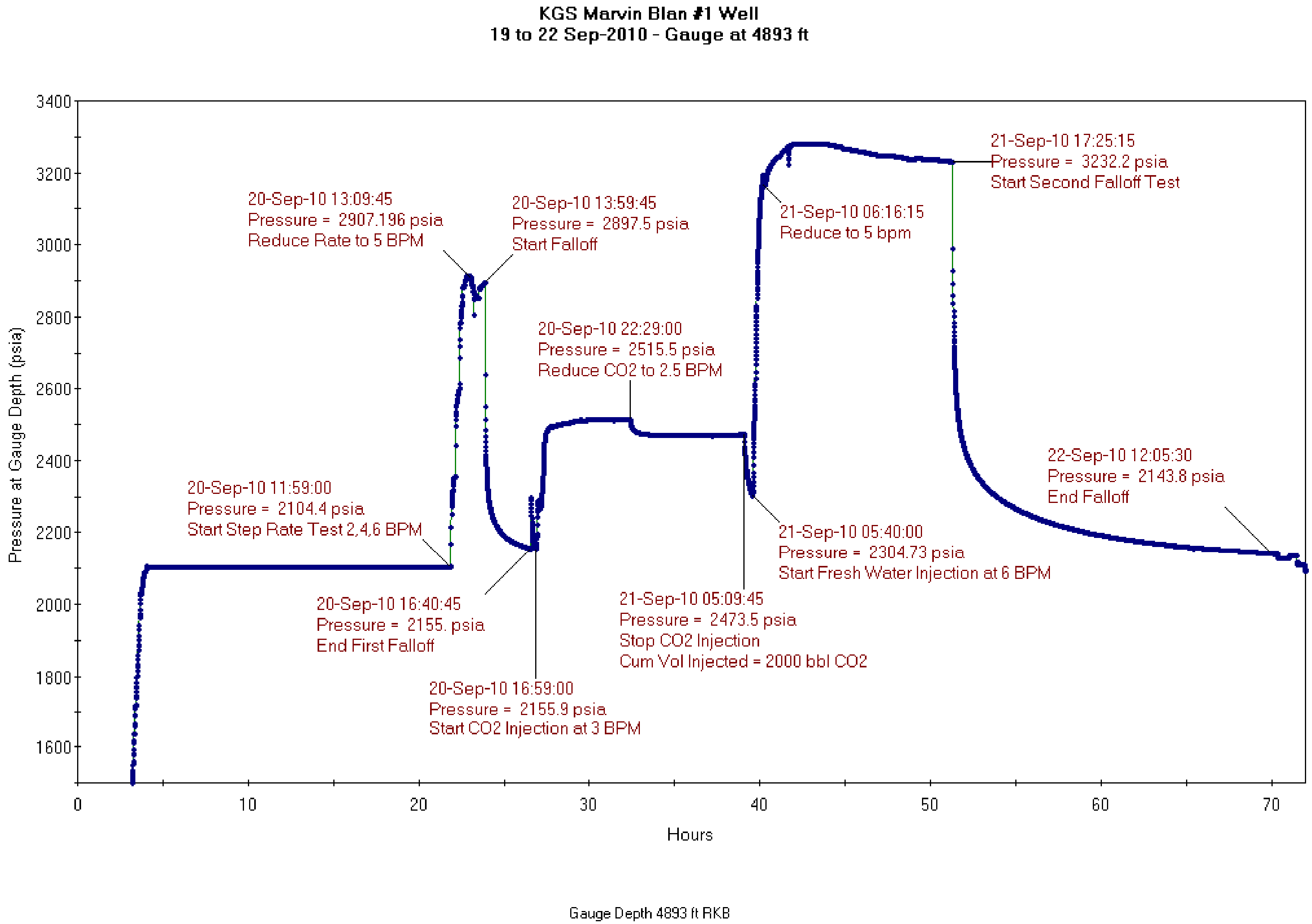
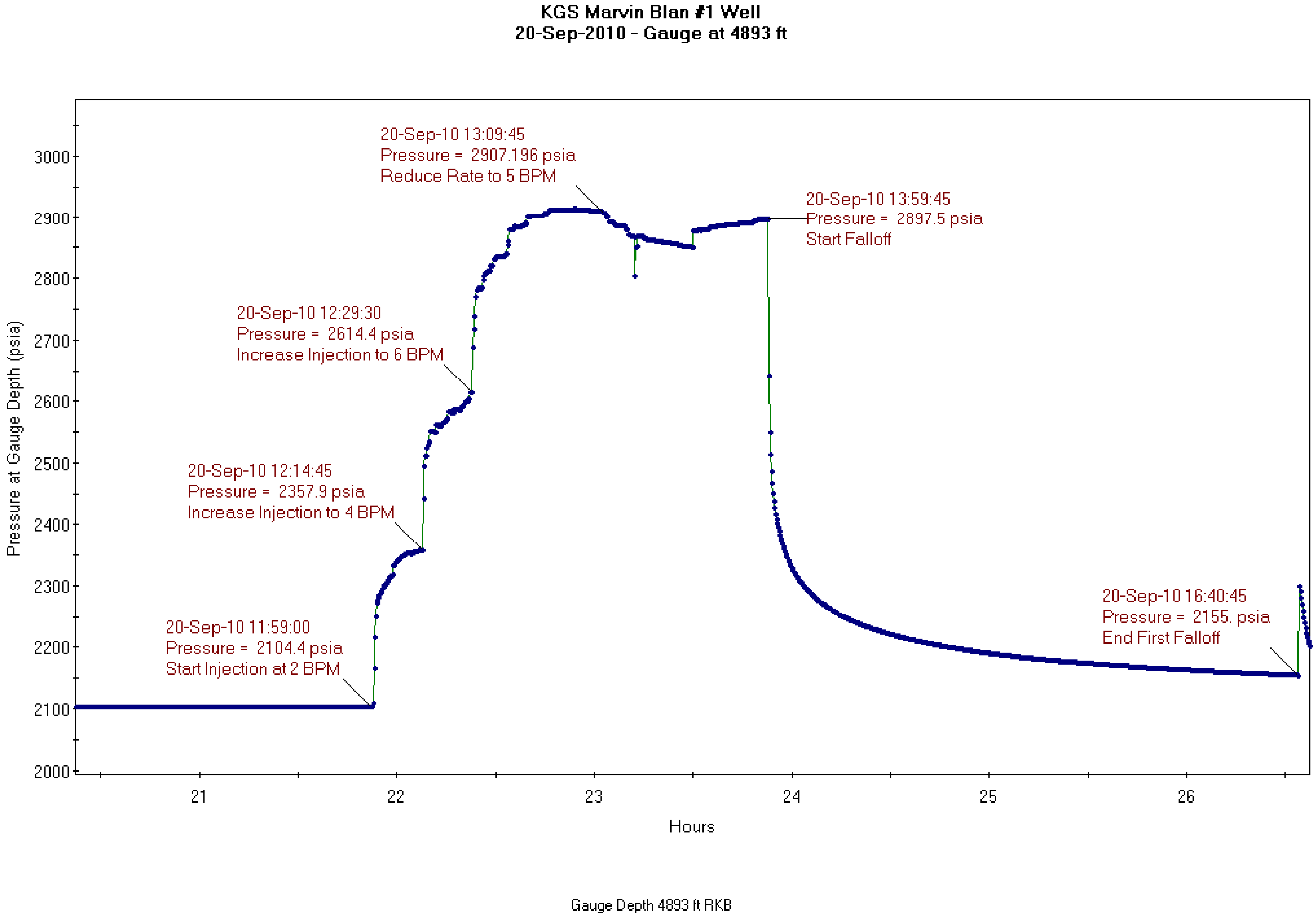
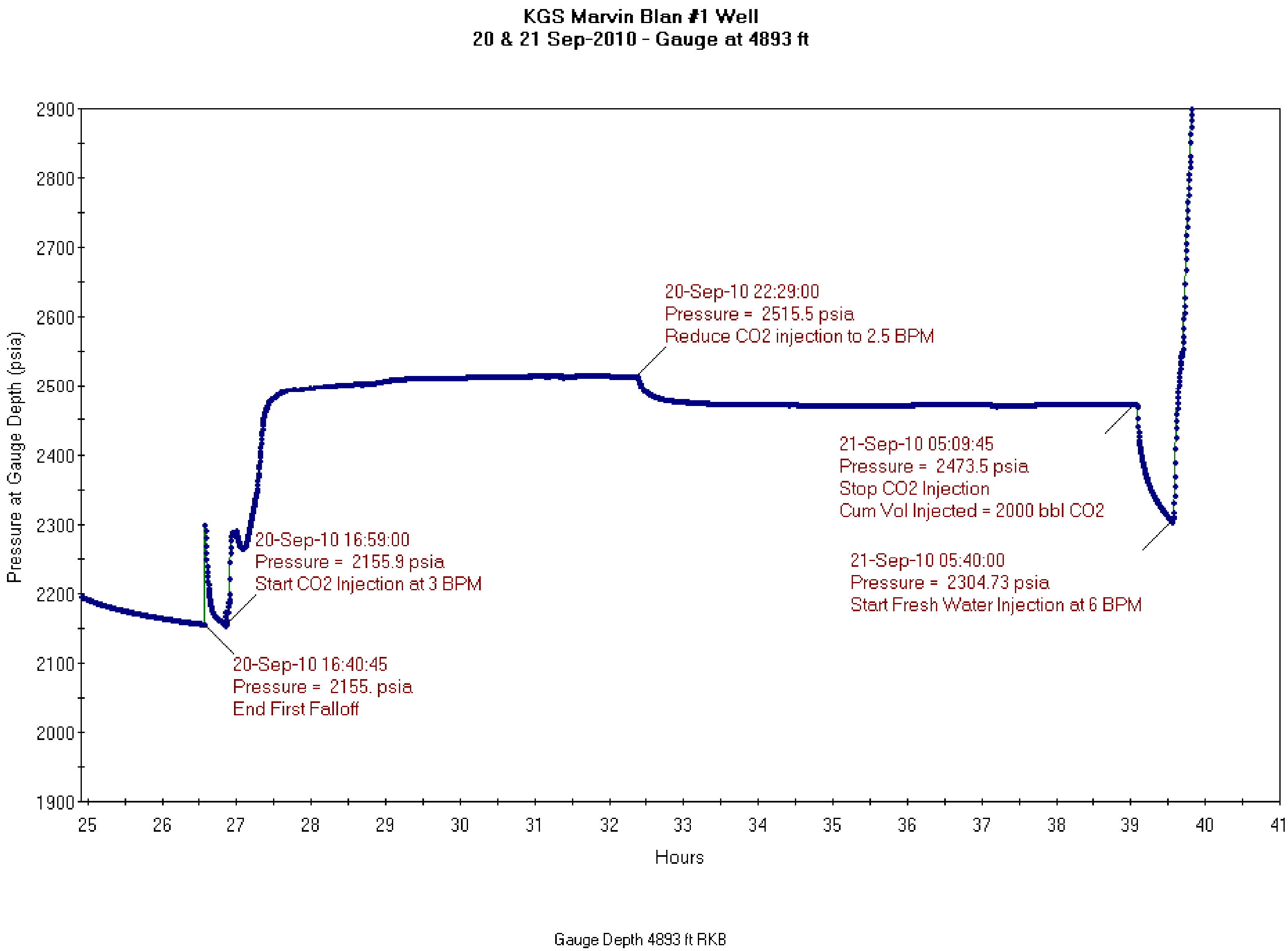
Test Overview



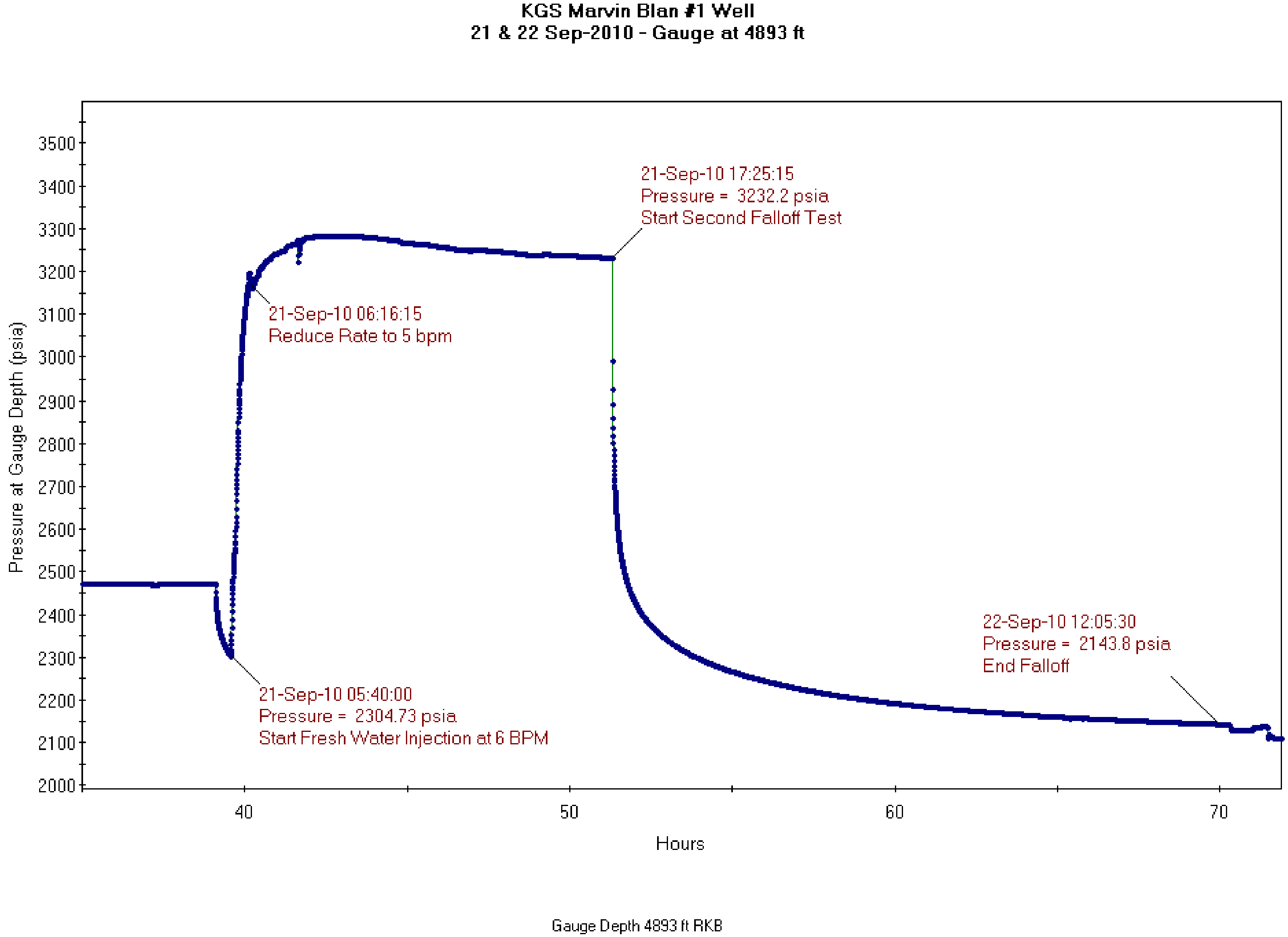
Short Injection and Falloff Period



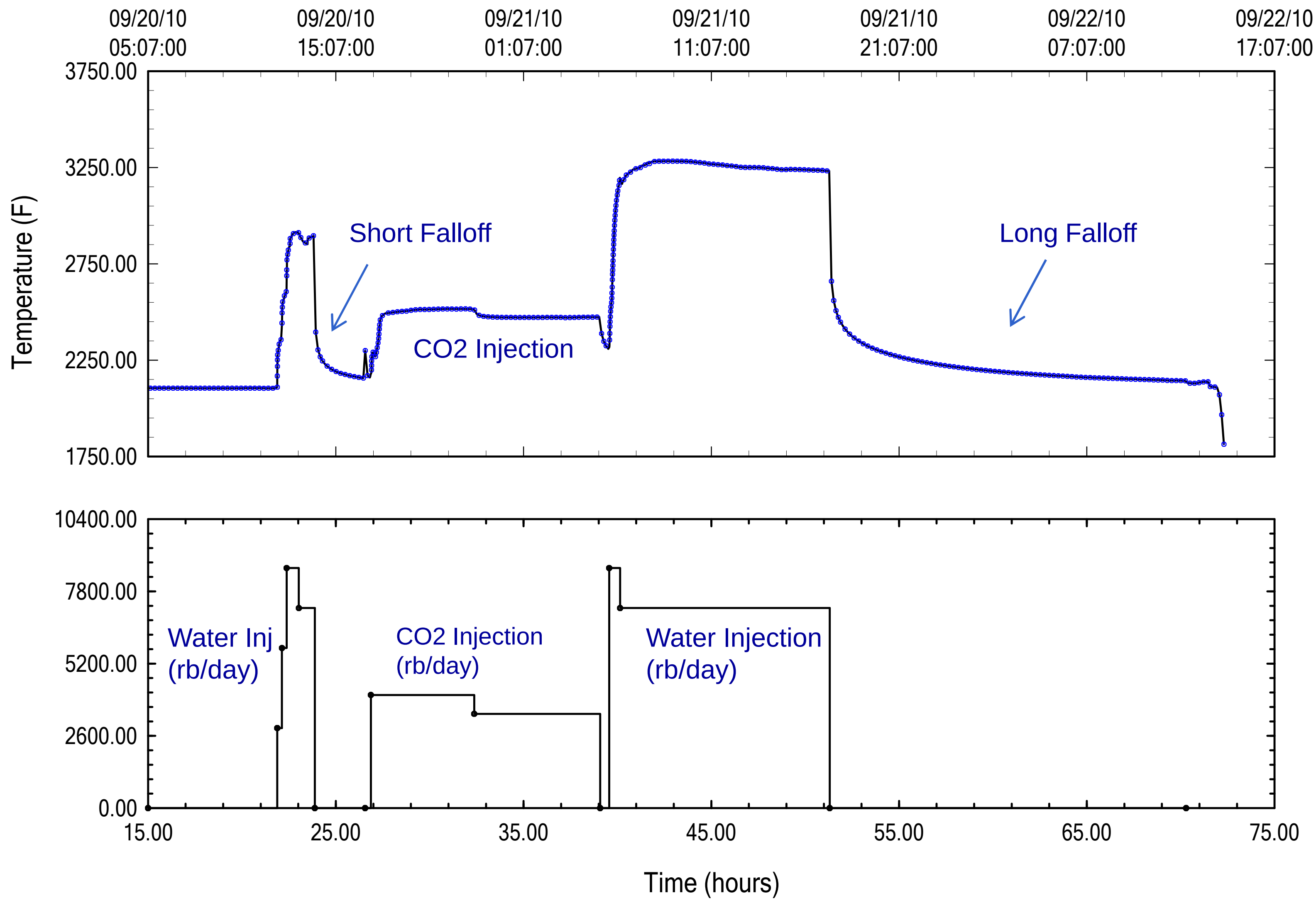
CO2 Injection Period



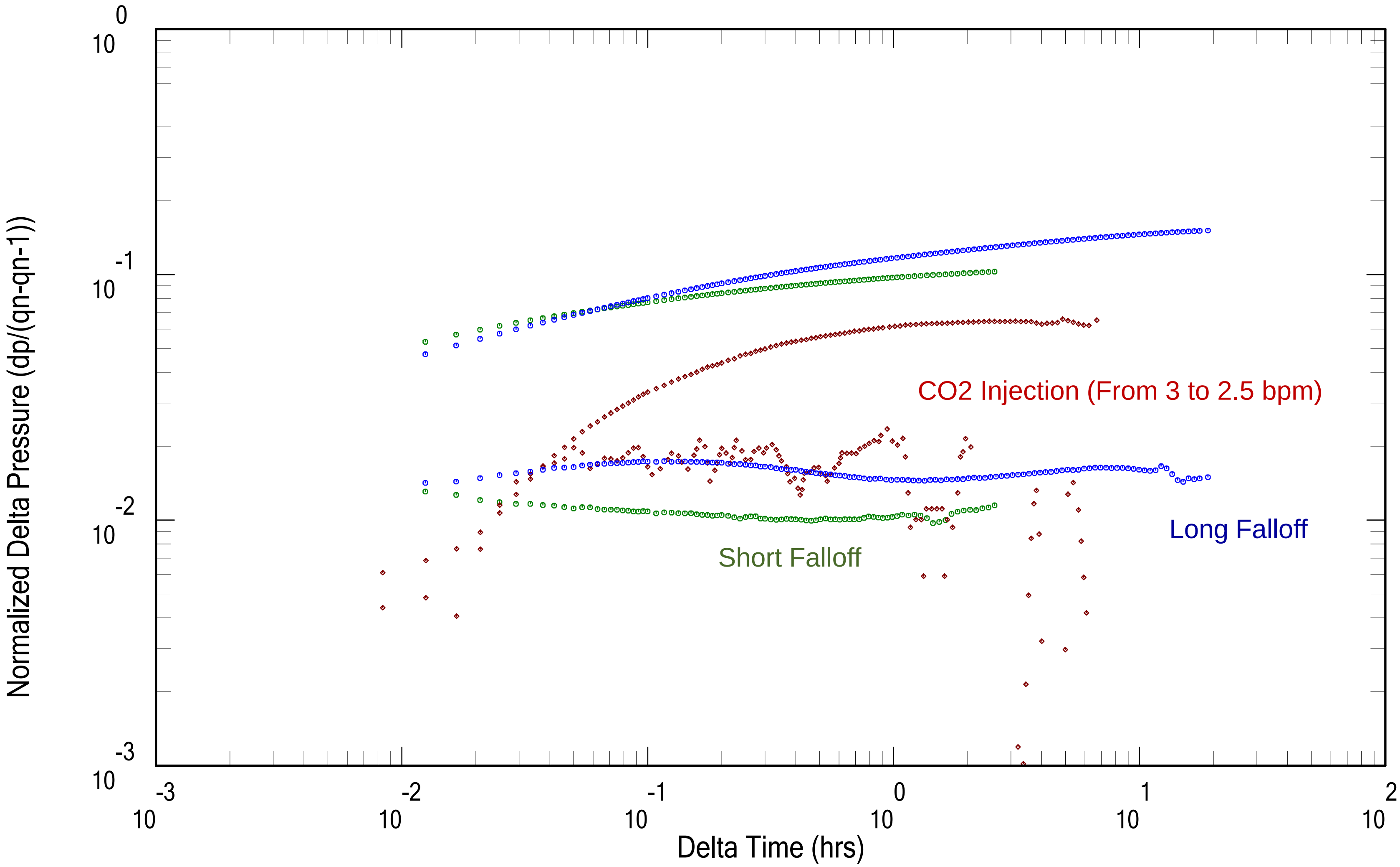
Long Injection and Falloff Period



KGS Marvin Blan #1 Well
2010 Injection Rate History used in Analysis

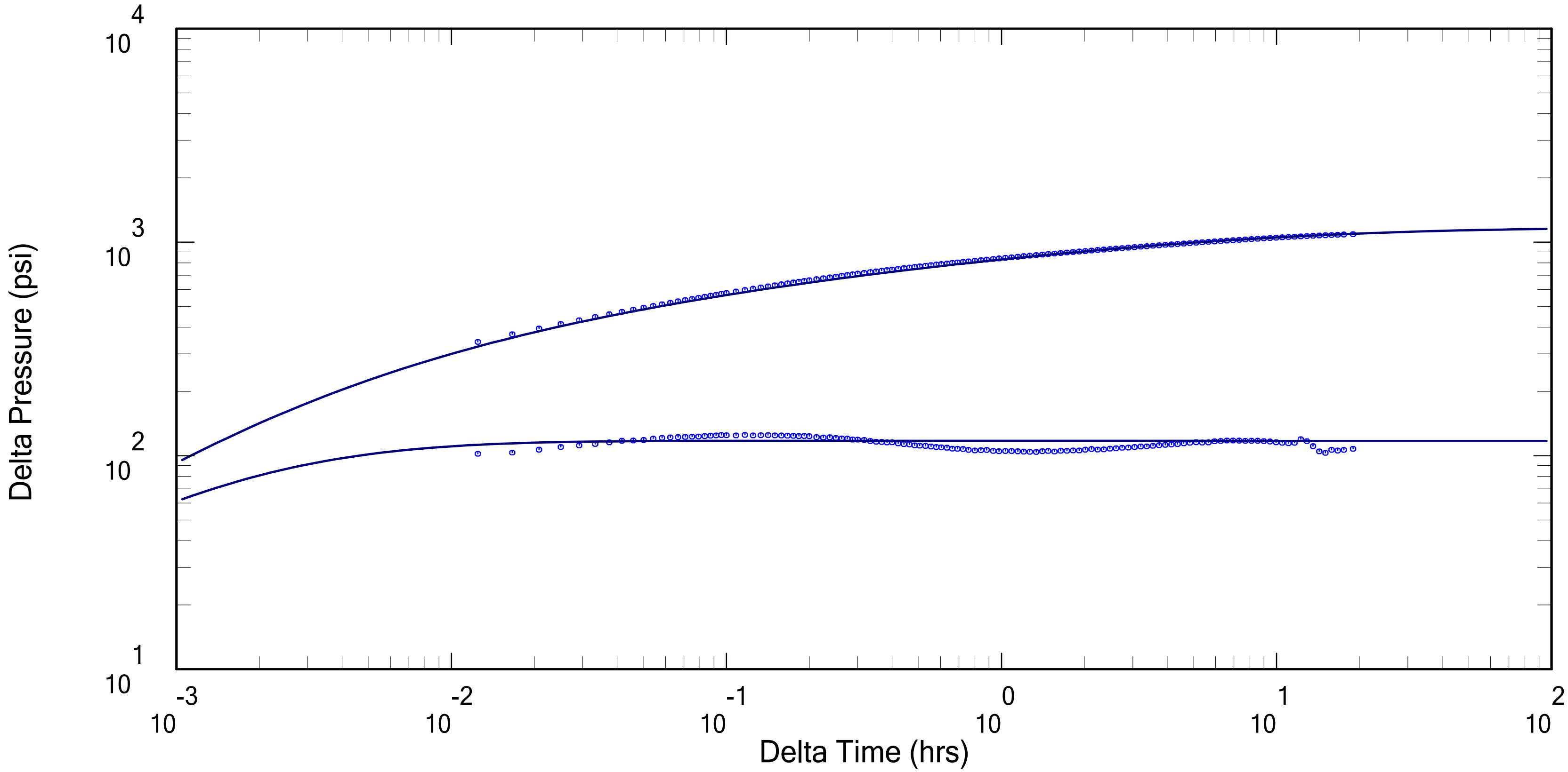


KGS Marvin Blan #1 Well
Falloff Test Comparison



Log-log Plot

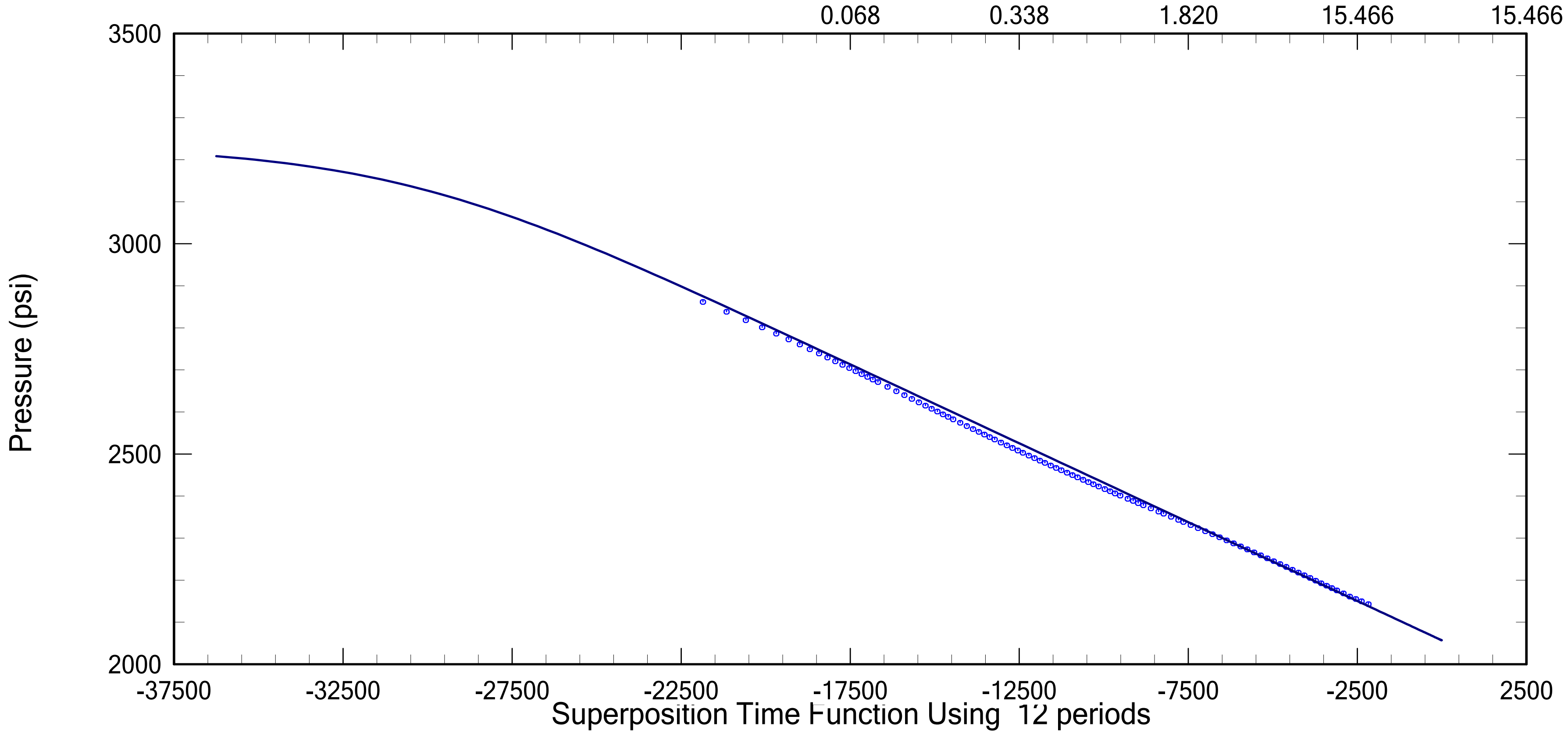
Long Falloff – Homogeneous Model



MODEL RESULTS

Constant Storage	Skin Model	Homogeneous	No Boundaries	h : 230 ft
C1 : 0.002 bbl/psi	Skin : -2.43	k : 12.500 md		mu : 0.663 cp
		Est Pi: 2056.7 psi		phi : 9.7%
				ct : 6.600E-06 1/psi
				rw : 0.328 ft
				FVF : 1.00

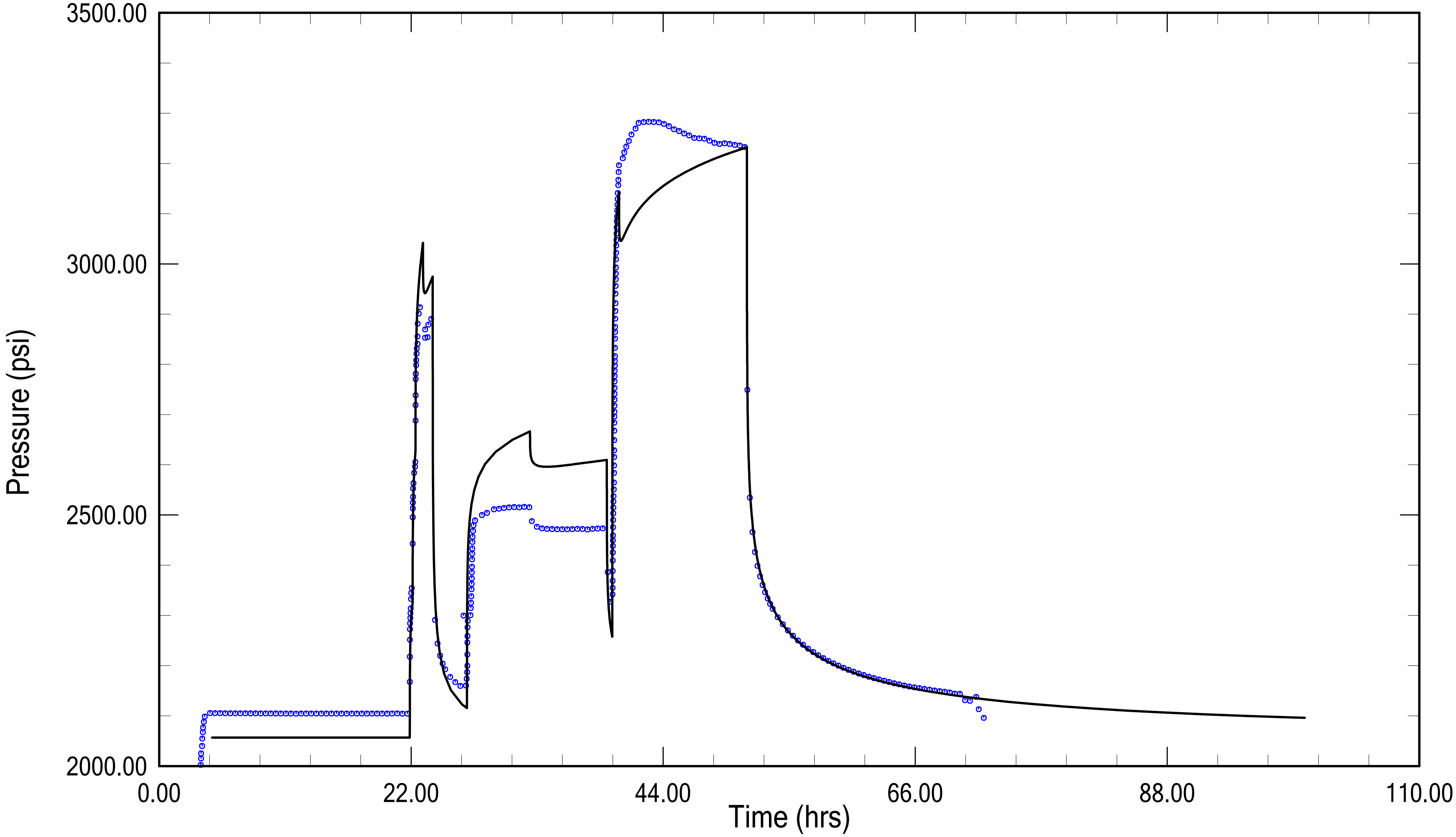
Semi-log Plot
Long Falloff – Homogeneous Model



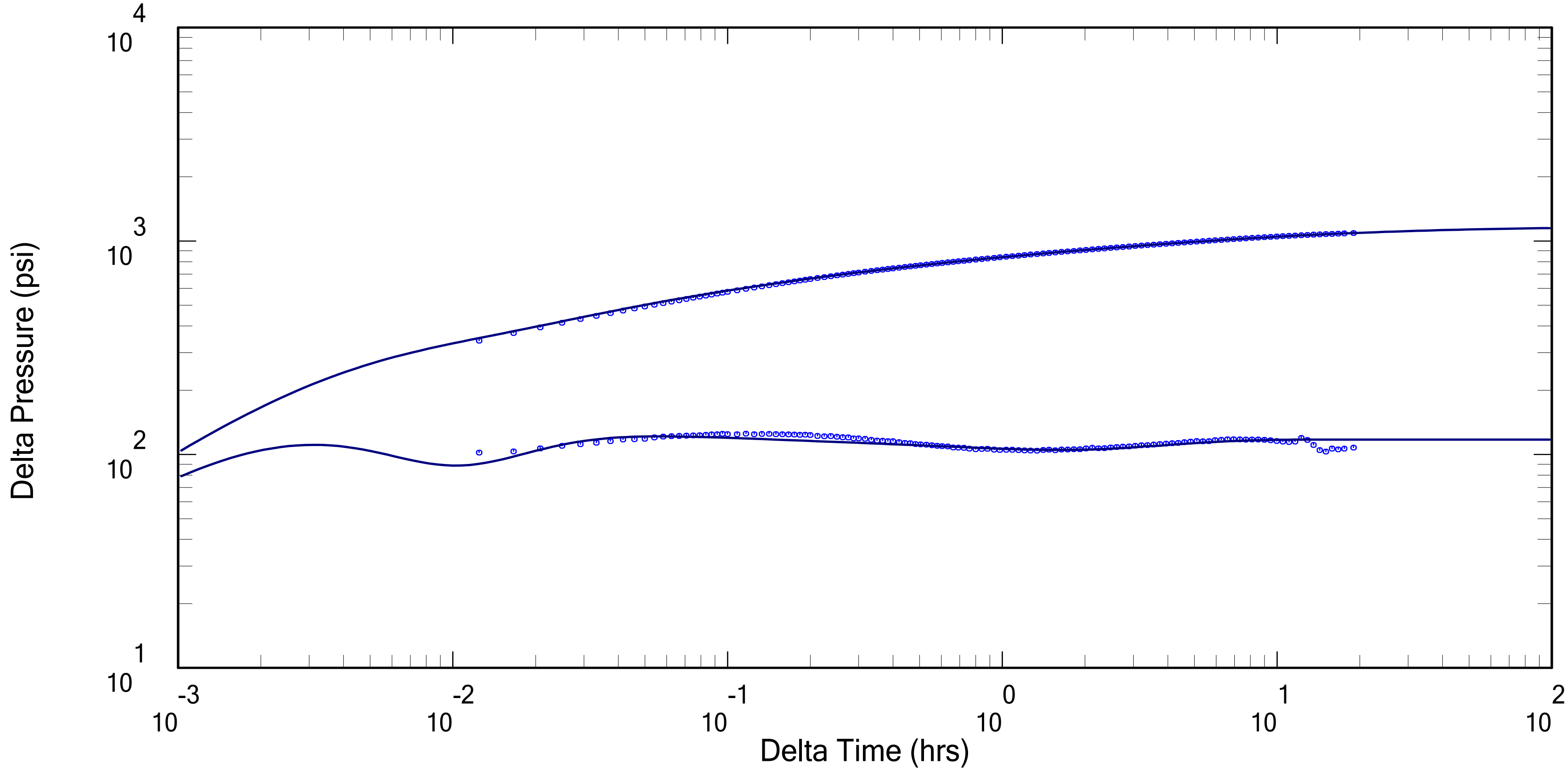
MODEL RESULTS

Constant Storage C1 : 0.002 bbl/psi	Skin Model Skin : -2.43	Homogeneous k : 12.500 md Est Pi: 2056.7 psi	No Boundaries	h : 230 ft mu : 0.663 cp phi : 9.7% ct : 6.600E-06 1/psi rw : 0.328 ft FVF : 1.00

Pressure History Simulation Plot
Long Falloff – Homogeneous Model



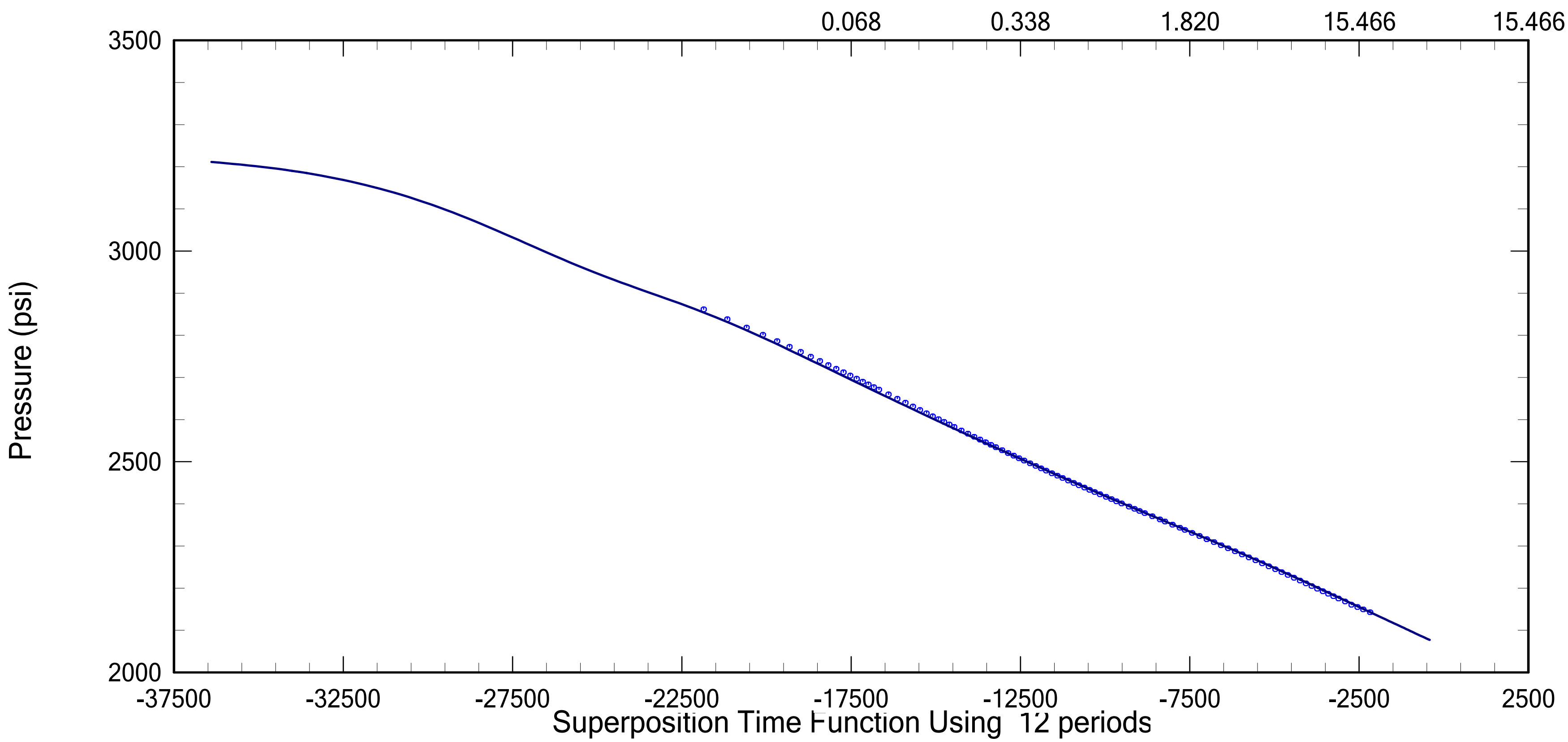
Log-log Plot
Long Falloff – 2 Porosity Model



MODEL RESULTS

Exp Function	Skin Model	2 PHI SLABS	No Boundaries	h : 230 ft
C1 : 0.002 bbl/psi	Skin : -2.45	k : 12.500 md		mu : 0.663 cp
C2 : 0.004 bbl/psi		Omega : 0.700		phi : 9.7%
COD : 1.100		Lambda: 3.000E-6		ct : 6.600E-06 1/psi
		User Pi: 2061.5 psi		rw : 0.328 ft
				FVF : 1.00

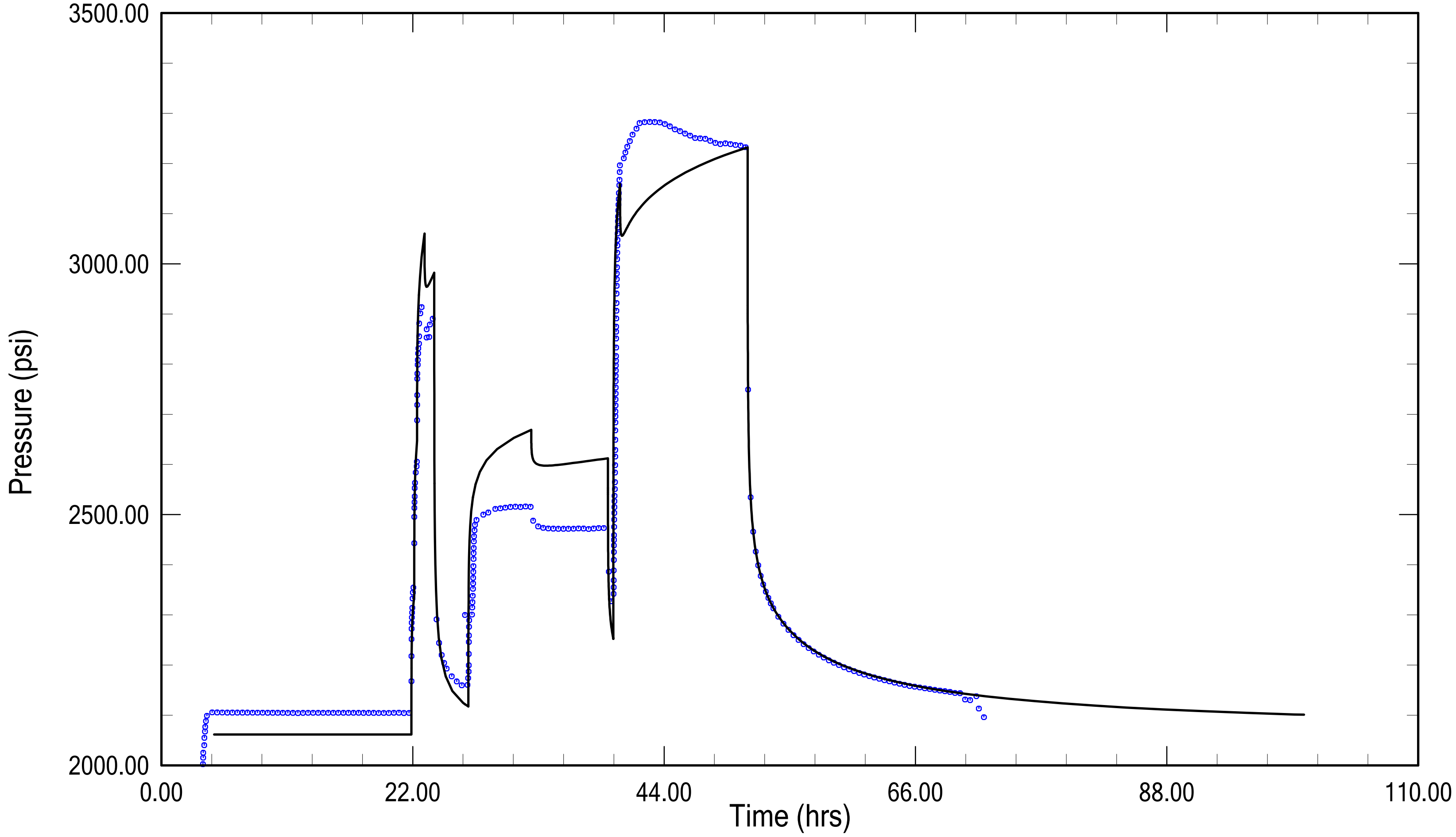
Semi-log Plot
Long Falloff – 2 Porosity Model



MODEL RESULTS

Exp Function	Skin Model	2 PHI SLABS	No Boundaries	h : 230 ft
C1 : 0.002 bbl/psi	Skin : -2.45	k : 12.500 md		mu : 0.663 cp
C2 : 0.004 bbl/psi		Omega : 0.700		phi : 9.7%
COD : 1.100		Lambda: 3.000E-6		ct : 6.600E-06 1/psi
		User Pi: 2061.5 psi		rw : 0.328 ft
				FVF : 1.00

Pressure History Simulation Plot
Long Falloff – 2 Porosity Model



Appendix 3

3D Vertical Seismic Profile Reports

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Appendix 3A

KGS 3D VSP Modelling: 3D Illumination

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SR2020 Inc.

See Your Reservoir in HD™

KGS 3D VSP Modeling

3D Illumination Modeling

July 26th 2010

Basic survey information

- Client: *KGS*
- Client Rep:
- Field: *Marvin* Area:
- Survey dates: *August 15-25 2010 tentative*
- Seismic datum : *500 ft AMSL*
- Well name: *Blan 1*
- Surface source line interval: *75 ft*
- Number of shot points modeled: *1022*
- Maximum Horizontal offsets: *1400 ft*
- Target Depth*: 5000 ft*
- Receiver array: *81 levels at 25 ft spacing*
- Receiver depths (Depths below datum): *3000-5000 ft*

3D VSP Pre-Survey Modeling

- Velocity model building is conducted using existing VSP velocities for a 1D stratigraphy
- The current modeling examines the effect of an 80 level receiver array with 25ft spacing.
- Bottom receiver is positioned slightly above at target depths so a direct (depth-time) tie can be achieved during the survey
- Sources are located with maximum offsets of ~2700ft (SW corner)
- Target illumination horizon is at 5000 ft

1D velocity model

- The client has provided a VSP report For the Blan 1 well in pdf format
- No numeric velocity values were given
- 1D velocity function was obtained after rough digitizing of figure 3.5 from the report
- Only major layers were digitized
- This velocity model was used as initial 1D profile for the modeling

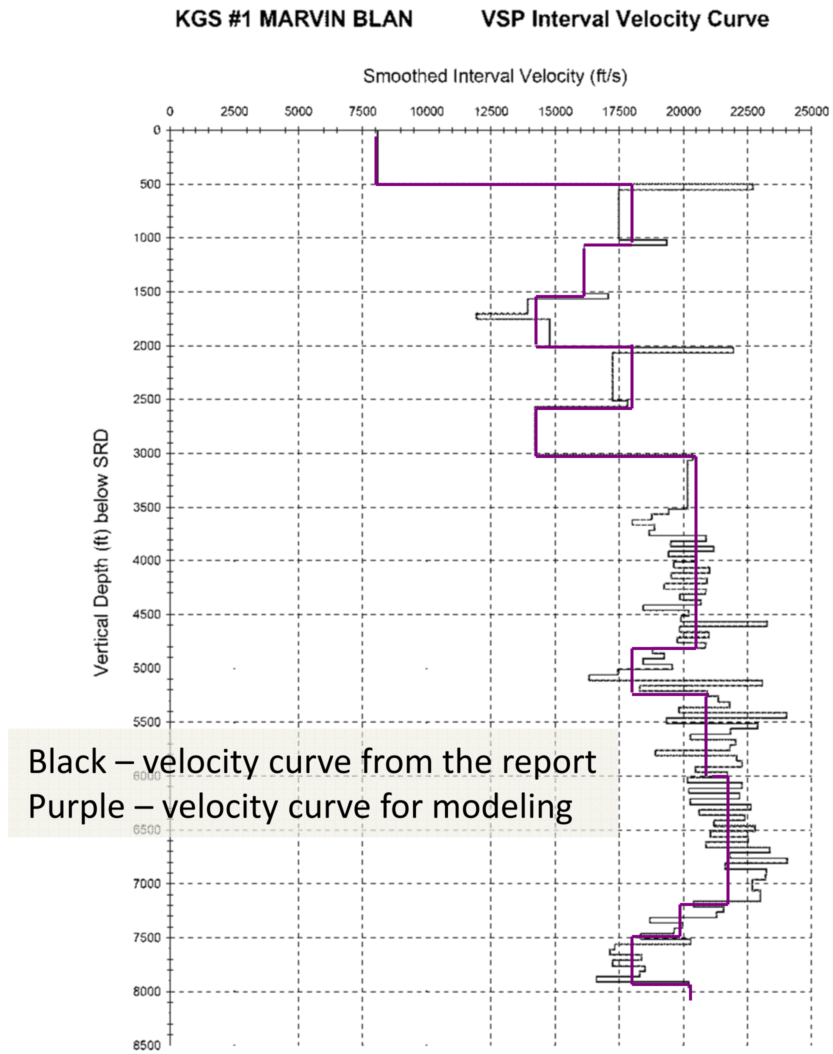
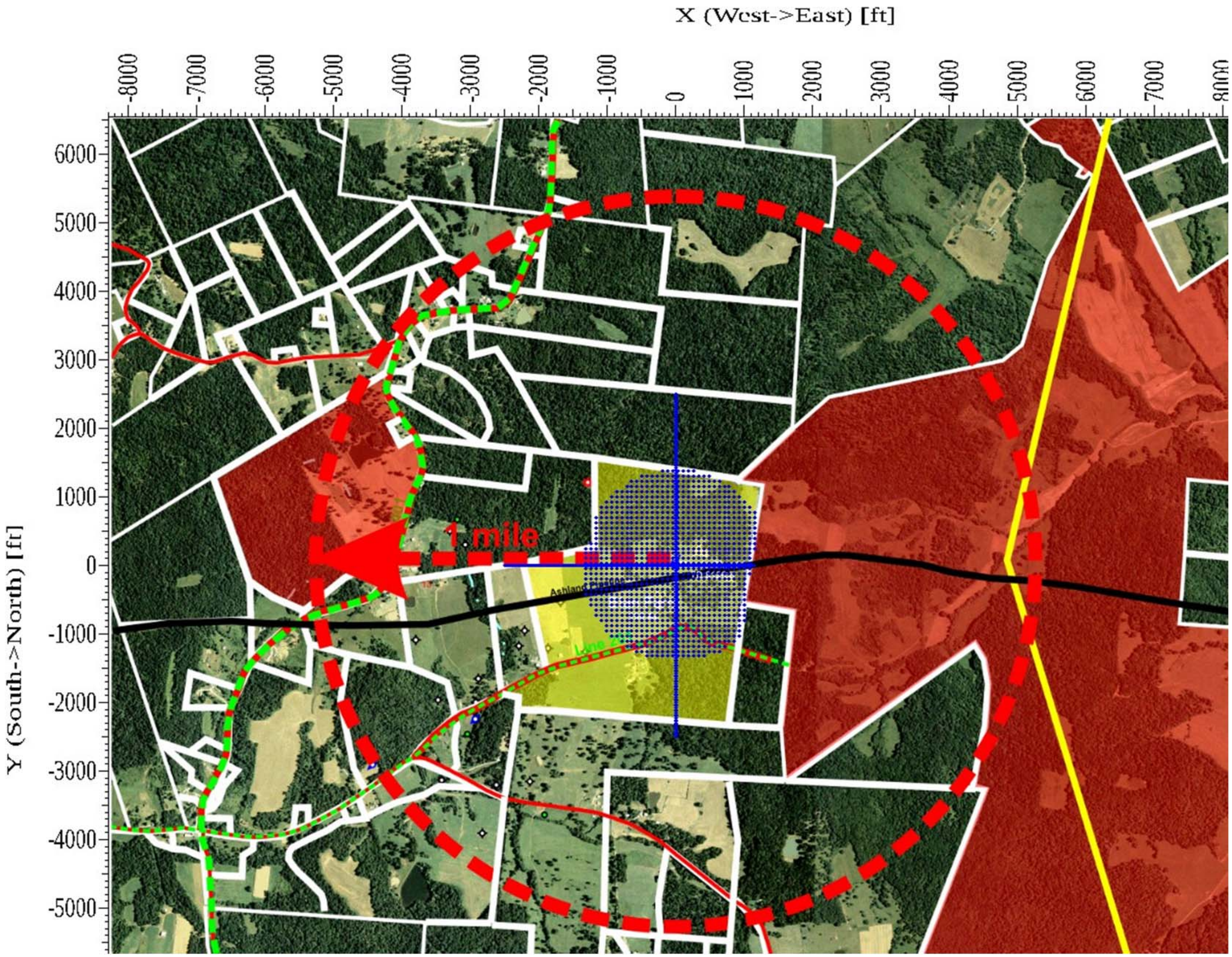


Figure 3.5

3D Source Spacing Effects

- A regular spaced grid with maximum offset of 1400 ft was analyzed
- The grid itself was not regular however. Deeply forested area does not allow for a regular grid. Only shots located in a wide open are could be used during acquisition, and therefore only those shot points were modeled
- Also two 2D lines were suggested:
  - NS line at 25 ft spacing with maximum offset of 2500 ft
  - EW line at 25 ft spacing with maximum offset of 2500 ft to the West and 1325 ft offset to the East

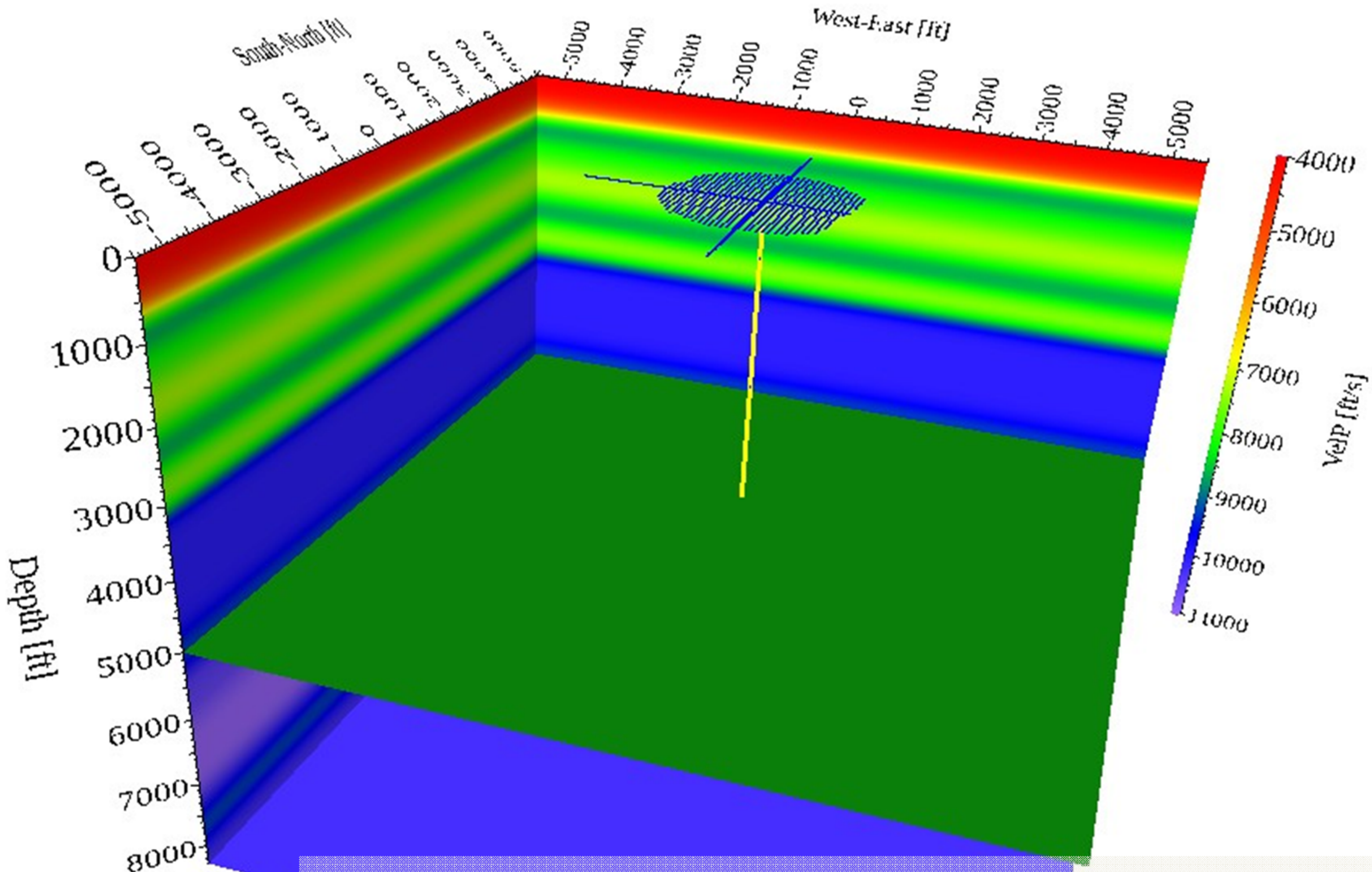
Shot Points Lay Out



3D map:
75 ft spacing,
1022 shots

2D lines:
25 ft spacing,
146 shots (EW)
201 shots (NS)

3D view of the survey, target horizon and 3D model

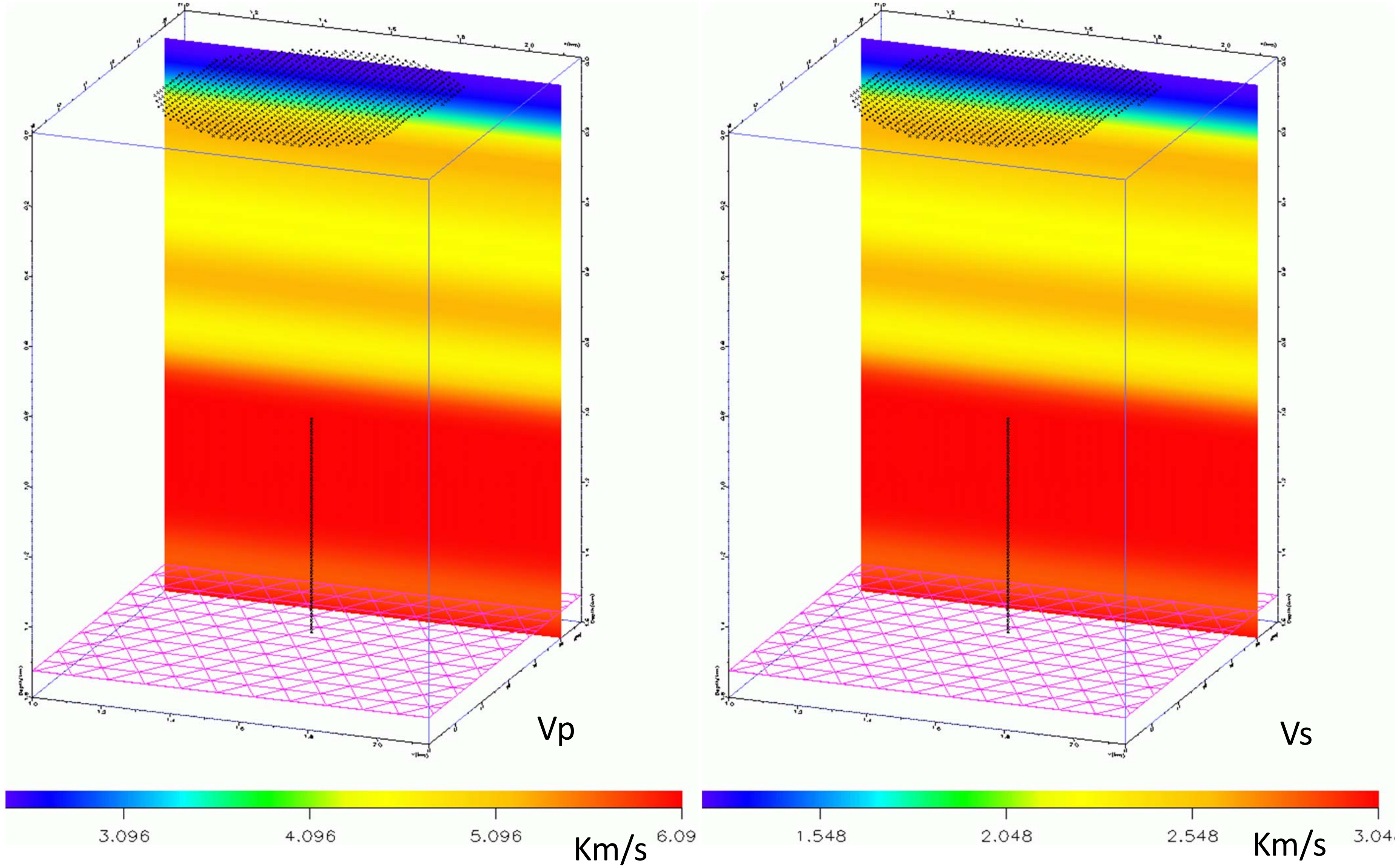


1D velocity function was smoothed over 350 ft to satisfy 3D Norsar requirement. The it was extrapolated into a 3D cube. A flat horizon at 5000 ft was used as a illumination target

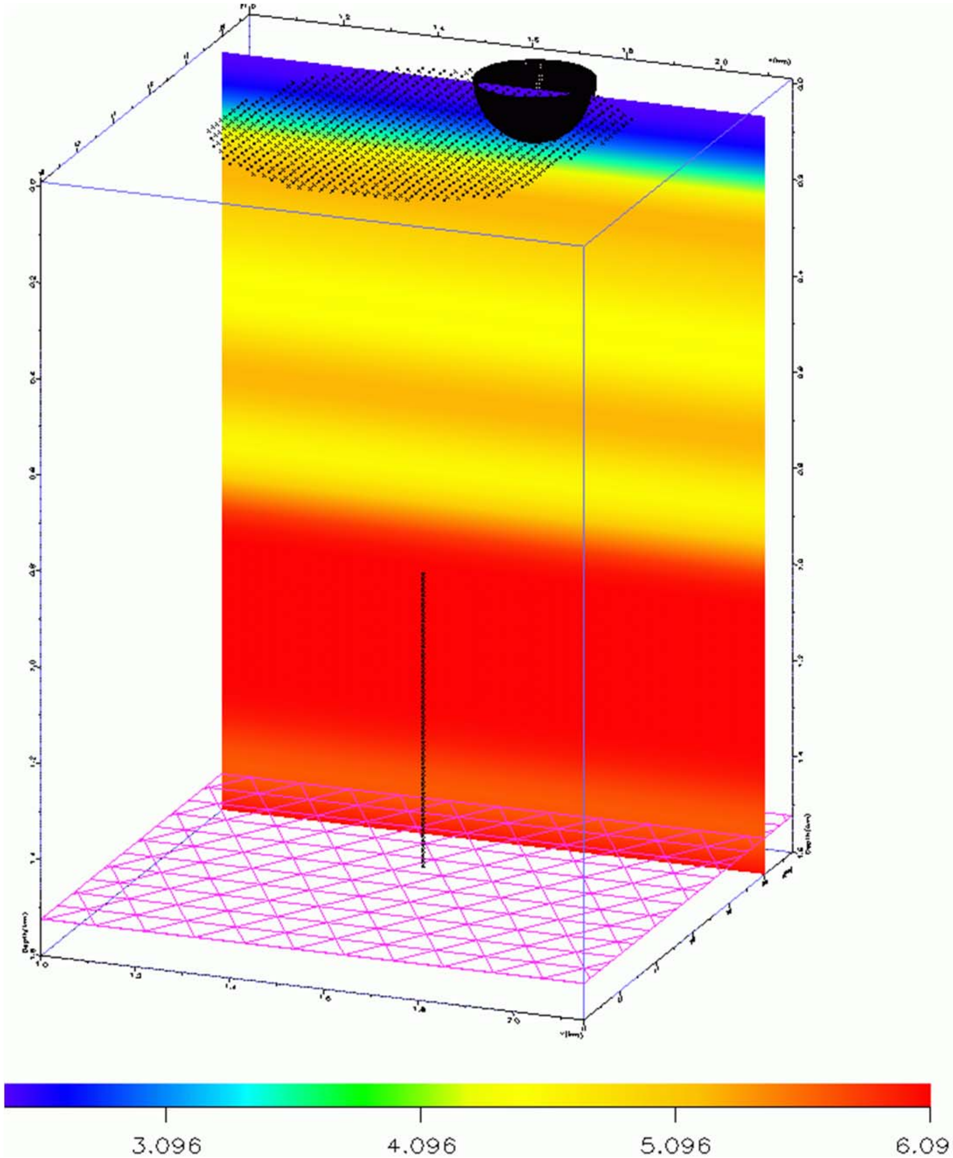
NORSAR 3D Illumination Ray Tracing

- NORSAR 3D modeling software is used for illumination ray tracing
- The ray tracing is conducted using the wavefront construction method
- For ray-tracing stability the velocity model was previously smoothed in the vertical direction over 350 ft
- To perform ray-tracing more rapidly, the receiver array was used as the sources and the source array was used for the receivers

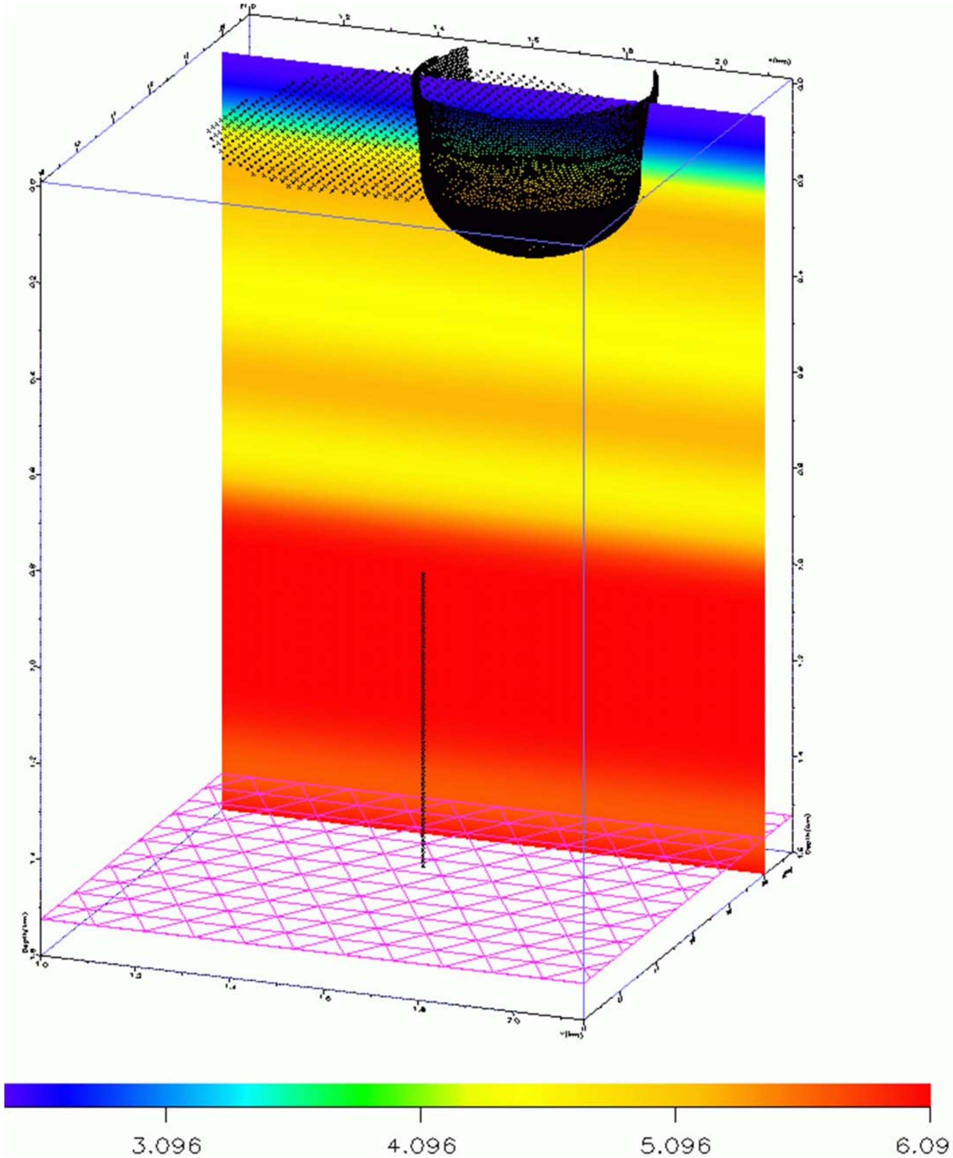
3D velocity model and survey geometry import in Norsar



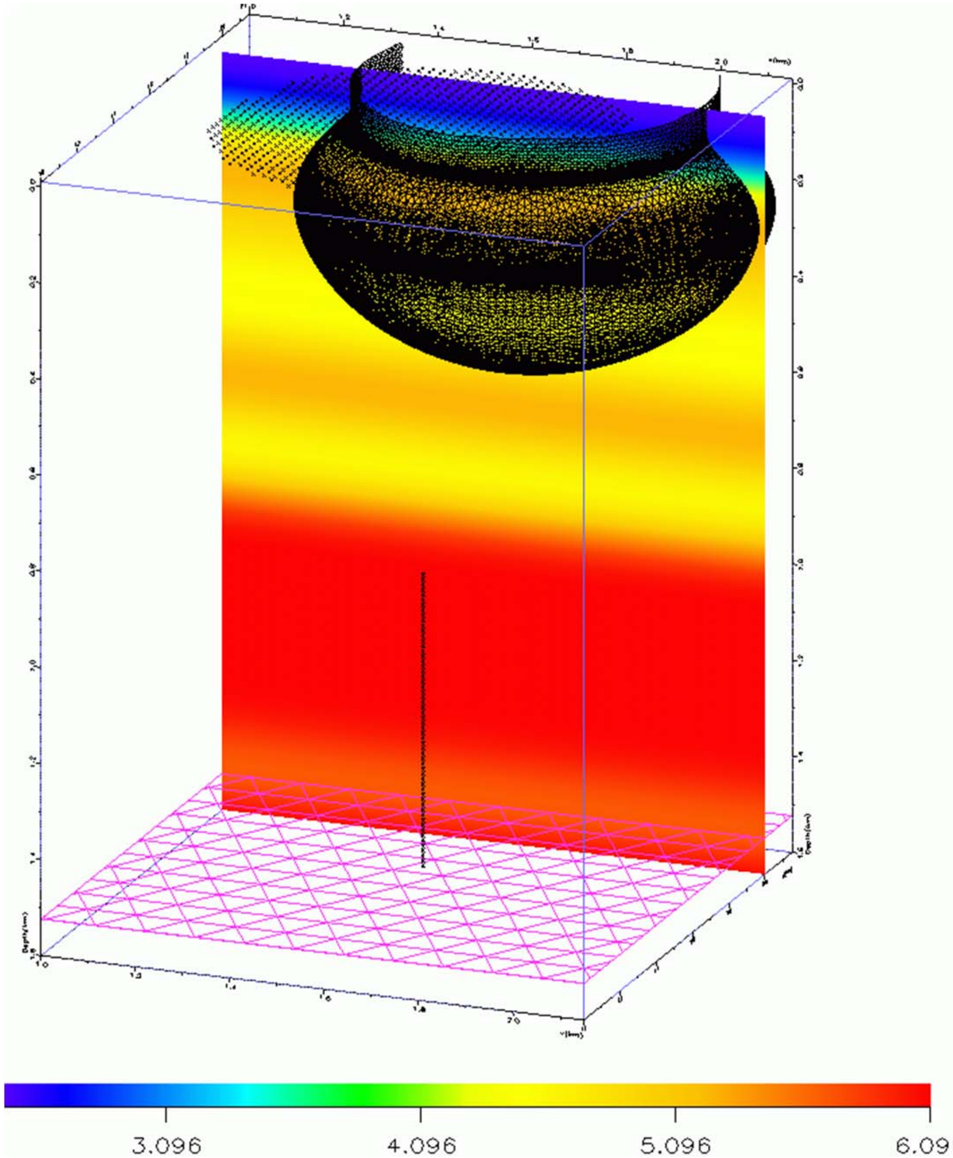
Wavefront tracing trough the model



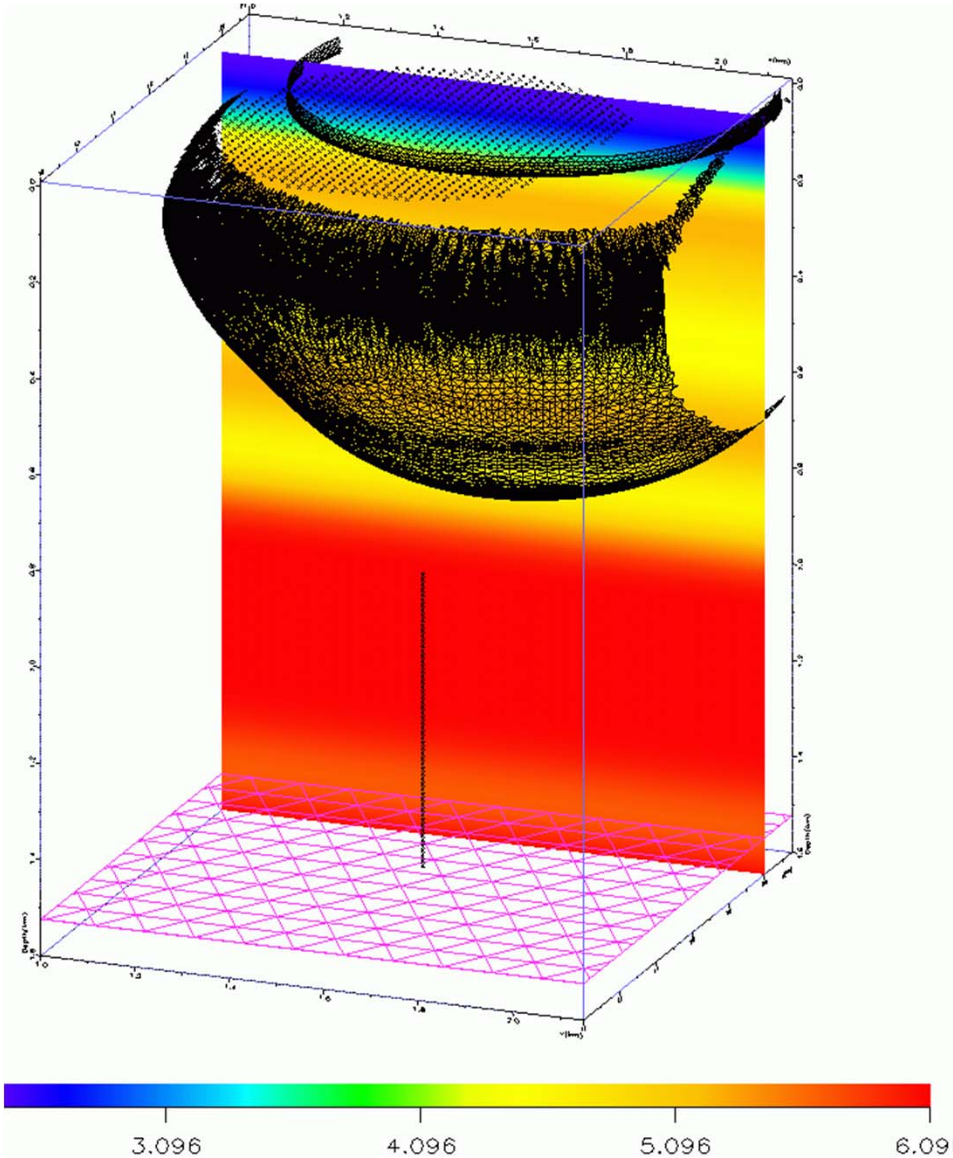
Wavefront tracing trough the model



Wavefront tracing trough the model



Wavefront tracing trough the model



NORSAR 3D Illumination Ray Tracing

- Ray tracing provides several different reflection attributes on the target horizon
- The most important of these reflection attributes are the hitcount, which is a measure of the fold, and the angular aperture, which indicates the range of angles available for illuminating a particular bin position

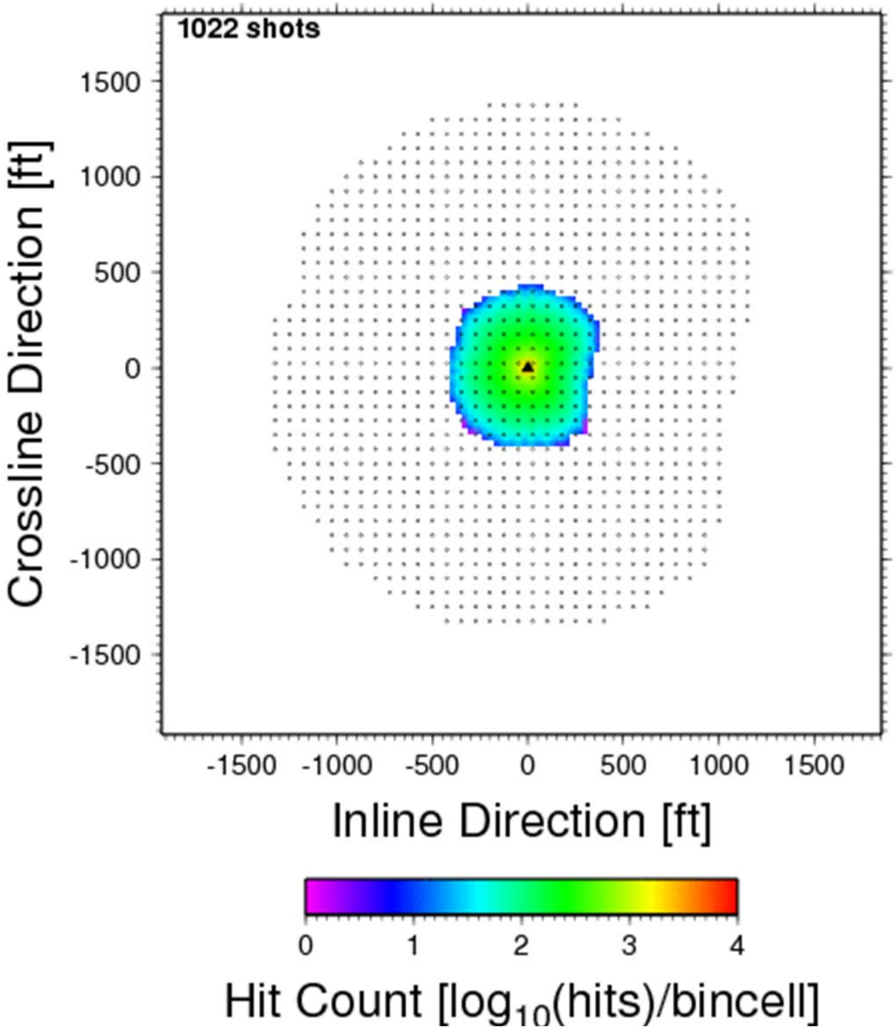
Illumination Attributes

- Hit Count maps indicate the area where reflections from the survey geometry would be available. The logarithmic scale indicates the number of hits that are available at each bin location.

- Angular Aperture is a determining factor on the final image quality. For better resolution in the image a wide range of angles, arriving at a particular reflection point, is required for proper stacking of the information. Wider angular apertures are indicative of a robust survey that will provide a wide range of angles.

Hit count on target horizon. PP waves

Illumination includes all reflections in the data including supercritical ones.

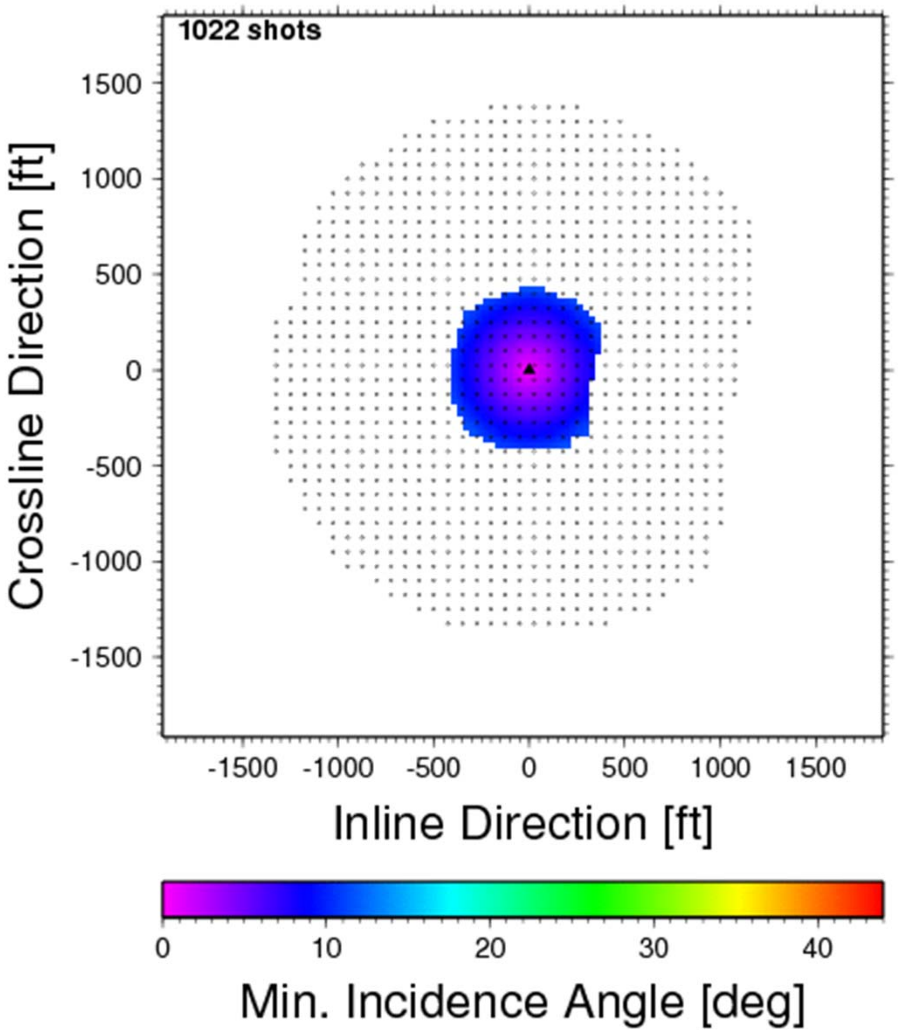


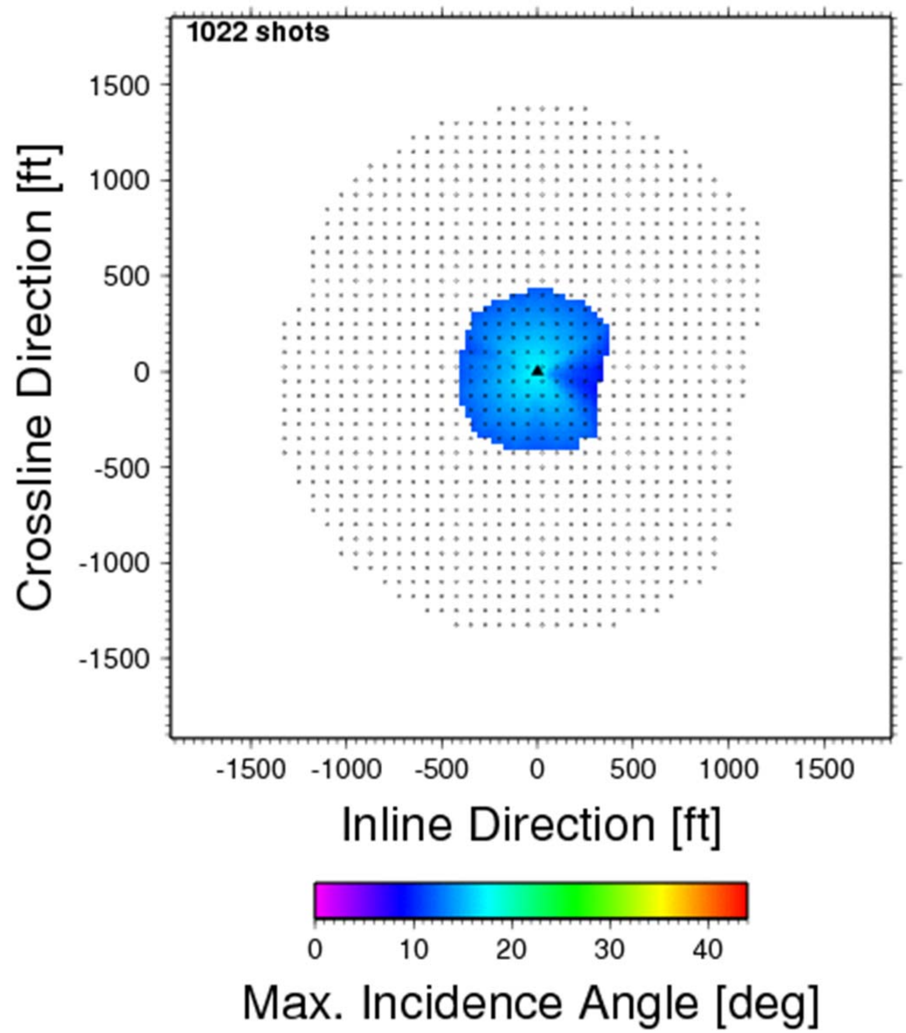
Triangle is location of the Blan1
Dots are 3DVSP sources

The fold is decreasing with the offset

Maximum image offset is ~400 ft due to target depth of ~4200 ft and max offset of ~1400 ft

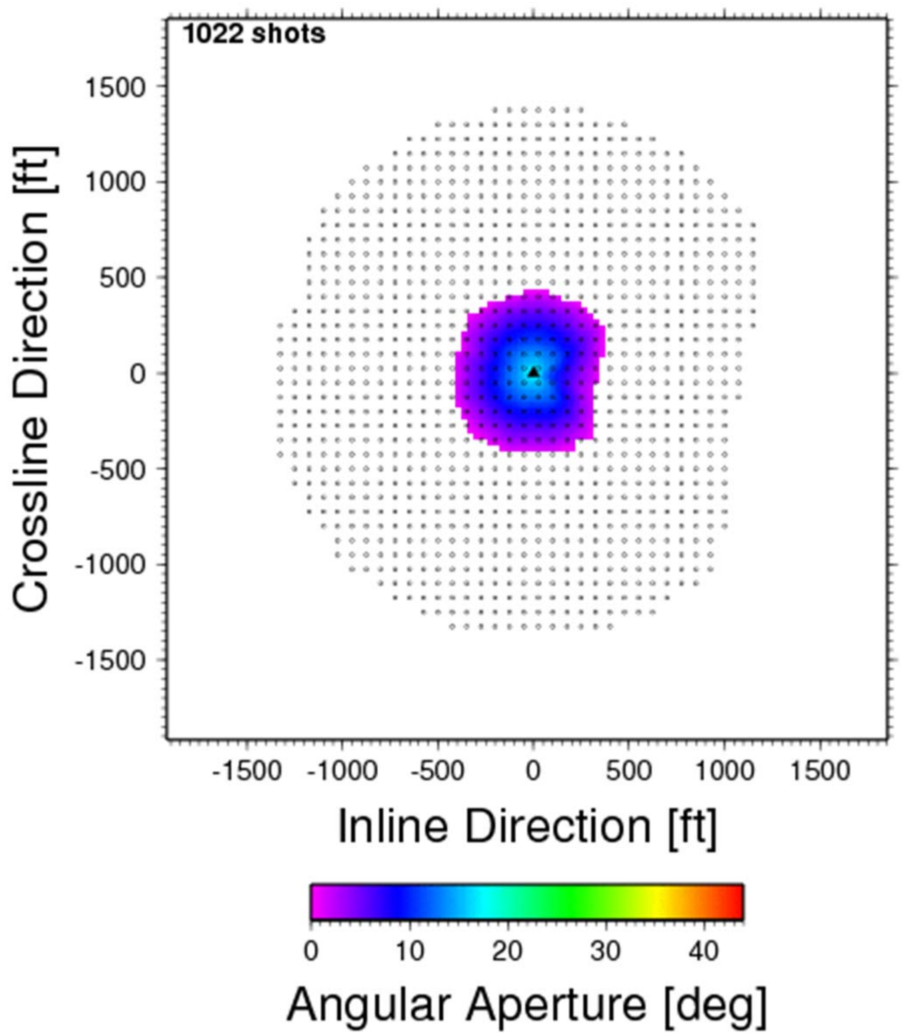
Min and Max incidence angle on target horizon. PP waves





Due to small offsets comparably to target depth, angular aperture is narrow

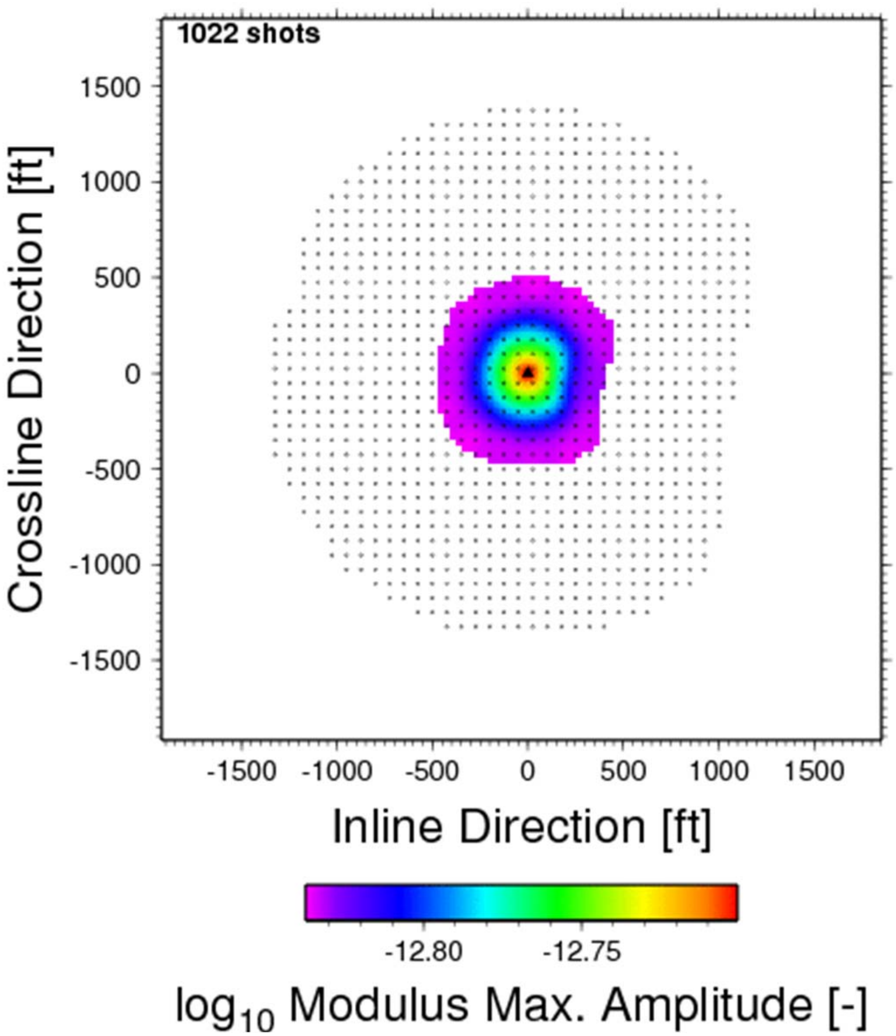
Angular Aperture on target horizon. PP waves



The image beyond 45 degree max incidence angle contour is subject to supercritical reflections, lower fold and potential wavelet distortion.

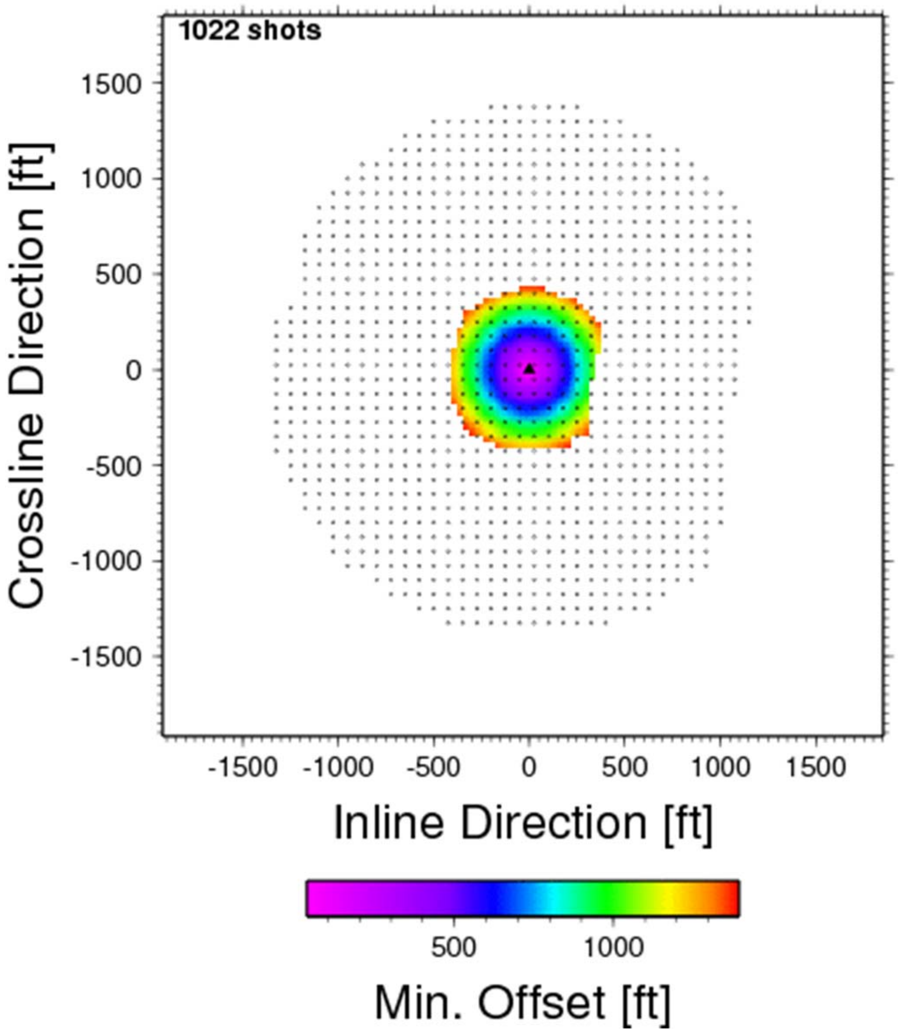
Due to small offsets again, no supercritical reflections are expected

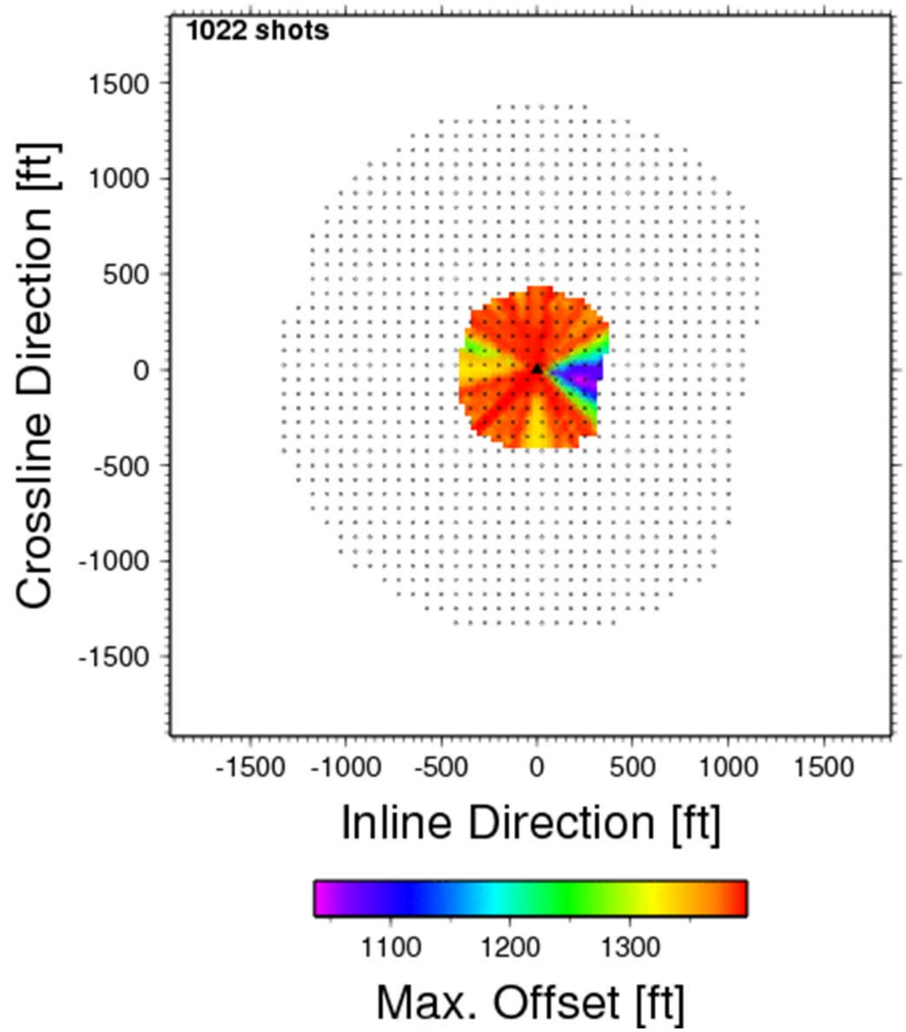
Amplitude Modules on target horizon. PP waves



Amplitudes are decreasing with offset

Min and Max offset on target horizon. PP waves

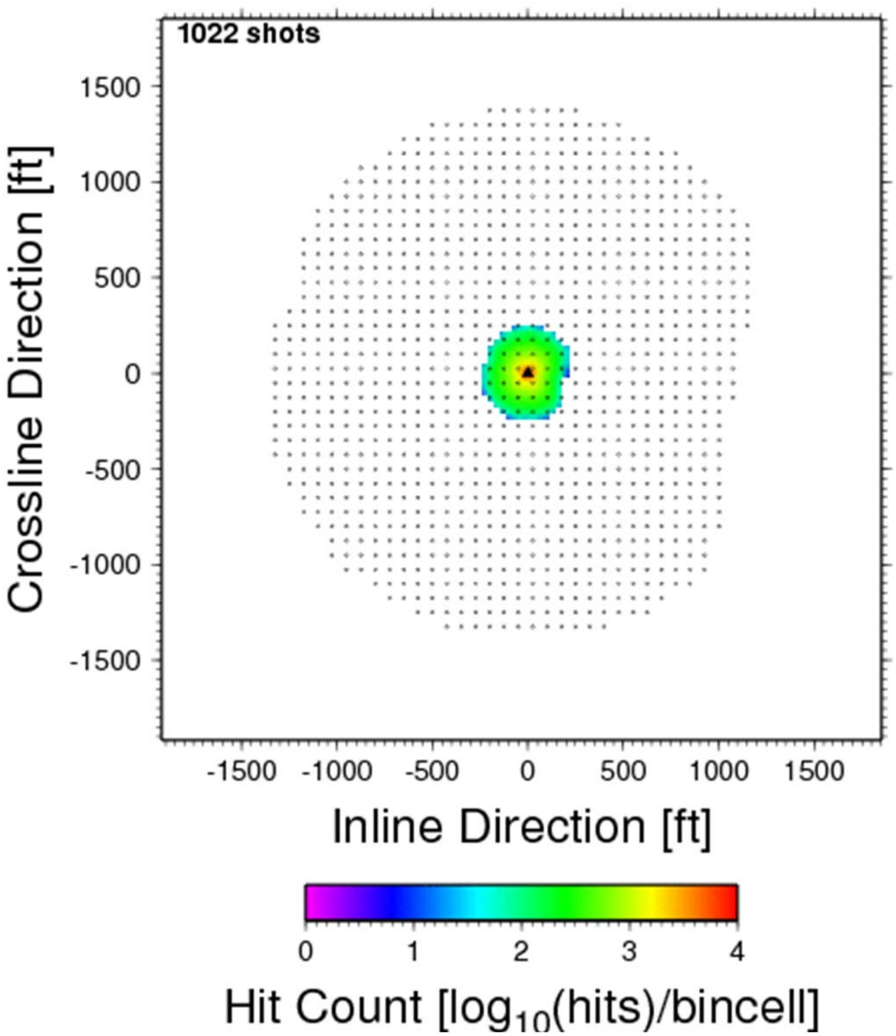




All offsets are contributing to the map

Hit count on target horizon. PS waves

Illumination includes all reflections in the data including supercritical ones.

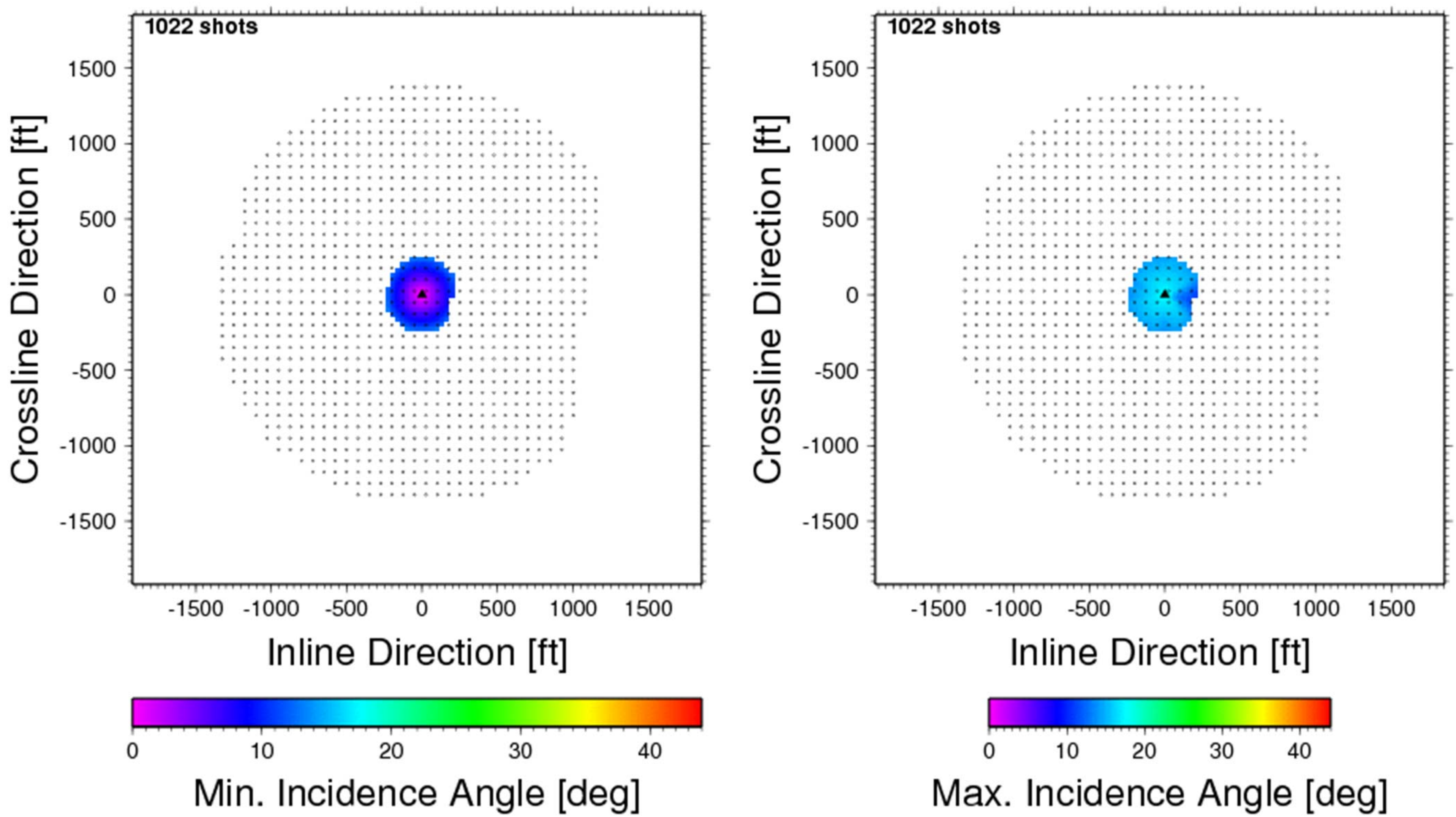


Triangle is location of the Blan 1
Dots are 3DVSP sources

The fold is decreasing with the offset

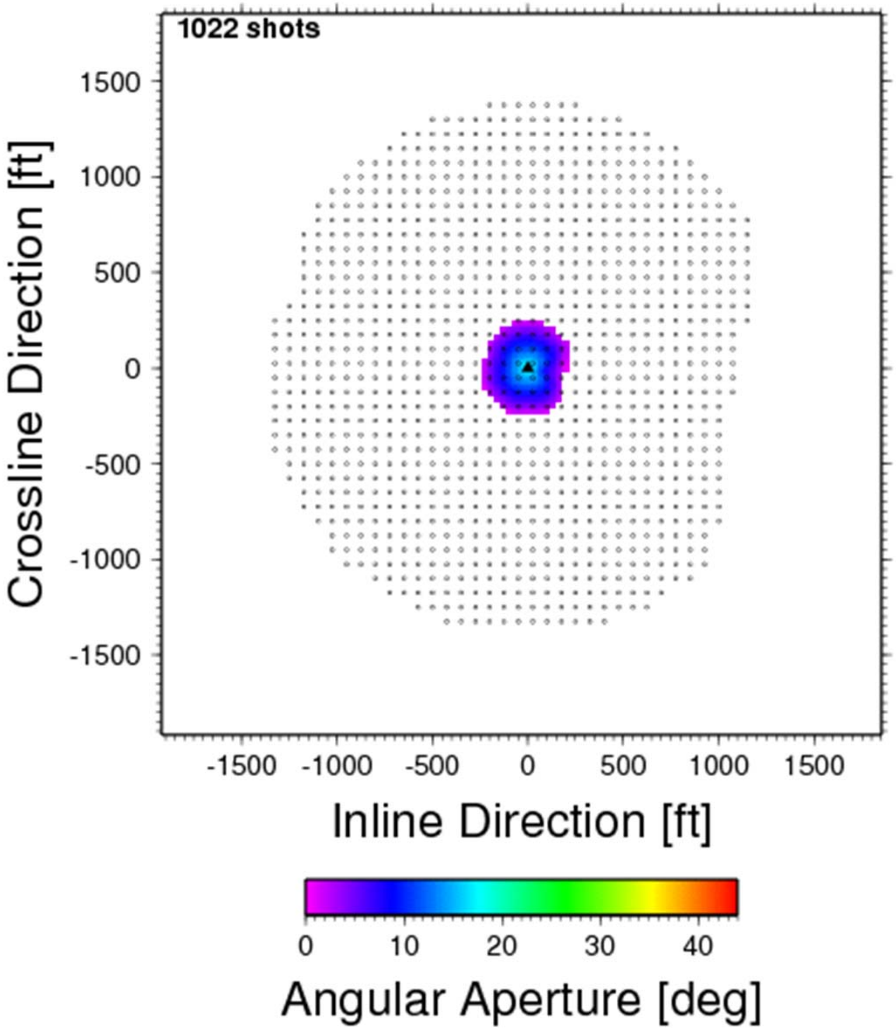
Maximum image offset is ft 250 ft due to target depth of ~4200 ft and max offset of ~1400 ft

Min and Max incidence angle on target horizon. PS waves



Due to small offsets comparably to target depth, angular aperture is narrow

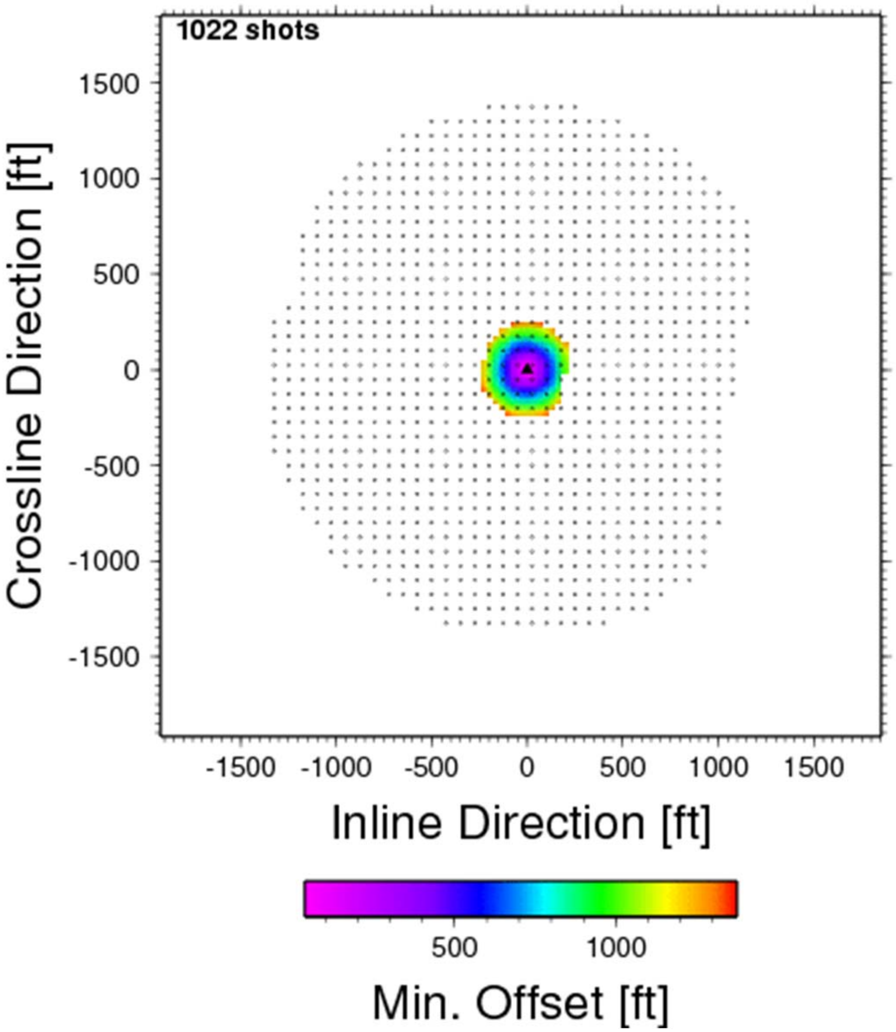
Angular Aperture on target horizon. PS waves

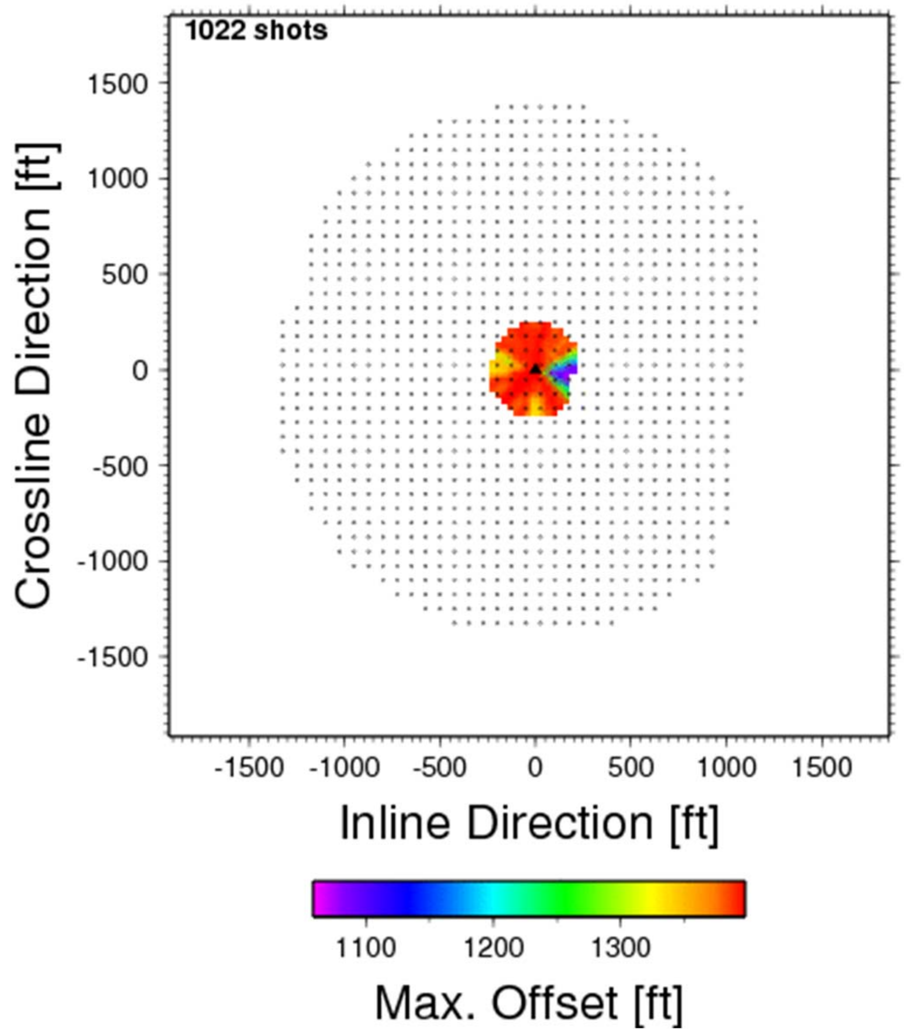


The image beyond 45 degree max incidence angle contour is subject to supercritical reflections, lower fold and potential wavelet distortion

Angular aperture is very narrow

Min and Max offset on target horizon. PS waves





All offsets are contributing to the map

Image Diameter and Fold

- Given that the target horizon is flat and velocity model is in general smooth, the image diameter is about 400 feet including areas with low fold (hit count)
- High contrasts in velocity and variations in topography and target horizons will alter the image extend
- Mode dense source grid would provide higher fold
- Bigger offsets might be suggested to increase the image size and to increase high fold areas diameter

Summary Remarks

- Velocity changes in the field at some depths and it would be preferable to place the receivers in such a fashion that they capture these changes. The longest the VSP array the more optimal the velocity control will be.

- Going closer to the target provides a wider angular coverage and the quality of the image would be enhanced.

- The velocity model exhibits significant changes that cause significant bending of the rays. The ray-bending effectively would reduce the illuminated area. These changes in velocity associated to high velocity layers control the wave kinematics and guide the image's final diameter of illumination.

- Maximum source offsets were modeled out to 1,400 ft
  - If the source offset was to decrease there would be a decrease on image radius

Appendix 3B

3D VSP Shotpoint Map

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NodeID	Northing	Easting	Elevation	Description
1	2172108.08	1367116.23	622.79	BSIGPSOPUSPOINT
9	2173050.78	1367589.50	619.42	EXISTINGWELL
5010	2172647.77	1366425.74	630.40	10,,
5011	2172656.47	1366475.68	630.46	11,,
5012	2172664.81	1366524.32	629.06	12,,
5013	2172673.51	1366574.41	626.05	13,,
5014	2172681.87	1366623.07	622.93	14,,
5015	2172690.22	1366671.81	619.08	15,,
5016	2172698.82	1366721.37	616.09	16,,
5017	2172707.72	1366771.28	614.40	17,,
5018	2172716.53	1366820.87	613.40	18,,
5019	2172725.13	1366869.47	611.78	19,,
5020	2172733.87	1366919.64	610.45	20,,
5021	2172742.34	1366968.81	610.12	21,,
5022	2172750.96	1367017.48	609.90	22,,
5023	2172759.09	1367067.31	611.14	23,,
5024	2172767.42	1367115.66	612.54	24,,
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

NOTE: 5,000 WAS ADDED TO THE POINT NUMBERS STAKED IN THE FIELD FOR THE ELEVATION POINTS ON THE GRID. SO POINT #64 STAKED IN THE FIELD IS THE SAME AS POINT #5064 SHOWN HEREON.

NOTES:

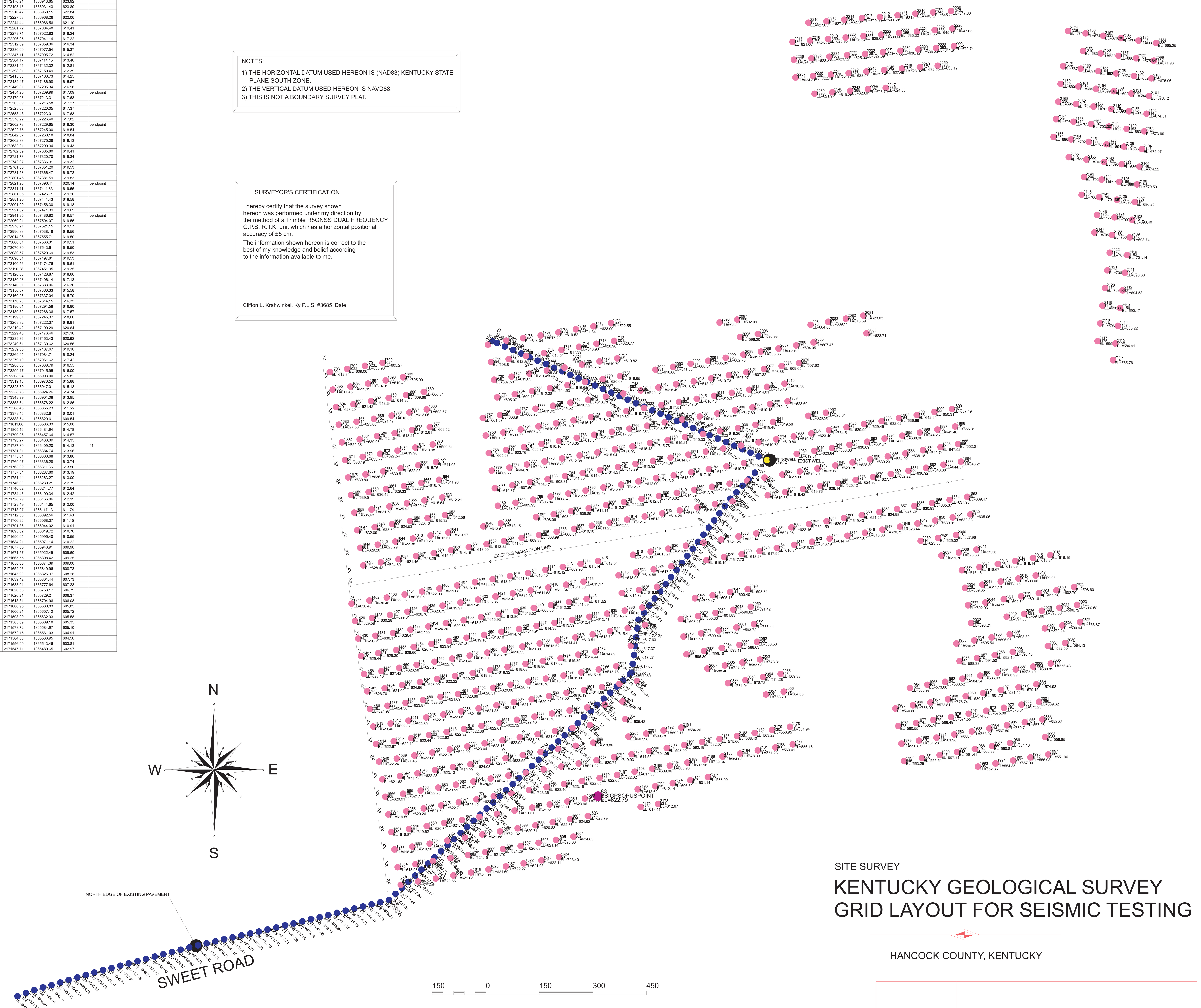
1) THE HORIZONTAL DATUM USED HEREON IS (NAD83) KENTUCKY STATE PLANE SOUTH ZONE.
2) THE VERTICAL DATUM USED HEREON IS NAVD88.
3) THIS IS NOT A BOUNDARY SURVEY PLAT.

SURVEYOR'S CERTIFICATION

I hereby certify that the survey shown hereon was performed under my direction by the method of a Trimble R8GNSS DUAL FREQUENCY G.P.S. R.T.K. unit which has a horizontal positional accuracy of ±5 cm.

The information shown hereon is correct to the best of my knowledge and belief according to the information available to me.

Clifton L. Krahwinkel, Ky P.L.S. #3685 Date



SITE SURVEY

KENTUCKY GEOLOGICAL SURVEY GRID LAYOUT FOR SEISMIC TESTING

HANCOCK COUNTY, KENTUCKY

BransonSurveys,inc.

330SECONDST.,HENDERSON,KY 42420

REVISIONS	FIELD:9-1-10	SCALE:1"=150'	DWGNAME:KGSHANCOCK
	PLAT:9-9-10		DRAWINGBY: CLK

ORDERED BY: KENTUCKY GEOLOGICAL SURVEY, UNIVERSITY OF KENTUCKY

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Appendix 3C

Processing Report For Kentucky Geological Survey Blan#1

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Processing Report

For

Kentucky Geological Survey
Blan#1

November, 2010

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Brea, CA 92821
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Author: Xiaoli Yang
Geophysicist

Reviewed by: Martin Karrenbach, Ph.D.
Sr. Vice President

Disclaimer

SR2020 Inc. cannot and will not guarantee a certain outcome in the enclosed report. There are many factors that affect the processing of the data and the quality of the images that are outside SR2020's control. Examples of these factors include the quality of the input model the velocity information, and geological and velocity complexities. All processing is performed on a reasonable commercial effort basis only. However, SR2020 will perform the processing to our highest professional standards, which we believe meet or exceed the industry processing standards.

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CONTENTS

LIST OF FIGURES

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Executive Summary

SR2020 recorded a time-lapse 3D VSP for the CO2 injection project in Blan1 well as part of the DOE Grant #3048107146 entitled "An Evaluation of the Carbon Sequestration Potential of the Cambro-Ordovician Strata of the Illinois and Michigan Basins". SR2020's main partner was the Kentucky Geological Survey which designed and carried out CO2 injectability tests in the Blan1 well. The seismic borehole data acquisition was carried out before and after injection period.

During the pre-survey modeling a full areal source layout and a dense receiver array was designed for best capturing the small subsurface changes due to the CO2 injection. However, due to permitting, accessibility issues and deployment in cased hole only sections of the well, the acquired data set was sparser than desired. The source layout shows large patches of inaccessible areas while the receiver array was approximately 1000 ft above the injection zone. So illumination at the injection level is not uniform and only a few lines well sampled offsets exist. The velocity model below the deepest receiver had to be incorporated from prior surveys and well logs. Thus, no independent before and after VSP measurement exists at that depth level coincident with the injection test.

The velocity model was estimated on Baseline and Monitor survey from near offset shots. Slight overburden variations exist and are caused most likely by different noise conditions between the time-lapse surveys. The local 3D model around well fits the 3D direct arrival times from the areal source pattern very well. Source static variations were estimated from the averaged differences of pick versus computed arrival times. Generally the statics variations and statics difference variations are small except for some source locations located at the outer edge of the source pattern. Although the proper statics compensations have been applied those source locations can still anomalous due to different source coupling or other environmental factors that changed between the two surveys.

Baseline and Monitor survey processed identically using the same noise suppression, as well as deconvolution parameters and wave field separation parameters. Electrical noise trains were removed from raw data gathers by a multichannel adaptive filter on both data sets. The deconvolution recovered the expected source spectrum. Separation extracted the up-going wave field, subsequent radon filtering suppressed the converted waves and enhanced the up-going P-waves.

Depth migration in an accurate velocity model emphasizes consistent signals and reduces random or incoherent noise. Pre-stack depth migration was carried out in the overburden and injection zone. In order to maintain consistent illumination, only source locations that exist in both baseline and monitor survey are processed and imaged. However, the imaging capability is limited due to limited accessibility resulting in a limited coverage area, as well as limited repeatability due to varying noise conditions at the well site. The time-lapse analysis concentrated on depth migrated image volumes, due to the increased signal to noise ratio. A RMS amplitude scaling factor was to be applied before differencing the images. Characteristic changes are visible below 5000 ft depth correlating to the injection zone. However, due to the limited coverage the exact outline is difficult to interpret. Based on the adaptive subtraction, most changes seem to occur near the well and in the North-East direction.

1 Introduction

KGS lead a research effort for CO2 sequestration and performed a CO2 injection test in the Blan1 well. SR2020 collected a 3DVSP immediately before and after the injection period.

The following summary report outlines the processing steps to achieve the velocity model estimation and imaging performed to obtain time-lapse images. All processing results were presented to the client in the form of PowerPoint presentations and digital data files. Displays in this report represent an exemplary subset of the material already presented. For more detailed information, the PowerPoint presentations and digital files are listed in the appendix and are attached to this report.

2 Summary of Survey Parameters

Field:	Kentucky Geological Survey
Area:	KY Hancock County (NAD 83)
Date of survey:	September, 2010
Data Type:	VSP
Source type:	Vibroseis
Source Parameters:	linear sweep 12-130Hz, sweep length 12 seconds
VSP well:	*Marvin Blan#1*
Well KB:	*well ground level elevation: 620.3ft relative to MSL*
Well Location:	*X=1367587.938ft, Y=2173048.083ft*
Downhole receivers:	80-level 3C
Receiver spacing:	24.98 ft
Receiver depths:	1653.28 – 3626.7ft below datum
Injection depth:	~5, 070 ft below datum
Recording sample rate:	2.0 ms / 1.0 ms
Record length:	4 sec
TimeLapse Source Points:	719

3 Data Processing

3.1 Data Input, Geometry Assignment and QC

The time-lapse borehole seismic data were acquired in September 2010 before and after the CO2 injection operation. SR2020 used information from observer logs and header entries to complete geometry assignment for the VSP. Vibroseis sources were employed for the entire VSP survey. A full range of 80 downhole receiver locations was recorded.

Figure 1 shows the planned source layout with a dense 3D VSP indicated with blue dots, and two walk-away lines to farther offsets. The red circle indicates a 1 mile radius for reference. The initial desired layout of uniform source coverage around the injection well could not be achieved due to a variety of permitting reasons (infrastructure, agricultural, ownership) and access issues in densely wooded areas. So the final acquired source layout differs substantially from the desired modeled scenario. Details of the illumination modeling and ideal survey design can be found in the previous modeling reports listed in the appendix.

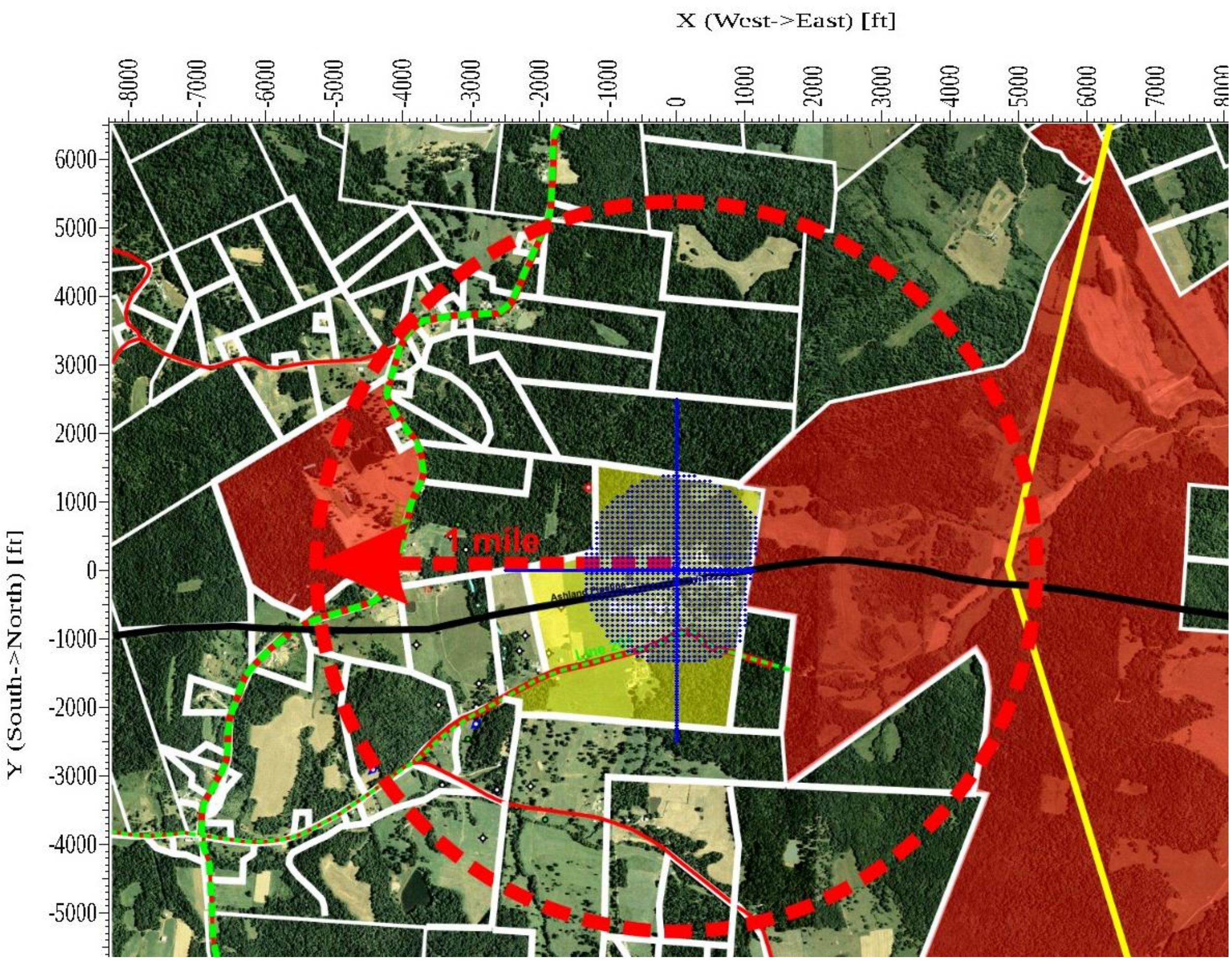

Figure 1. Areal picture of location of Blan1 well with planned source points overlay.

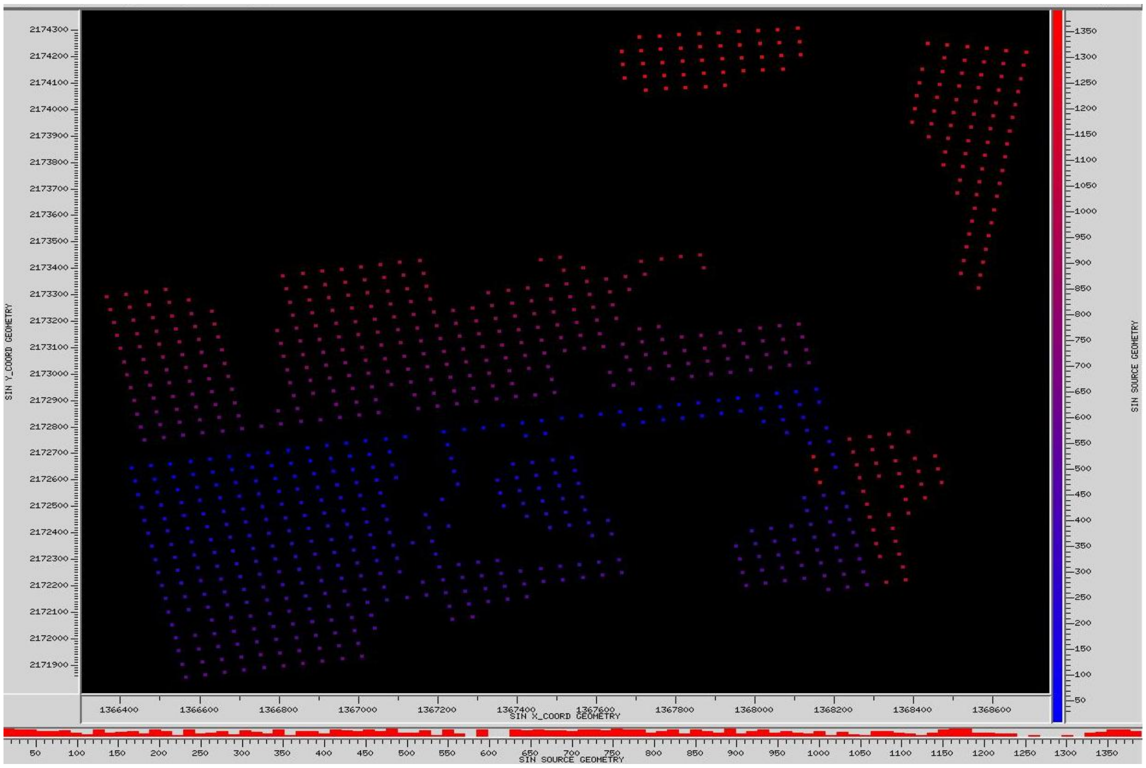

Figure 2. Baseline source map with color coded elevation.

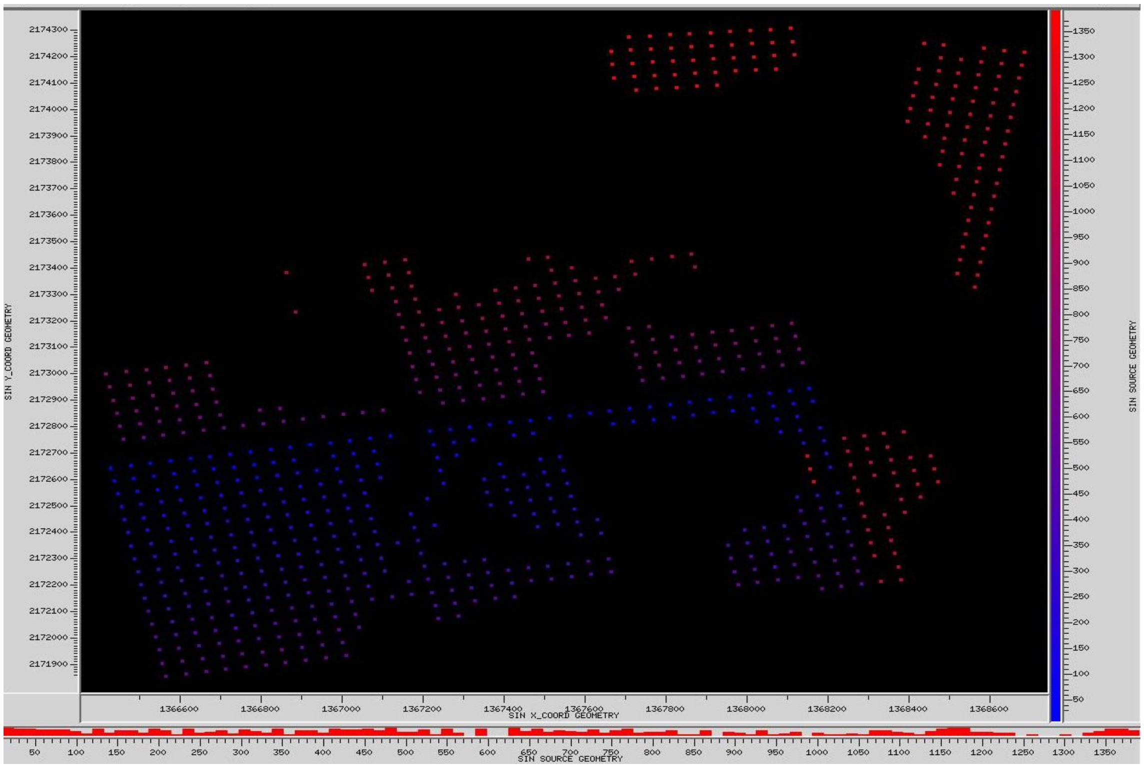

Figure 3. Monitor source map with color coded elevation.

Figure 2 and 3 show the source maps acquired for baseline and monitor survey with the elevation color coded. There are 719 source locations that were reoccupied identically in a time-lapse fashion. As is visible on the maps the only completely contiguous source recording is a line of sources extending roughly West-East following the access road traversing the well slightly to the East. Other azimuthal directions show significant missing sources at various offsets from the well, such that a full 3D image is impossible to obtain without footprint. Thus, many tests were carried out and documented in detail on the West-East line before applying it to the entire time-lapse data set.

3.2 VSP Processing Flow

The VSP data were processed starting with the raw data files and observer logs using the following main steps:

1. Data QC on Raw VSP data
2. Geometry Assignment
3. Geophone Orientation Estimation
4. Spectral Analysis
5. Standard ZO processing
6. P direct Arrival Inversion
7. ZO Velocity Profile Estimation
8. 3D Velocity Model Extrapolation
9. Deconvolution Operator Design
10. P-Reflection 3C Wave Field Separation
11. Pre-stack Depth Migration
12. Time-lapse Comparisons

Each of those steps was applied to all the VSP data and the following sections shows selected displays for each of those steps.

3.3 Raw Data Views

Figure 4 and 5 show a single shot gather of one component of the total wave field recorded at an identical source location. As can be seen, there is significant coherent and random noise present in the data. This being a relatively near offset source location a down-going tube wave can be observed. Figure 6 and 7 show similarly gathers at various offsets from the borehole. The noise level is similar for both baseline and monitor, with signal to noise ratio slightly increasing for the monitor survey. However, these noise conditions present a challenge in the further processing, where the aim is to enhance the up-going target time-lapse signal.

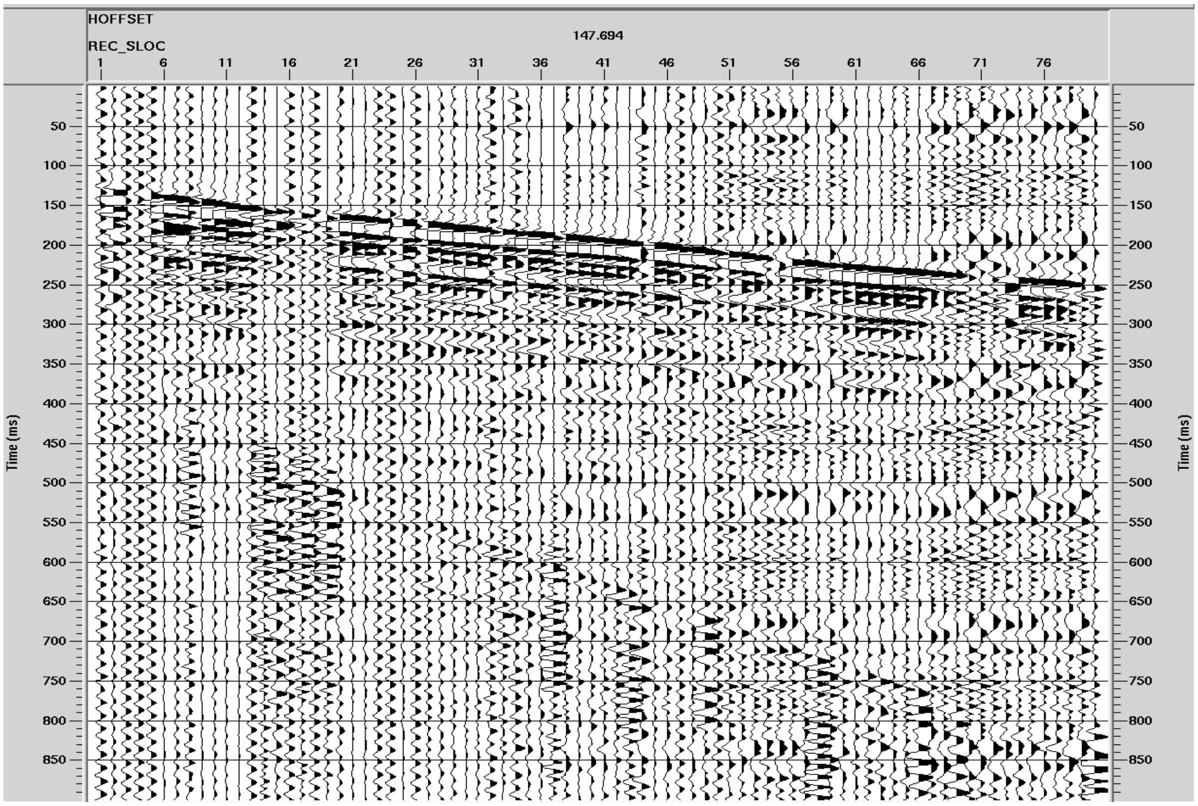

Figure 4. Baseline data exhibits electrical noise influence.

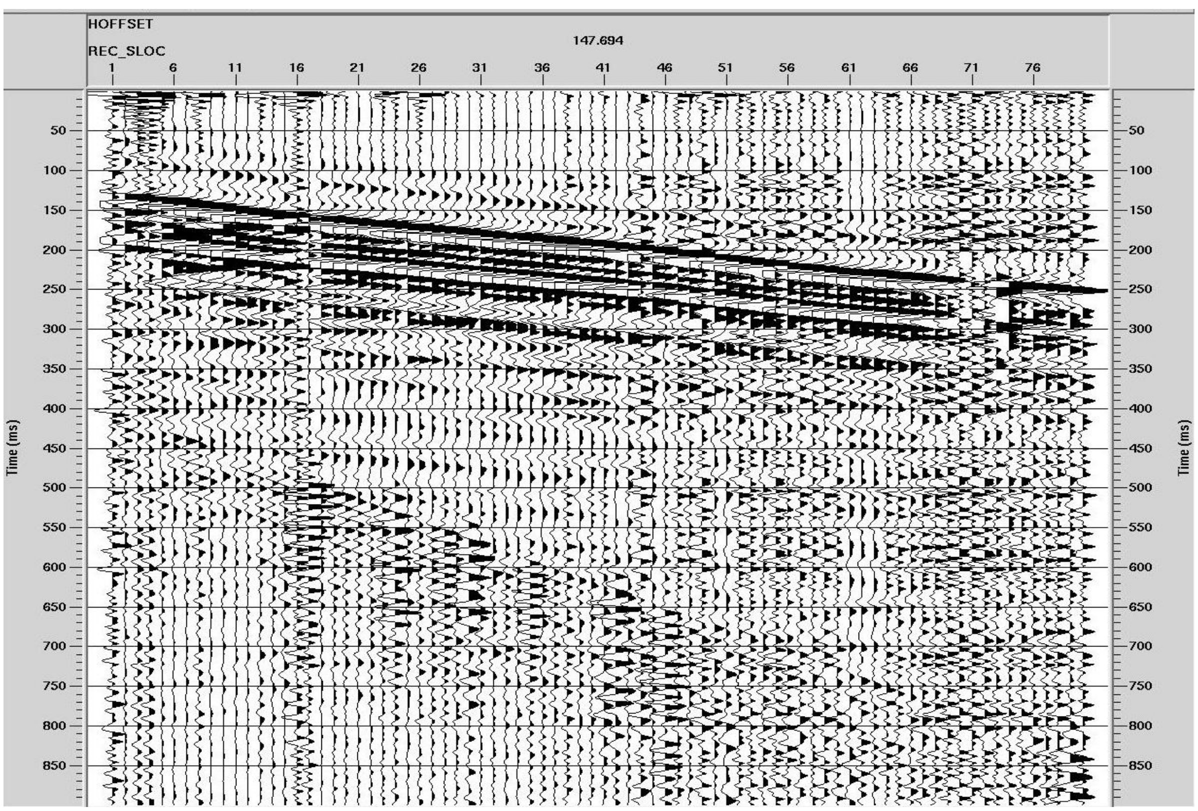

Figure 5. Monitor data exhibits electrical noise influence, but has slightly higher signal to noise ratio

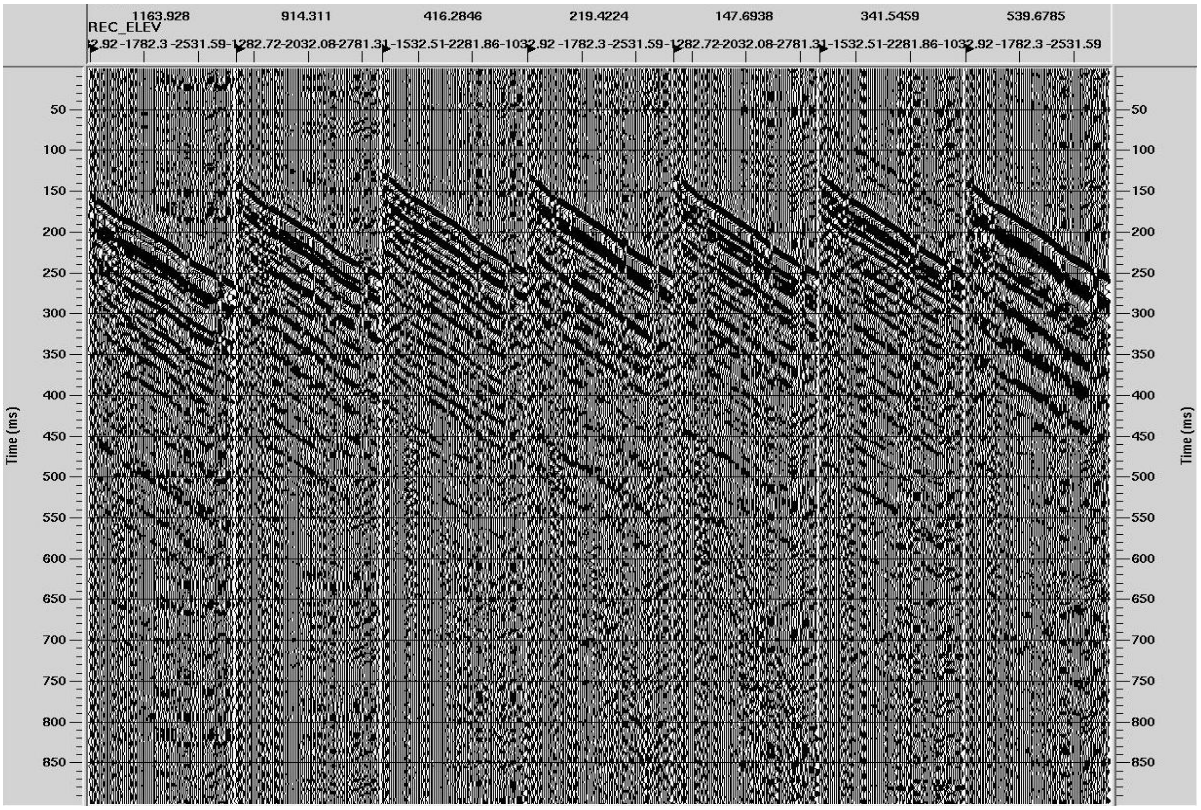

Figure 6. Baseline vertical component data across and West-East spread.

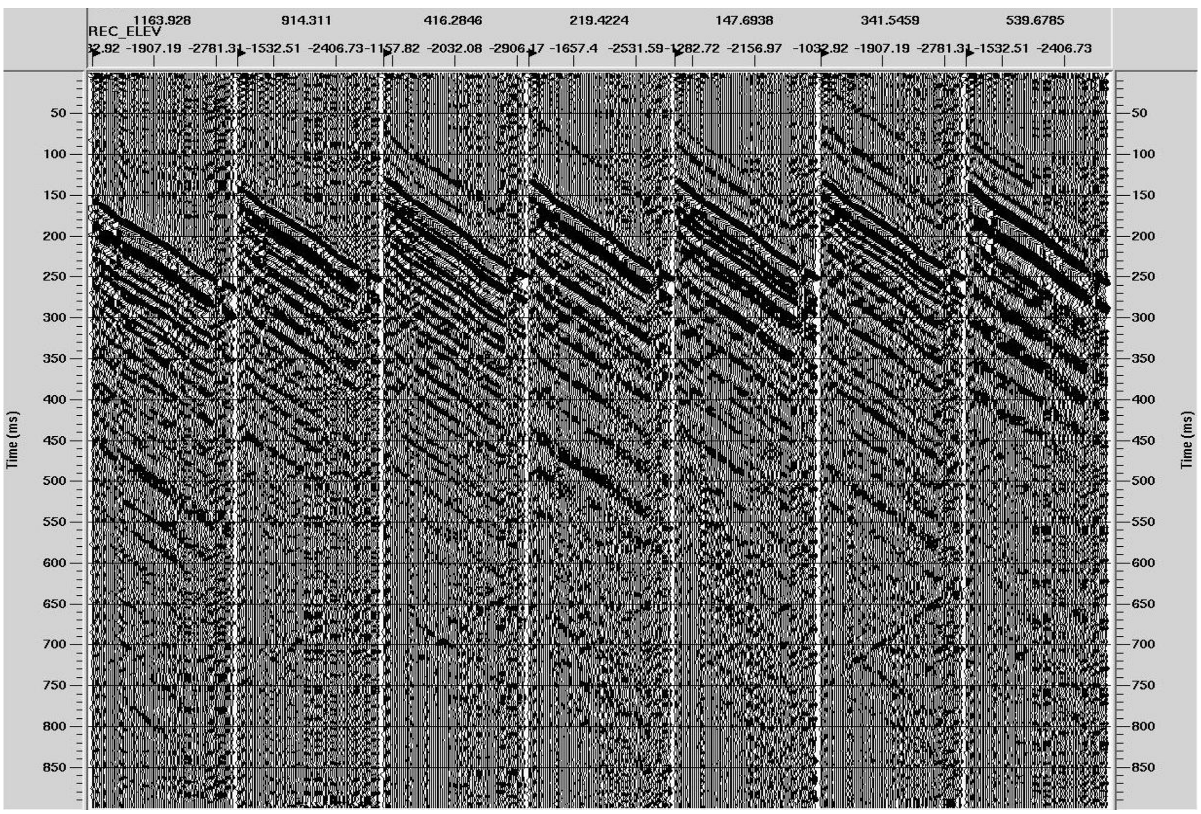

Figure 7. Monitor vertical component data across and West-East spread.

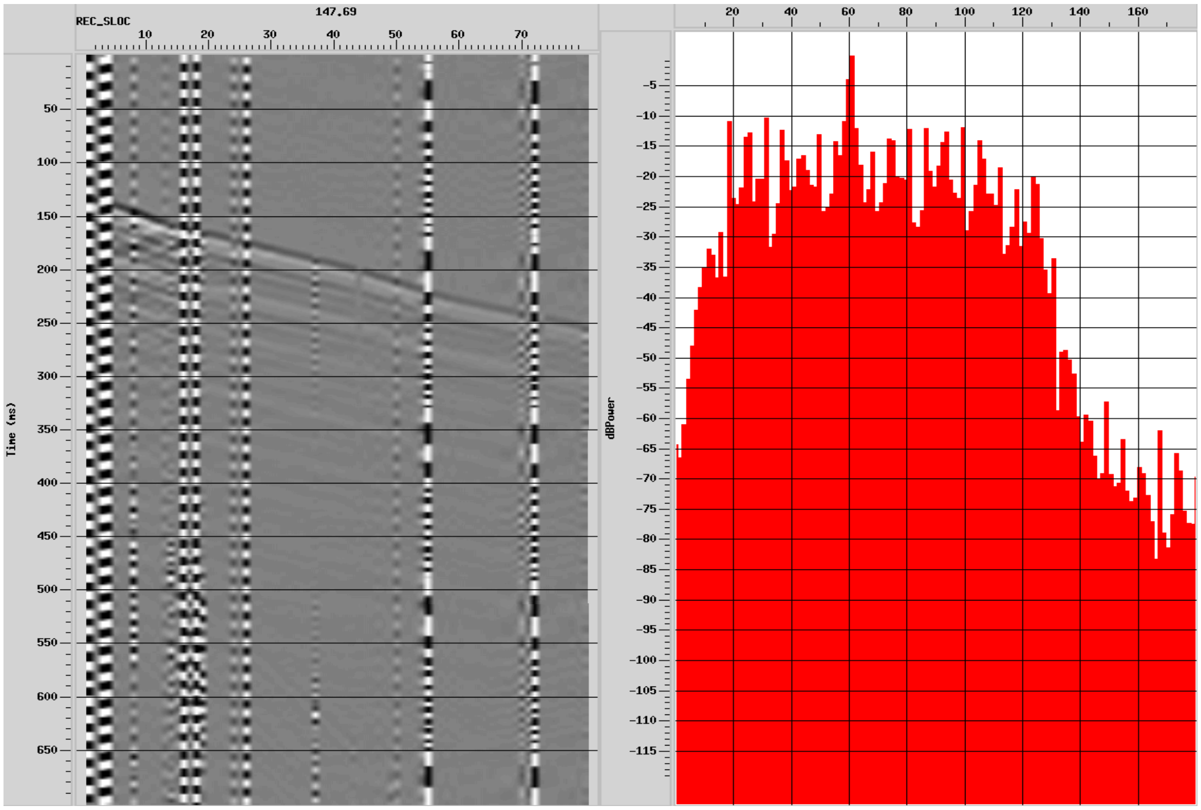

Figure 8. Baseline vertical component data spectrum near offset.

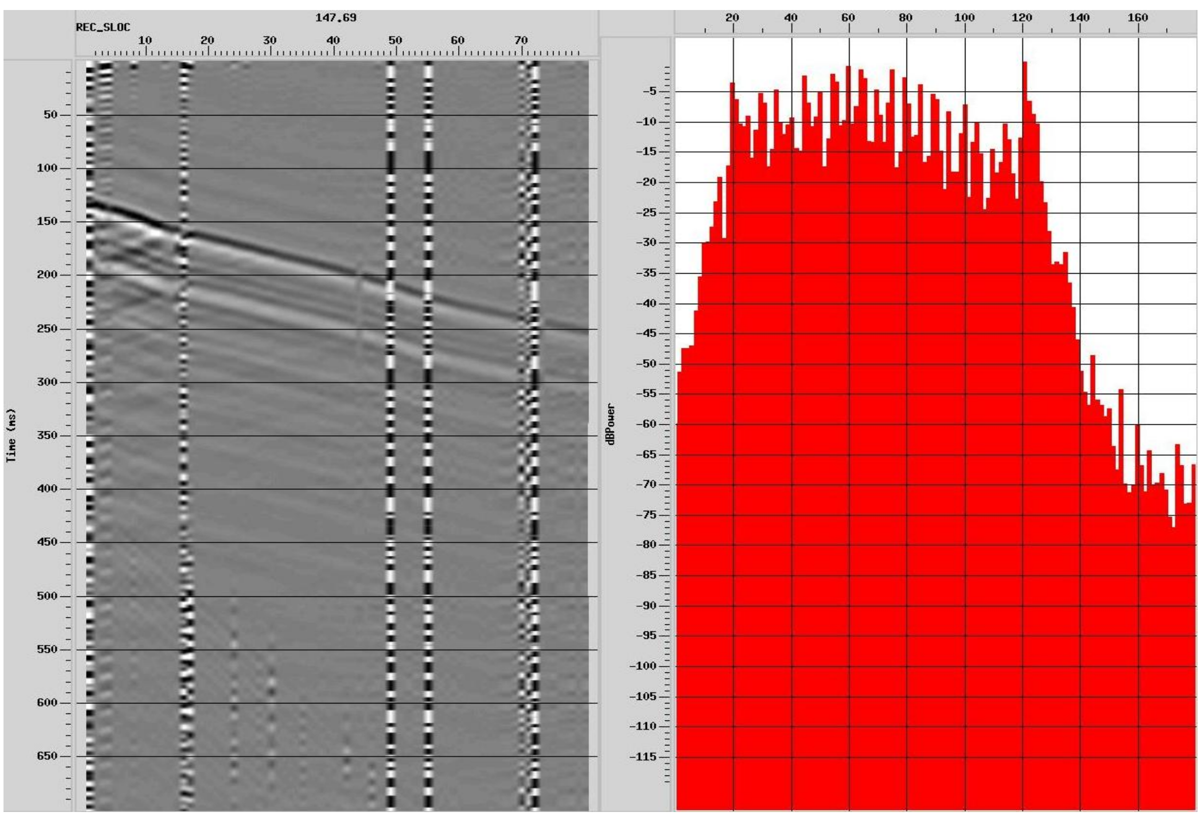

Figure 9. Monitor vertical component data spectrum near offset.

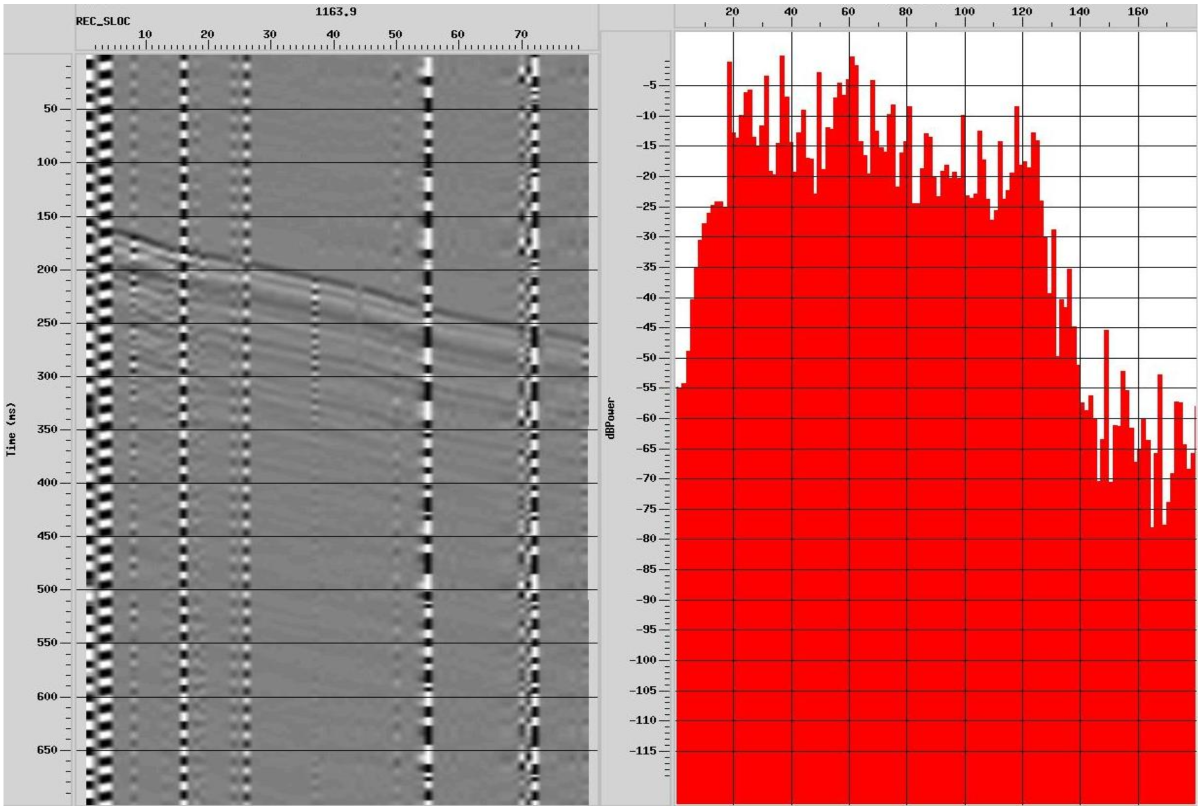

Figure 10. Baseline vertical component data spectrum far offset.

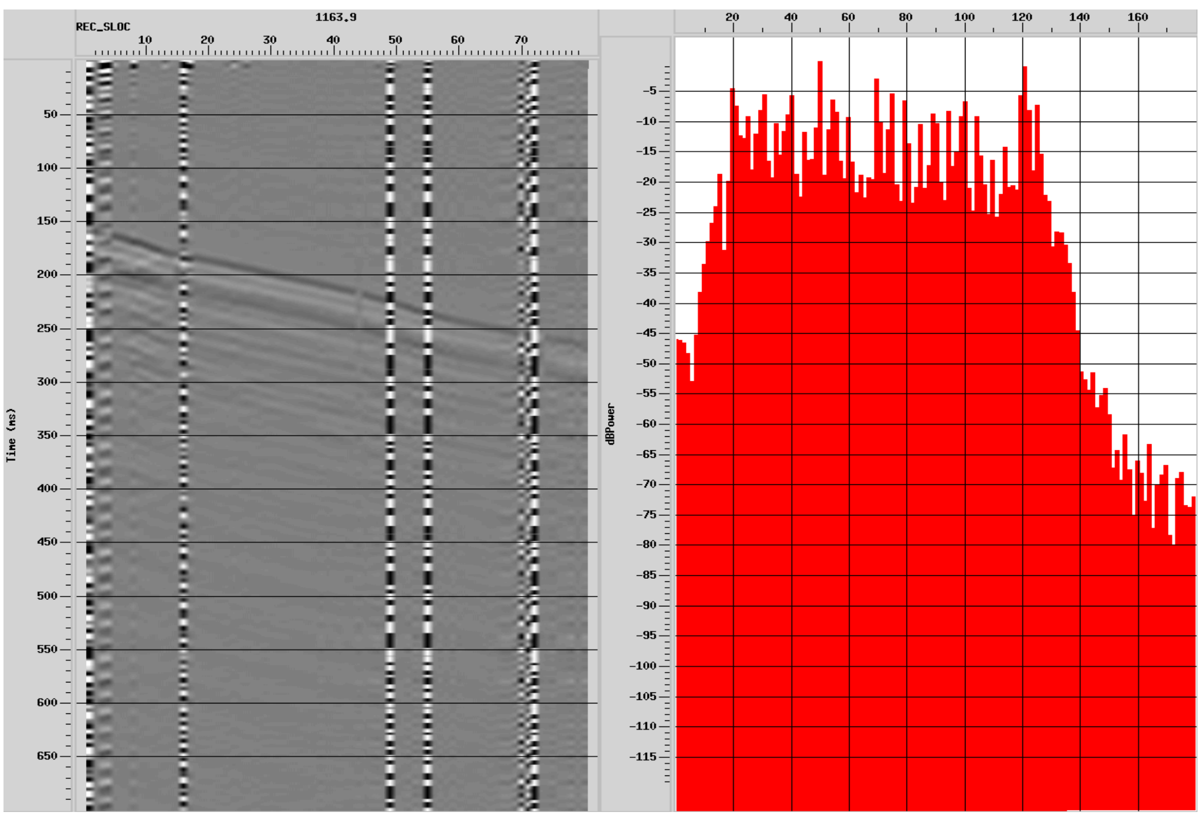

Figure 11. Monitor vertical component data spectrum far offset.

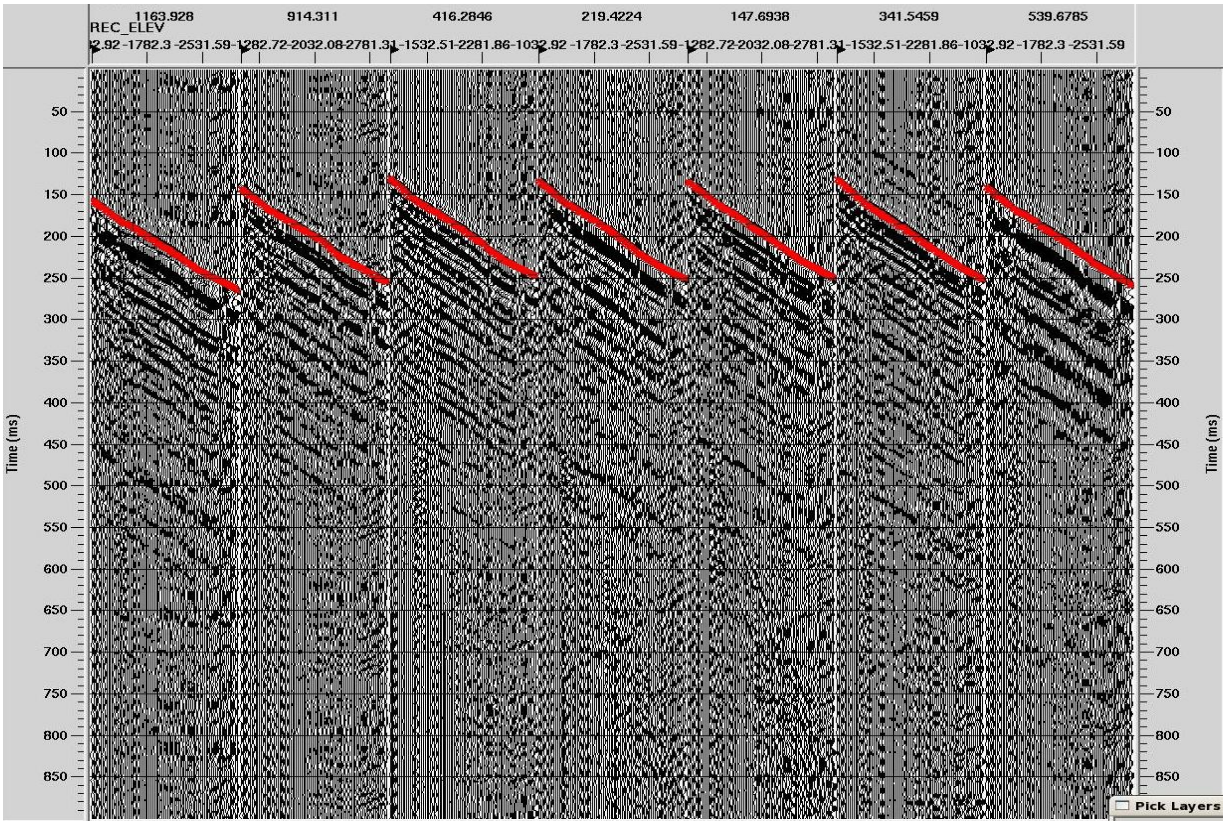

Figure 12. Baseline First Break picks on vertical component data on east west spread.

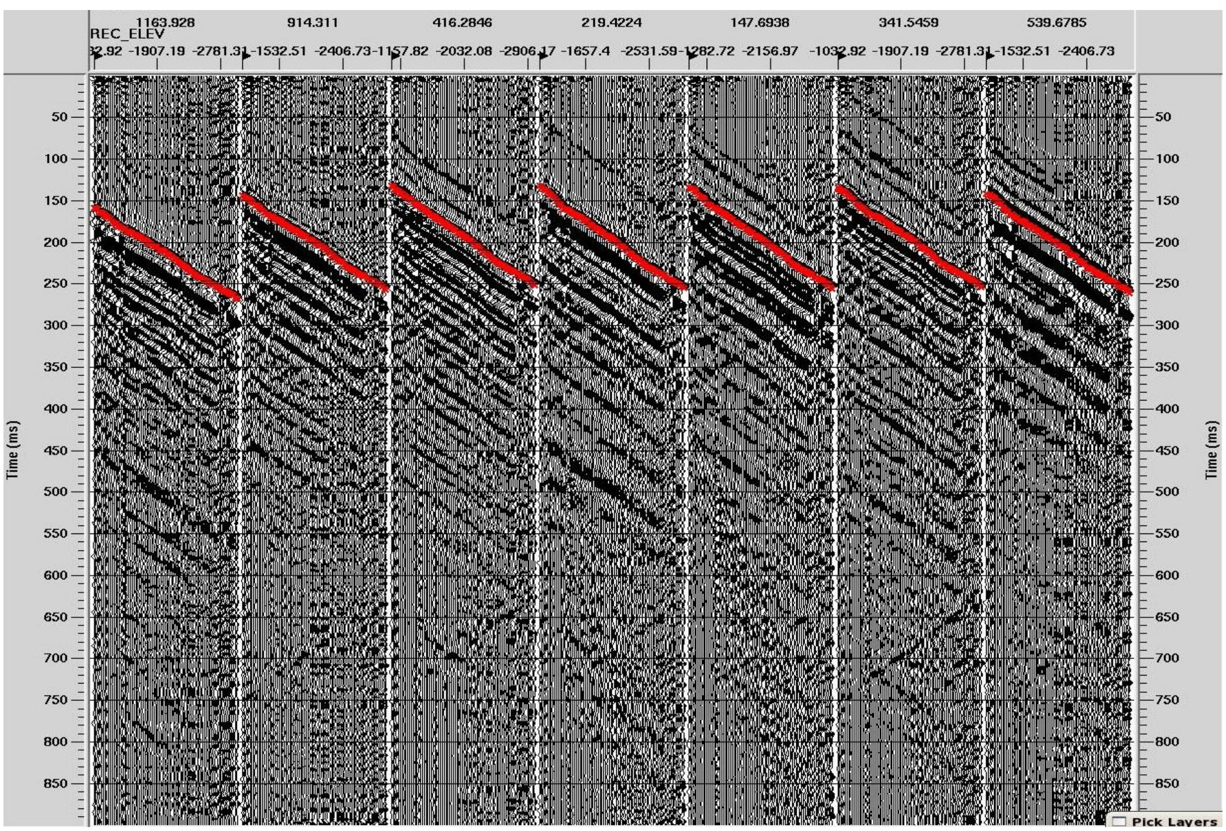

Figure 13. Monitor First Break picks on vertical component data on east west spread.

Figure 8-11 show the corresponding spectral displays. The raw data exhibits electrical noise, as can be seen in the raw data as well as in their amplitude spectra. These noise patterns will be suppressed in later processing through appropriate Notch filters and adaptive noise filters.

However, in order to perform the estimation of geophone orientation angles such filters have not been applied at this point in order to be able to focus purely on the first arrival p-wave energy. Figure 12 and 13 show the First Breaks overlaid on the shot gathers for both baseline and monitors. The FB picks for the baseline and monitor are consistent.

3.4 Geophone Orientation Estimation

Since the SR2020 receiver tools do not provide geophone orientation on their own, the geophone orientation has to be derived from a circular subset of shots around the borehole or using all source location simultaneously. In this case an approximate circle covering many azimuthal directions was used. Since the tool was removed and redeployed for the second data acquisition, the orientation of geophones does not remain constant between the baseline and monitor acquisition. The geophone orientation estimation had to be carried out for baseline and monitor independently. Figure 14 and 15 shows the hodogram display of a typical receiver level. The hodogram linearity for the incoming direct p-wave is of good quality for both baseline and monitor. While the linearity is comparable, the actual hogogram angles are different between baseline and monitor survey.

Figure 16-18 shows the same baseline seismic gather with various receiver rotations applied. Figure 16 shows all three components of a baseline seismic gather as it was recorded in the field. In Figure 17 all receivers have been rotated to the same EW-NS-V (XYZ) coordinate system. The line-up of downgoing energy on the various components becomes coherently aligned. While the (XYZ) rotated data is the starting point for all further processing, in Figure 18 the receiver is tilted in such a way that it points roughly towards the known source location. This particular orientation is useful for estimating and extracting the downgoing wave field, as for refined FirstBreak picking and deconvolution operator estimation.

Figure 19 – 21 repeats the display of those data rotations for the monitor survey. Qualitatively the same behavior can be observed. After rotating all receivers to a common coordinate system, energy becomes coherently visible on certain data components as we expect.

This TrueXYZ data set (EW-NS-V) is the basis for all further processing and has been stored as the reference data set for both baseline and monitor.

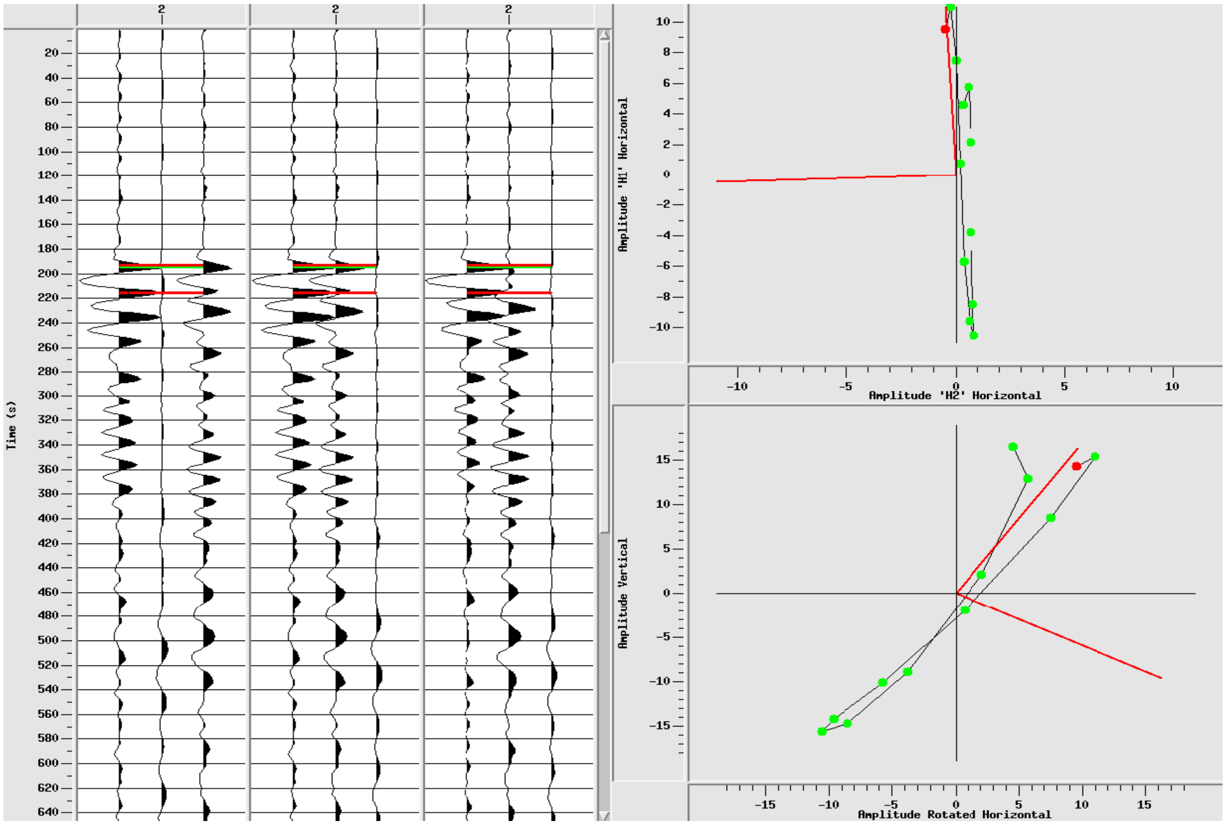

Figure 14. Baseline hodogram example, receiver 20.

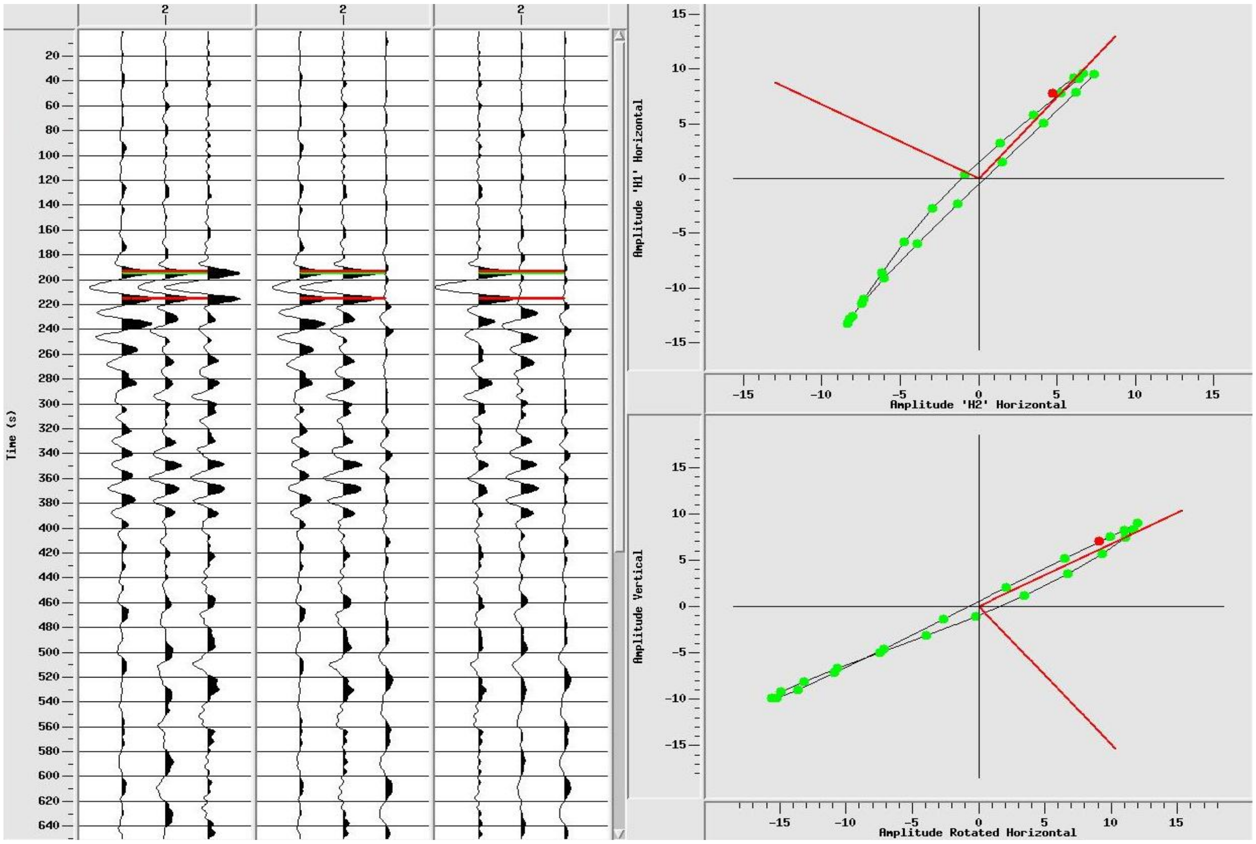

Figure 15. Monitor hodogram example, receiver 20.

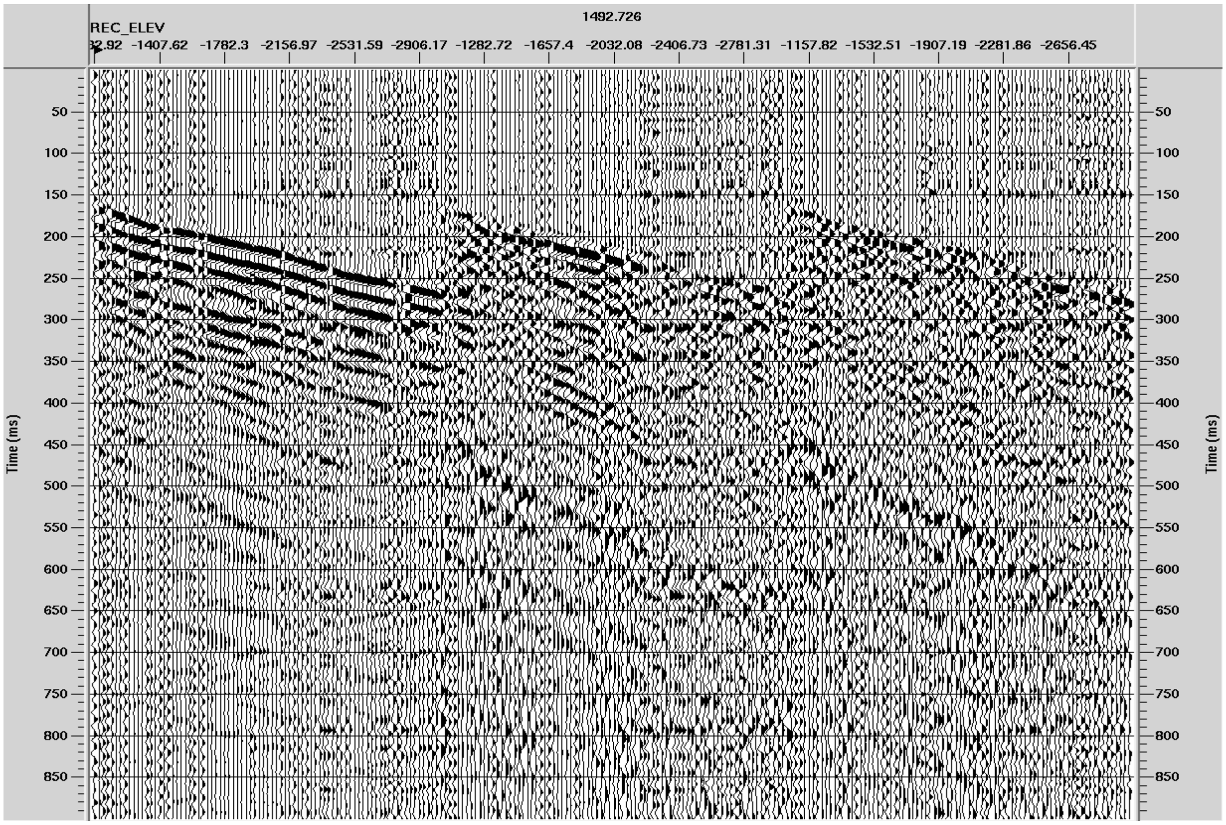

Figure 16. Baseline raw 3C data for mid offset.

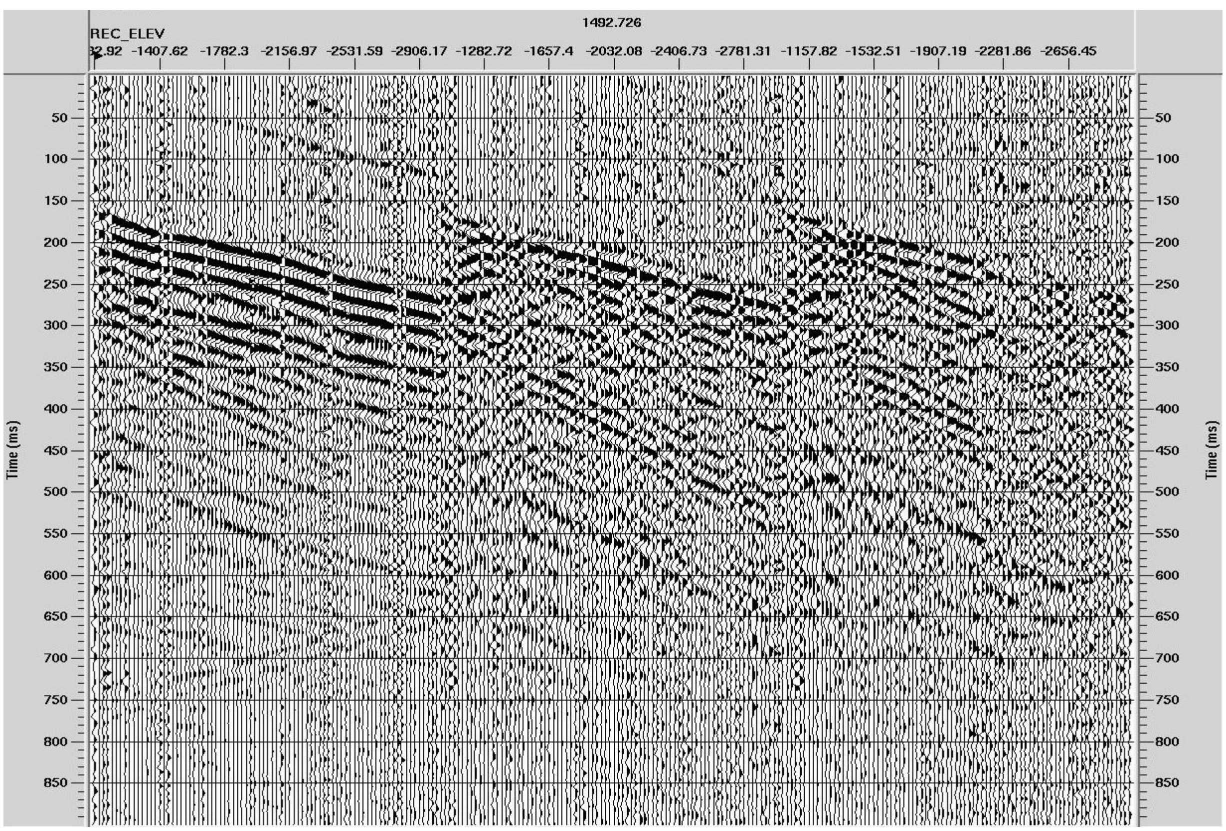

Figure 17. Baseline trueXYZ data for mid offset.

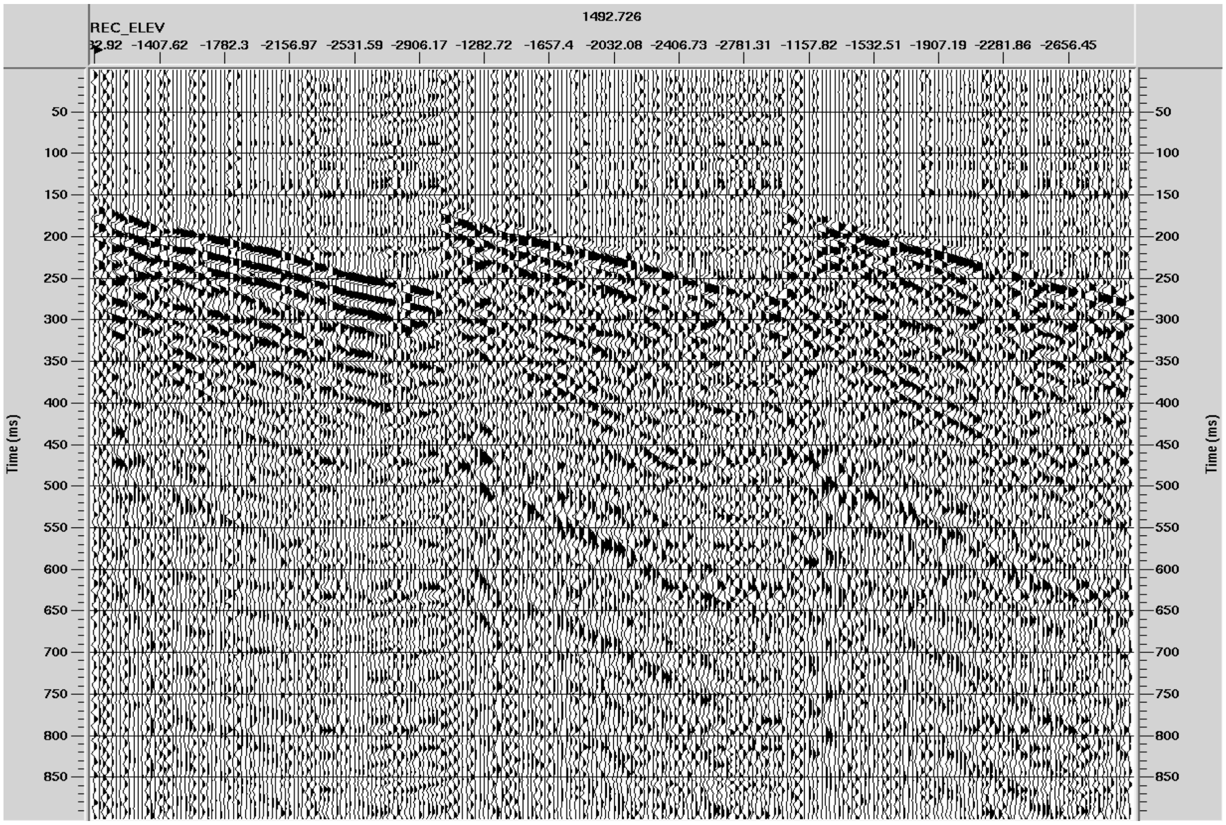

Figure 18. Baseline V-to-Source data for mid offset.

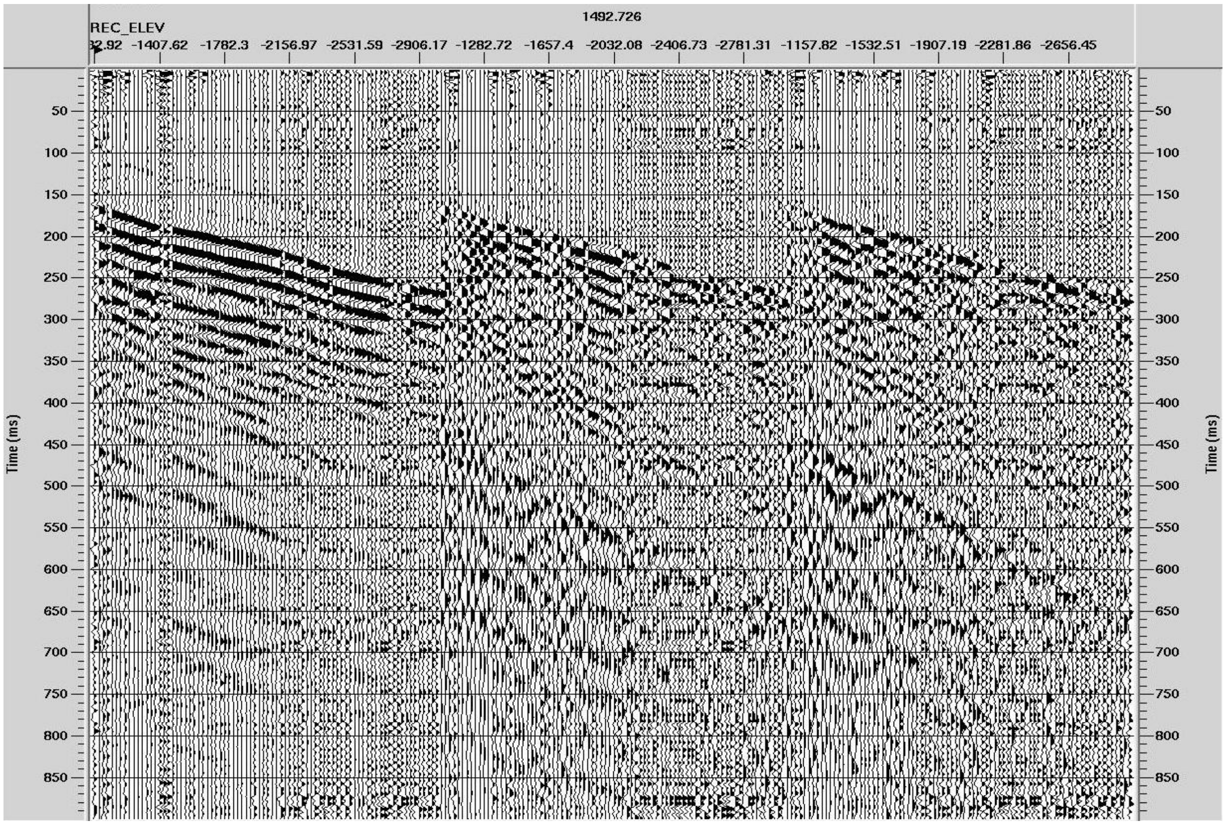

Figure 19. Monitor raw 3C data for mid offset.

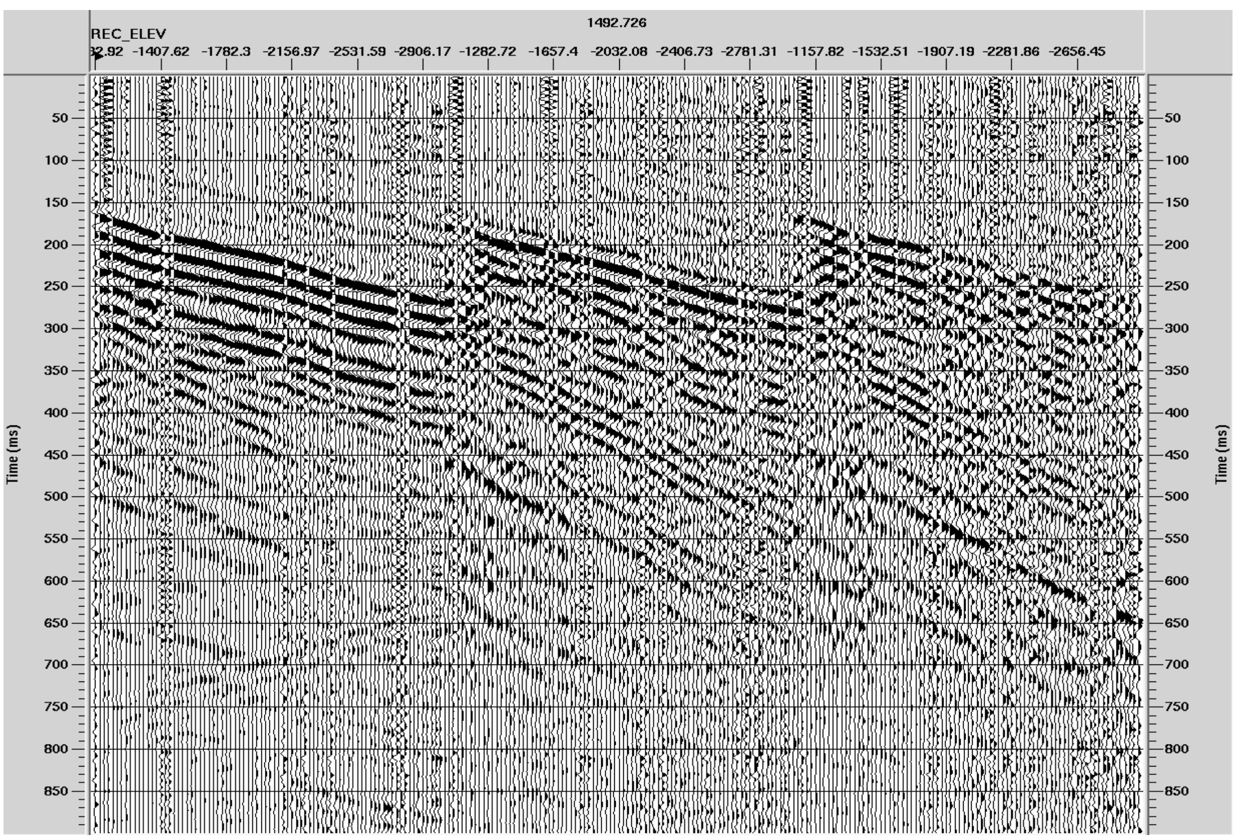

Figure 20. Monitor trueXYZ data for mid offset.

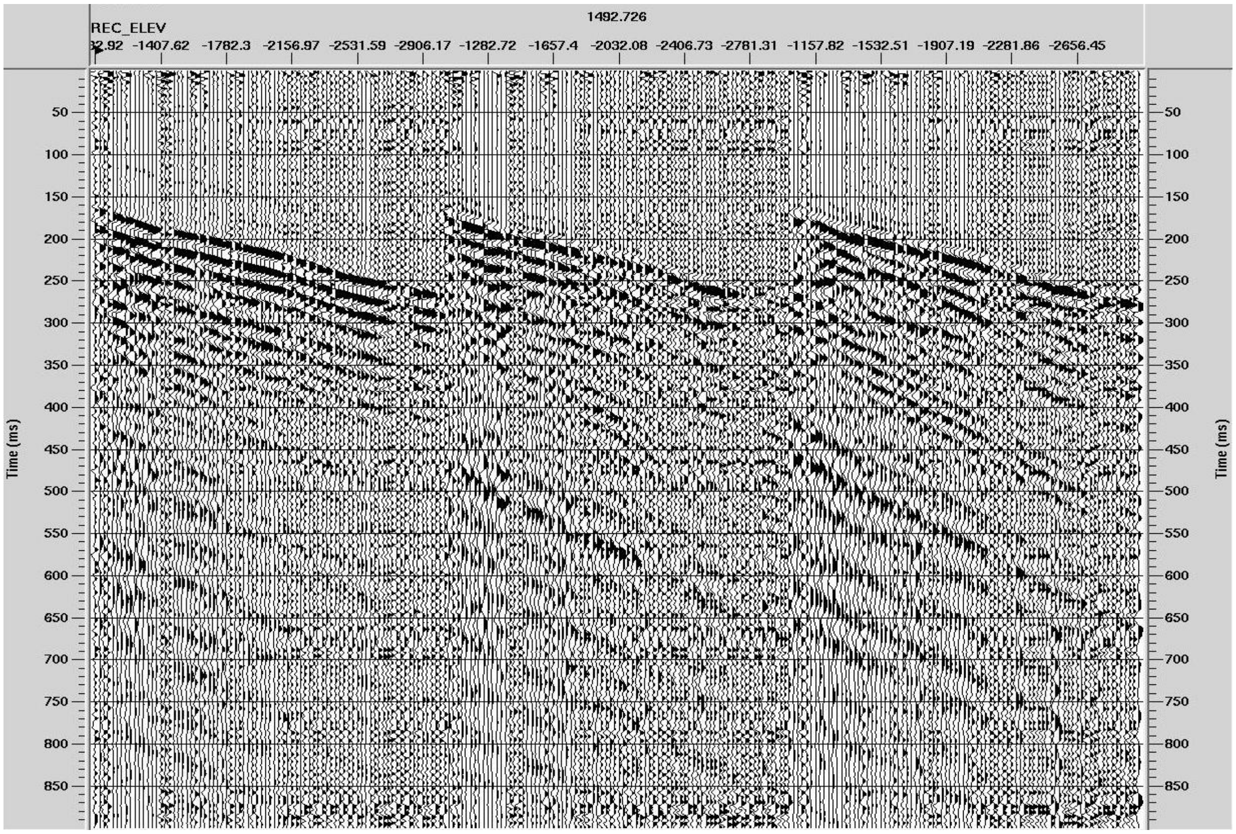

Figure 21. Monitor V-to-Source data for mid offset.

3.5 Deconvolution

The downgoing wave field might incorporate a variety of wave field effects that are related to source location, source mechanism and source near surface effects. To remove such effects we design a deterministic deconvolution operator on the isolated downgoing wave fields, and then apply this deconvolution operator to the upgoing wave field after separation. The deconvolution operator is designed in a deterministic manner, such that only effects that are present in the downgoing wave field are taken into account. Since no statistical spectral enhancement or spiking is applied, this deconvolution operator is safe for any of the subsequent time-lapse processing steps.

Figures 22-25 show that an operator length of 800 msec is able to collapse the downgoing energy into a compact zero phase wavelet for both the baseline and monitor seismic gathers at various distances from the well. Although the baseline and monitor survey were collected within days of each other, differences in the downgoing wave fields are visible, mainly due to compaction of the near source area or other environmental changes. Thus, for each source location in the baseline and monitor survey a unique optimal source deconvolution operator filter is designed, that can be applied to the up-going reflected wave field in subsequent steps.

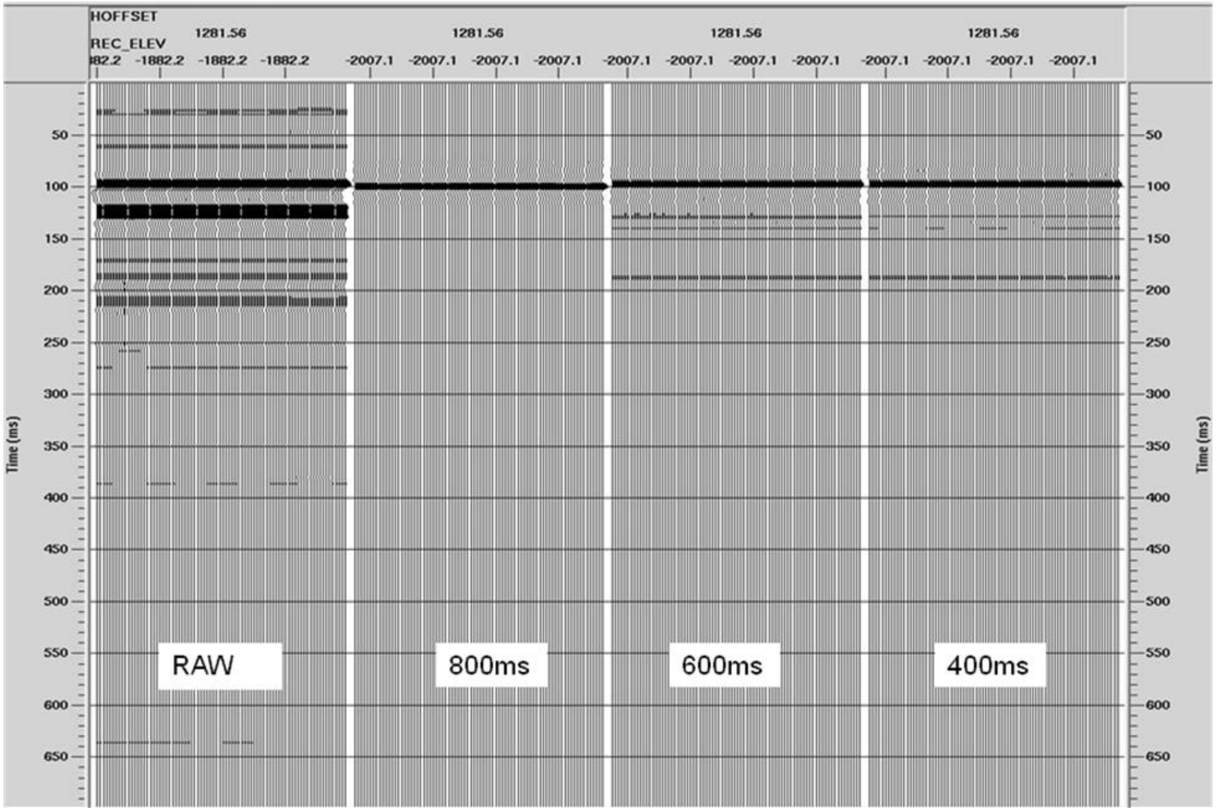

Figure 22. Baseline far offset Deconvolution filter 6,12,100,130Hz with 400,600 and 800 msec length.

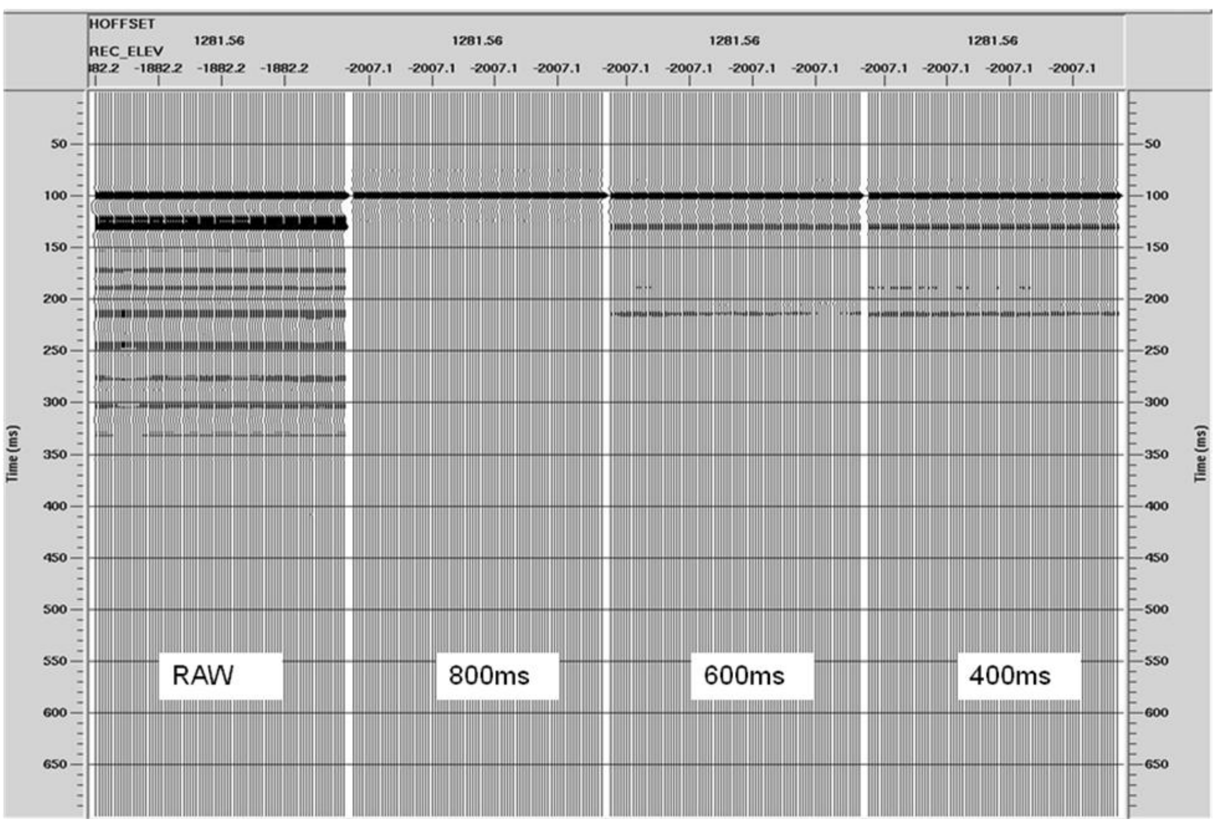

Figure 23. Monitor far offset Deconvolution filter 6,12,100,130Hz with 400,600 and 800 msec length.

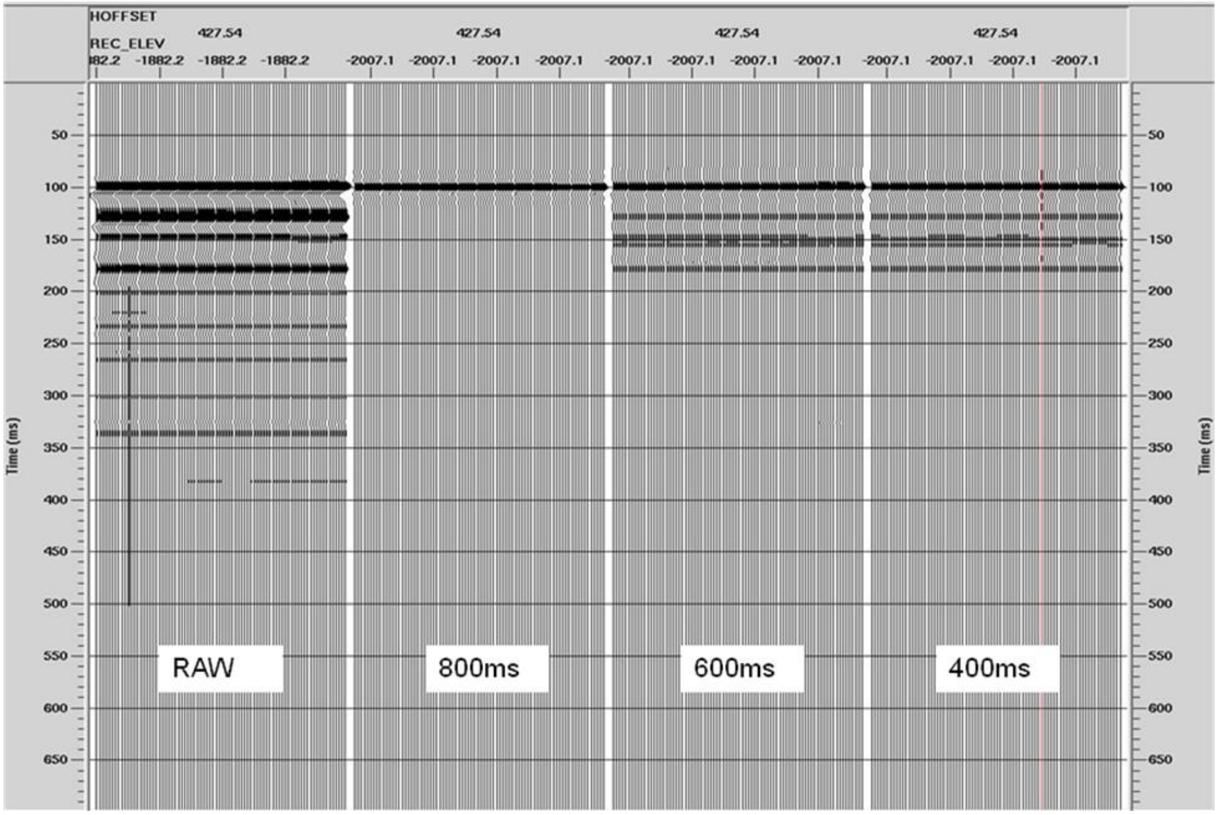

Figure 24. Baseline near offset Deconvolution filter 6,12,100,130Hz with 400,600 and 800 msec length.

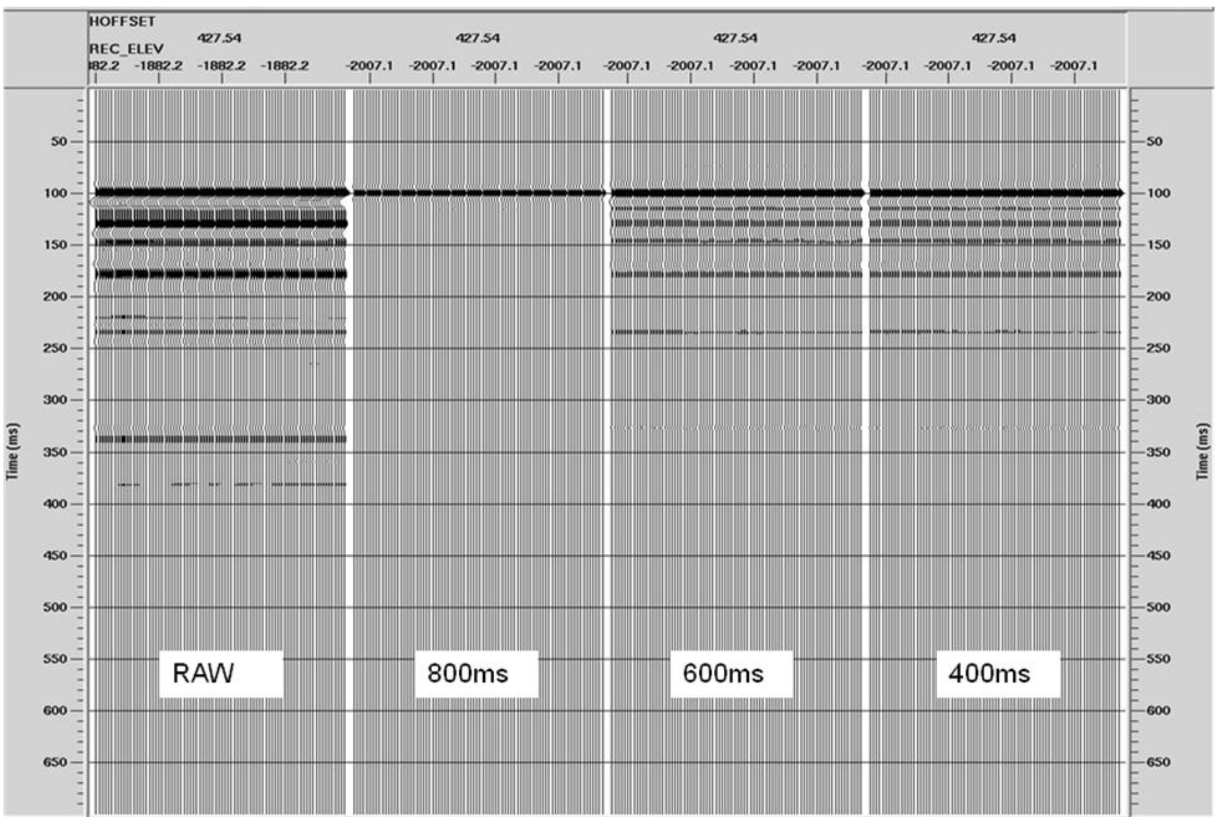

Figure 25. Monitor near offset Deconvolution filter 6,12,100,130Hz with 400,600 and 800 msec length.

3.6 Velocity Model Construction

First break picking and QC on all gathers was performed using an automatic First Break picker followed by manual editing of individual picks. A set of picks was determined and an initial velocity model was estimated using nonlinear iterative least squares estimation.

A near well gather served as a basis for the velocity model inversion within the geophone array. Figure 26-27 show the baseline and monitor gather with the FirstBreak arrival overlaid. The wave forms as well as the picks are very consistent between the Baseline and Monitor, thus, picked direct arrival times are nearly identical.

Since the receiver array was located in a depth range that did not have any injection present, we do expect hardly any change to be present in the velocity function.
Figure 29 shows the resulting velocity curves, the yellow and blue curves are inverted from the same source location for baseline and for the monitor, respectively. Their shape is nearly identical and in many places on the graph overlay each other. The slight discrepancy is likely to be within the picking error while the noise conditions were different.

Thus, a stable velocity function has been inverted within the array length. However, the depth range beneath the array does not provide direct transmission time measurements due to not having receivers present. Therefore, we used a scaled version of the p-wave sonic log to augment the velocity curve beneath the array. The sonic log samples velocity measurements at much higher frequencies than a VSP. However, since the smoothed and up-scaled sonic log is very similar in character to the VSP velocity curves that have been inverted, we estimate it be a good representation of the velocity model from the receiver array down to the injection zone and beyond.

In order to see if the general 1D velocity model can be extrapolated into a 3D model that is representative of the small region around the well under investigation, direct arrival times have been computed for all the source location into baseline and monitor survey. The reference elevation for this velocity model is 750 ft AMSL and all subsequent images are reference to that same datum.

Figures 32 and 33 show the computed versus picked direct arrival times for various baseline and monitor gathers respectively. In most cases the red picked curve overlays the blue computed curve with only minor discrepancies. Slight overall mismatches can arise if a near source effect has not been incorporated into the velocity model. In this case an overall slight shift is visible as a static shift. These static shifts will be analyzed subsequently in detail.

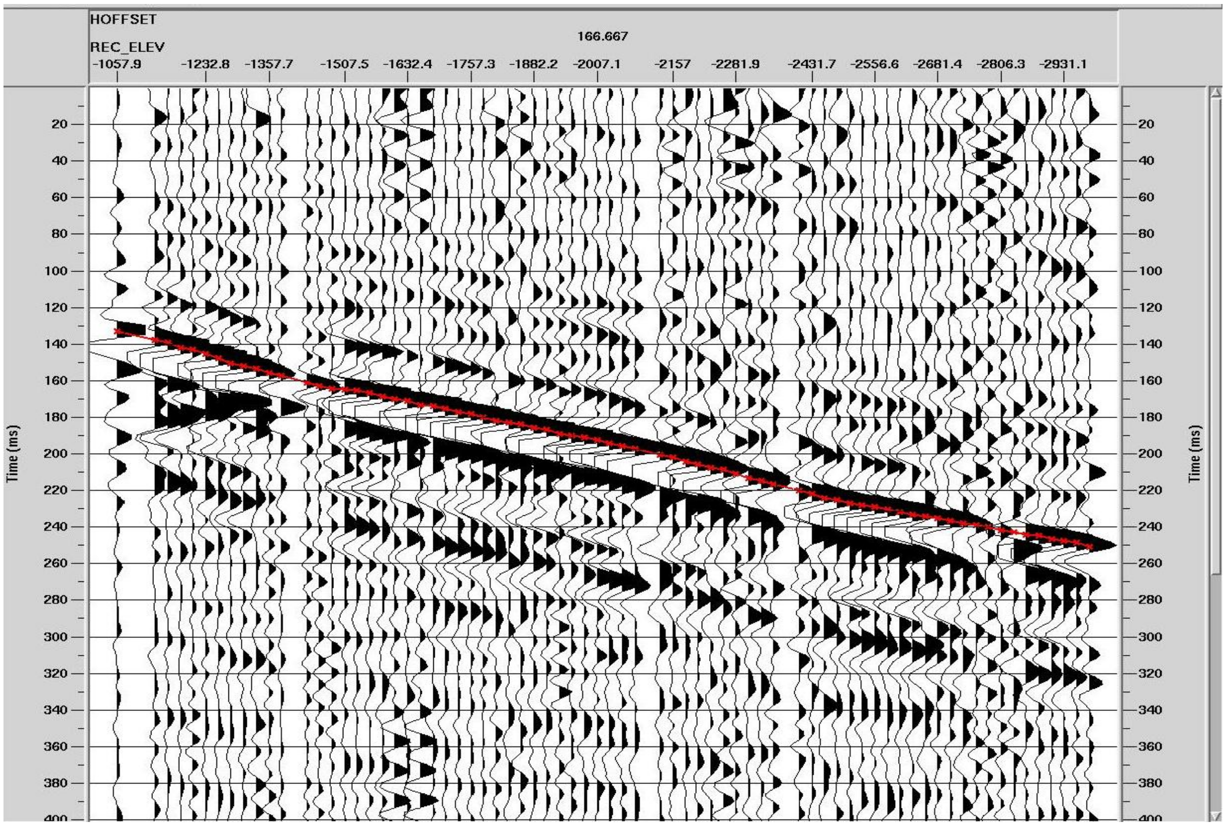

Figure 26. Baseline source at offset 166ft used in velocity estimation.

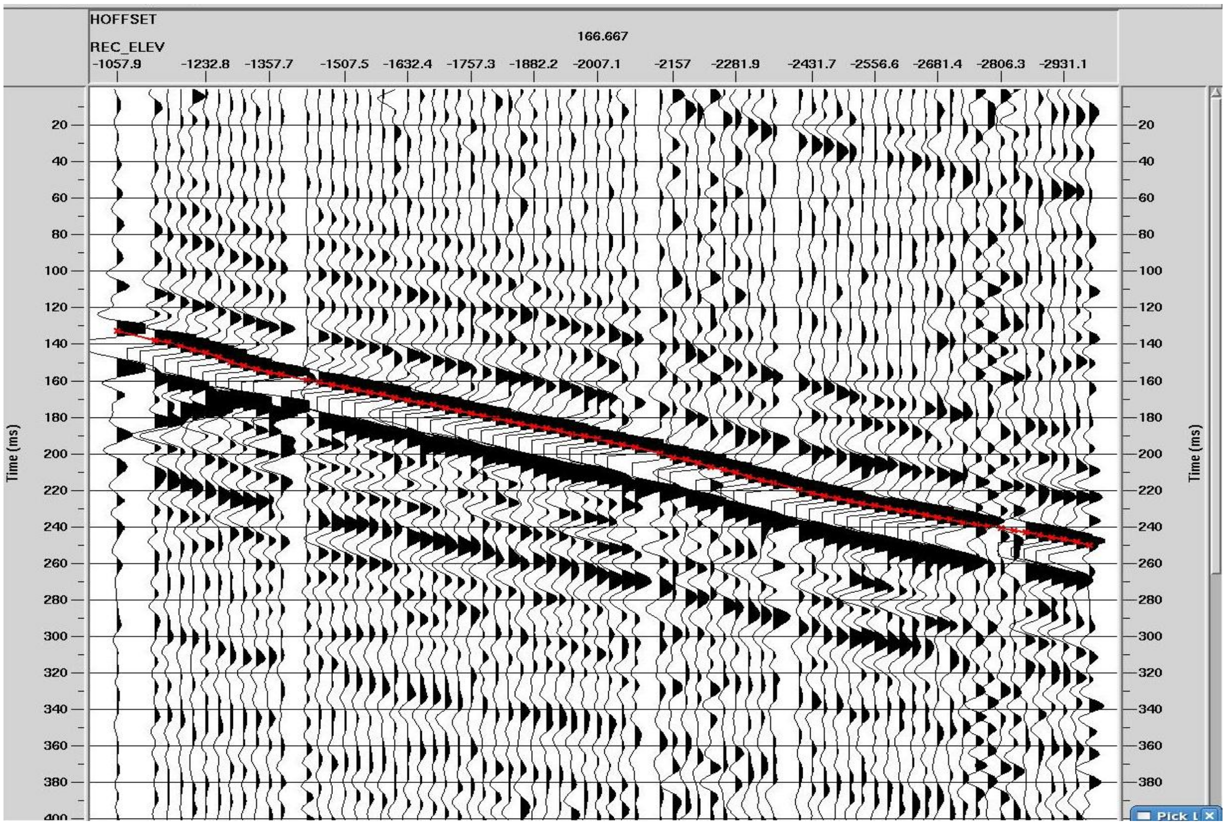

Figure 27. Monitor source at offset 166ft used in velocity estimation.

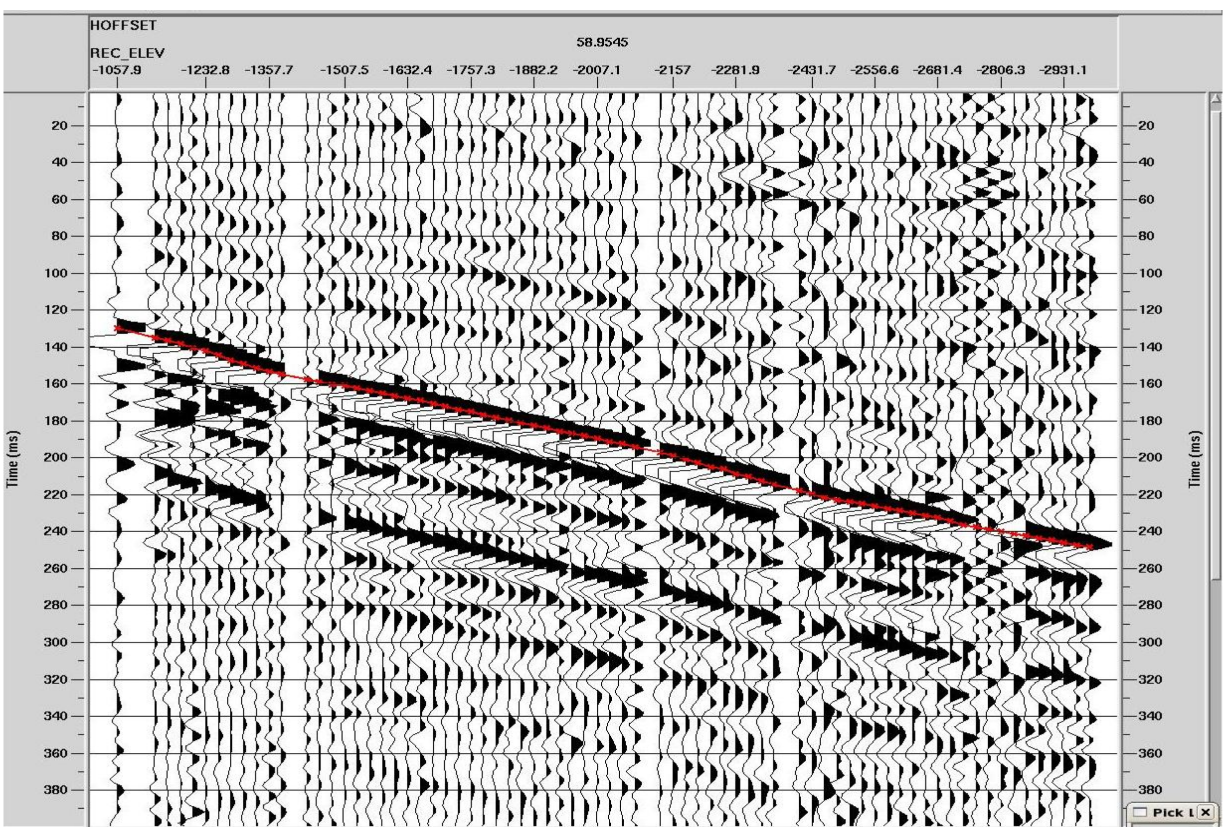

Figure 28. Baseline source at offset 59ft used in velocity estimation.

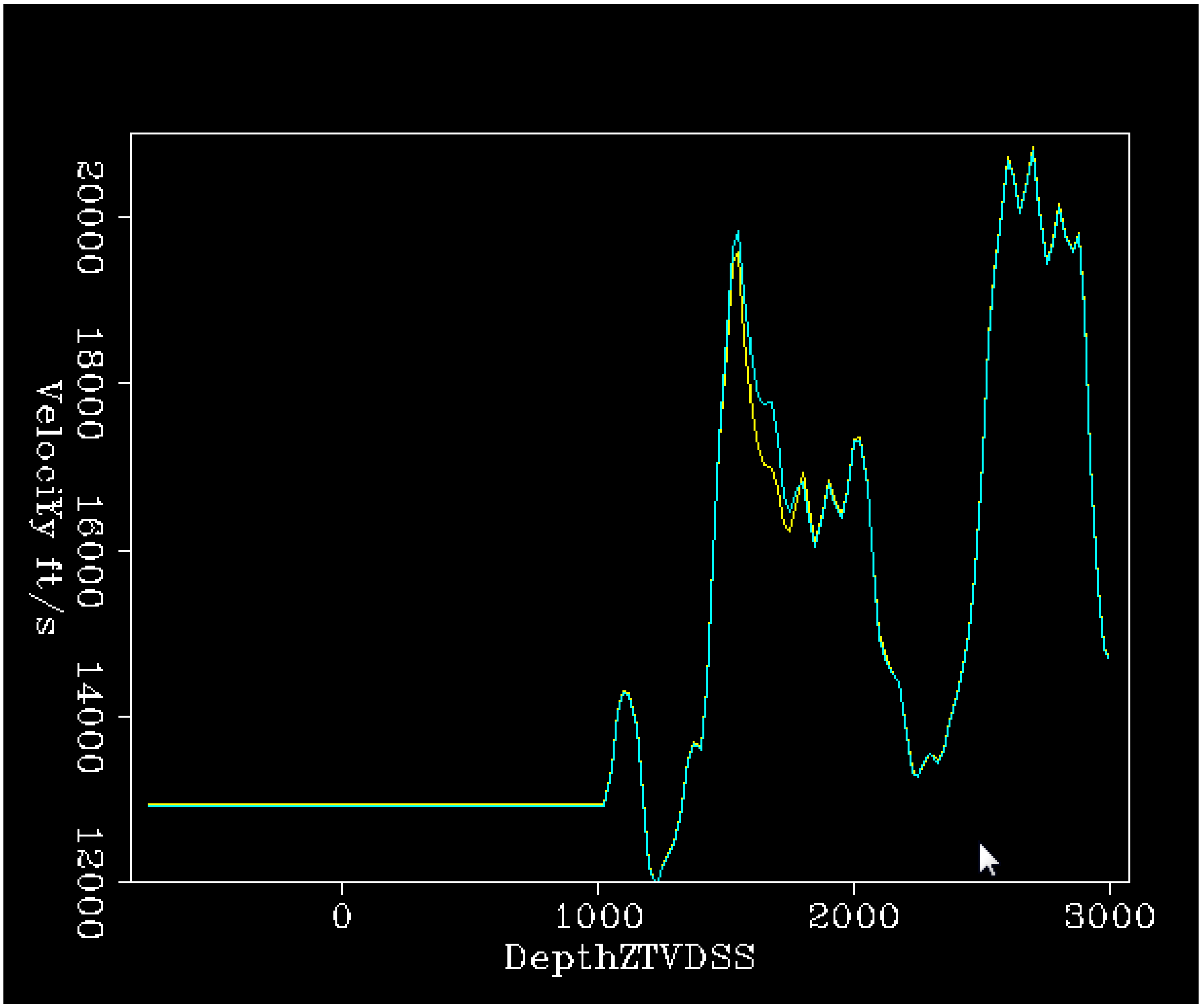

Figure 29. Estimated p-wave velocity profiles: yellow baseline at 166ft, blue monitor at 166ft. In most depth ranges the two velocity curves completely overlay.

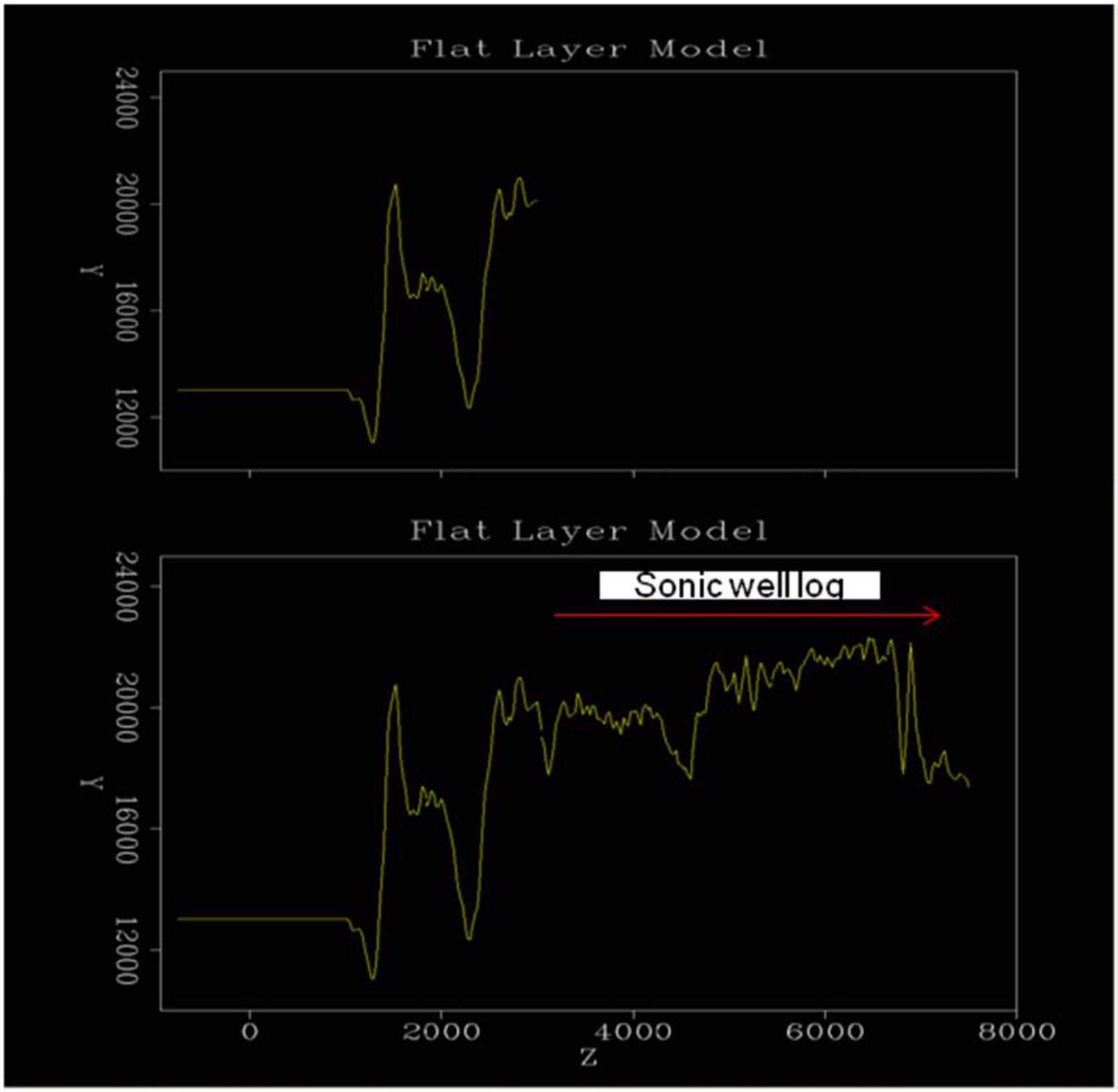

Figure 30. Estimated p-wave velocity profile augmented by up-scaled sonic velocities.

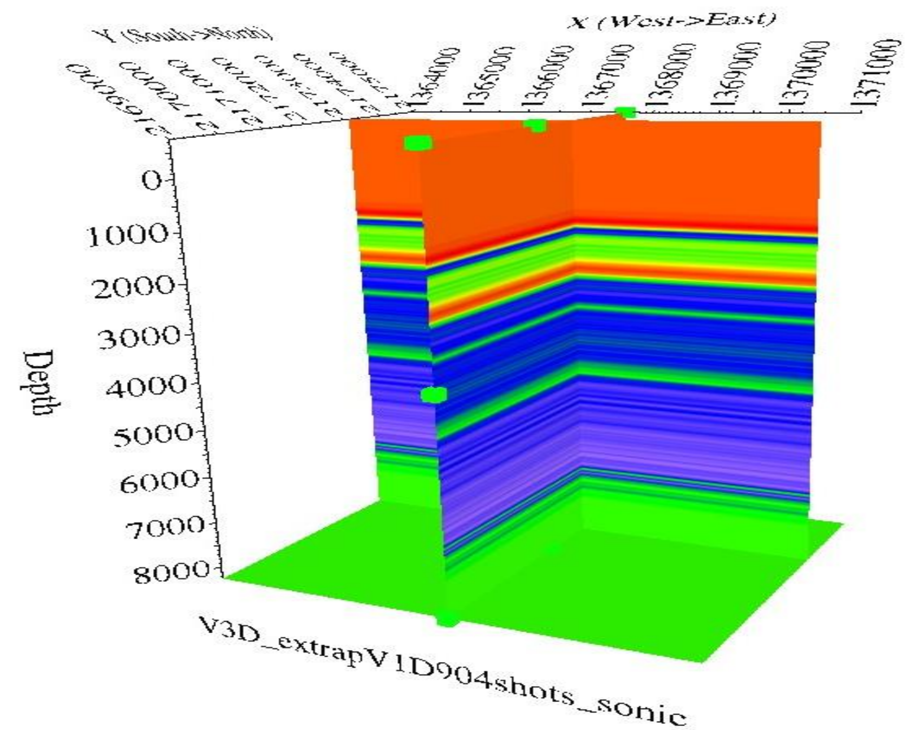

Figure 31. 3D velocity volume with top at 750 AMSL.

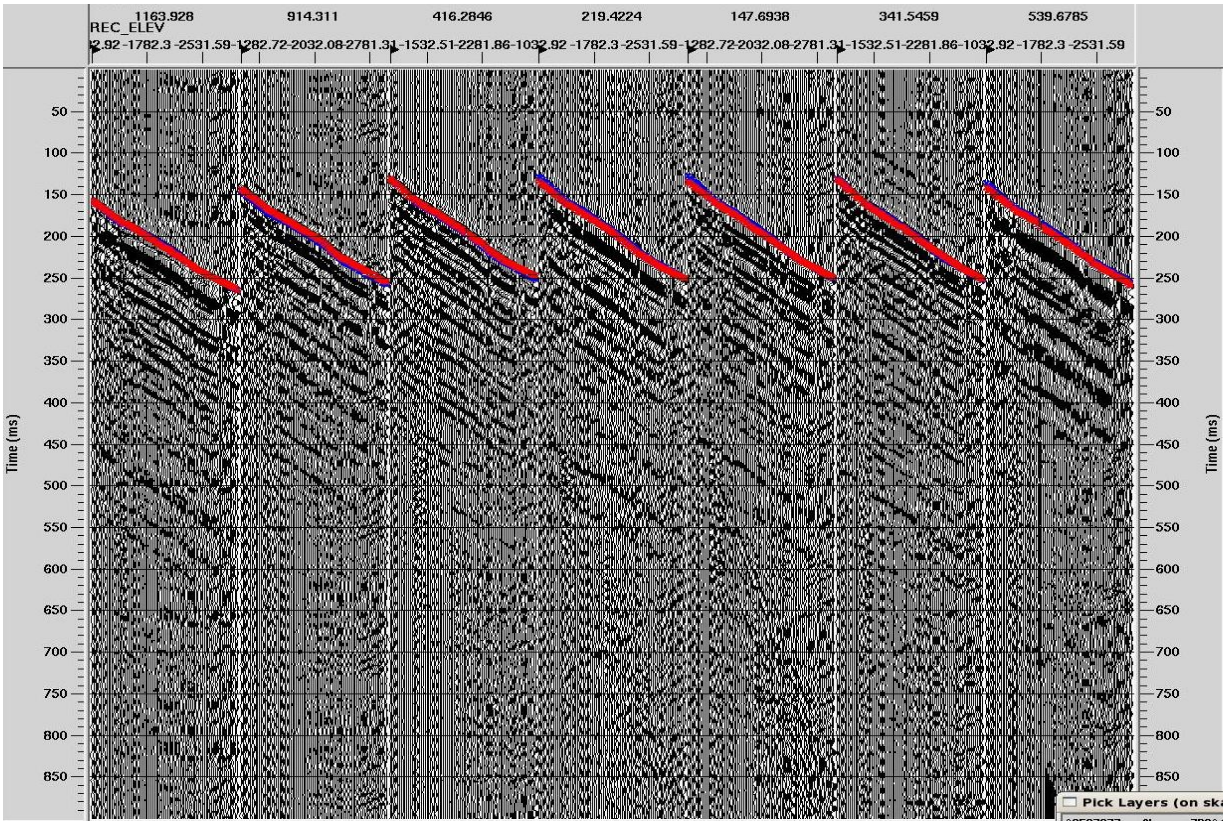

Figure 32. First Break Pick and Predicted overlay on seismic Baseline data (West-East).

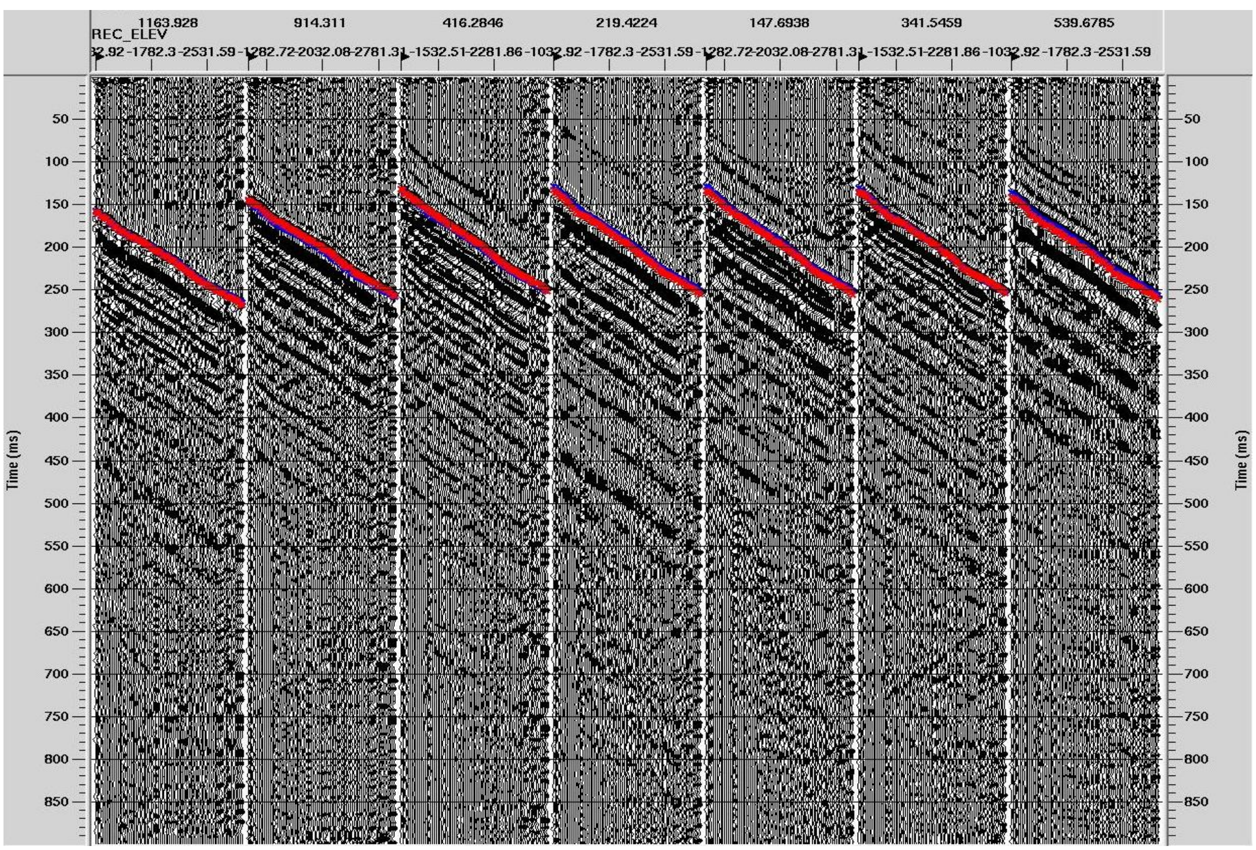

Figure 33. First Break Pick and Predicted overlay on seismic Monitor data (West–East).

3.7 Source Statics

Extensive data QC had been necessary, incorporating seismic header information and auxiliary observer logs, thus ensuring correct assignment of the source points. During the acquisition the near surface environment can be affected by local weather conditions, such as rain. The Baseline and Monitor acquisition occurred several days apart, during which local source coupling conditions could have changed.

Source statics estimation aims to remove any time shifts that might have been caused by a source specific timing effect. In this processing step we estimate source static values for Baseline and Monitor survey separately and compare their differences.

Using the available velocity model direct arrival times are computed from each source location to all receiver locations. This arrival is compared to the FirstBreak pick times and a model based source static value is computed. The overlays in Figure 32 and 33 show how well the FirstBreak picks match the computed arrival times, where the red and blue curve should overlay each other nearly identically for each source gather.

Figure 34 shows the estimated source static values as computed. The left hand side shows an interpolated view that exaggerates some of the features, while the right hand displays show the static value color coded while plotted at the actual individual source locations. Small source static values are near white color coded, while extreme positive or negative are blue and red respectively. The source statics values are generally small. There are several larger values, but they are generally located at the boundary of the source pattern, limiting the influence of such a source on the interior image.

Figure 35 shows the statics difference values between Baseline and Monitor surveys. In general the discrepancies are small indicated by the very pale colors. Nevertheless, these differences need to be compensated for. Some of the larger statics values at the edge of the acquisition can differ from Baseline to Monitor, since the source locations are acquired at different times and thus might have significantly different near surface conditions.

In preparation for the following processing steps, the source static values have been applied individually to both Baseline and Monitor data in order to remove any predictable source static effects.

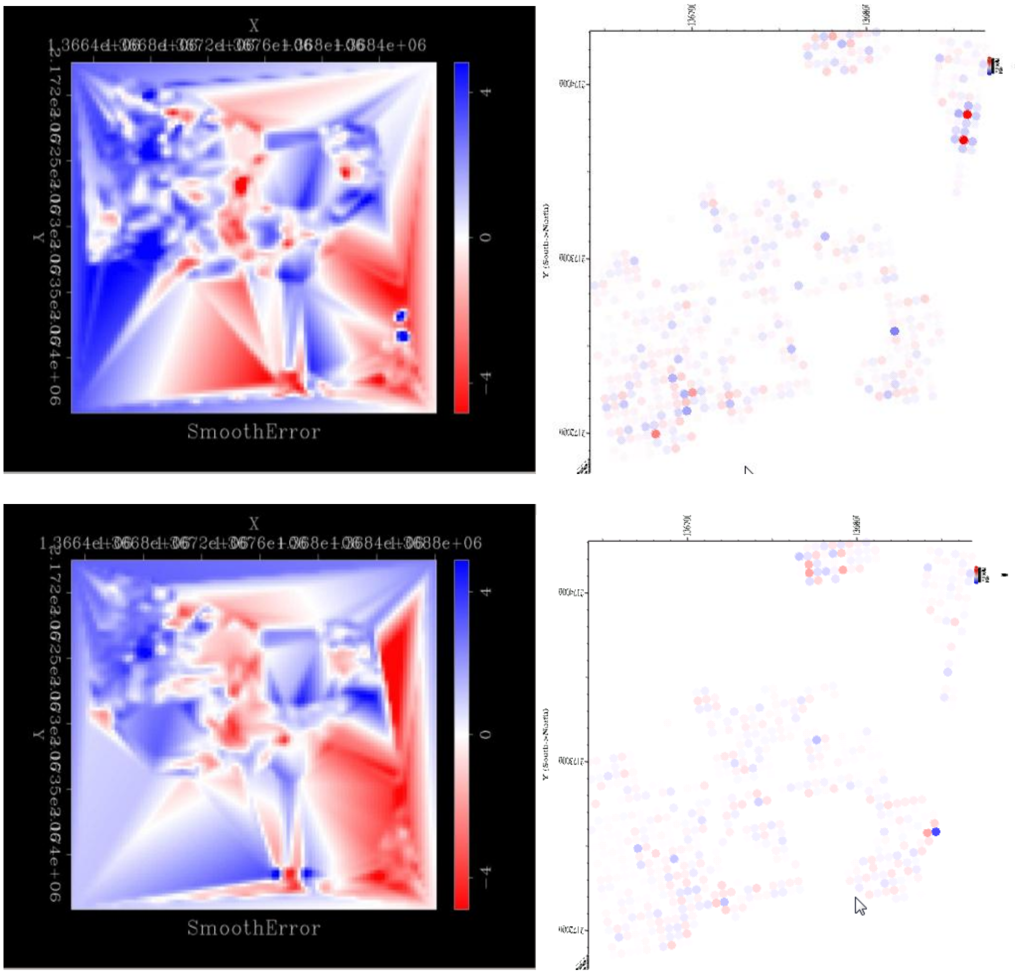

Figure 34. Top) Baseline statics map, bottom) Monitor statics map; left) gridded , right) on source locations.

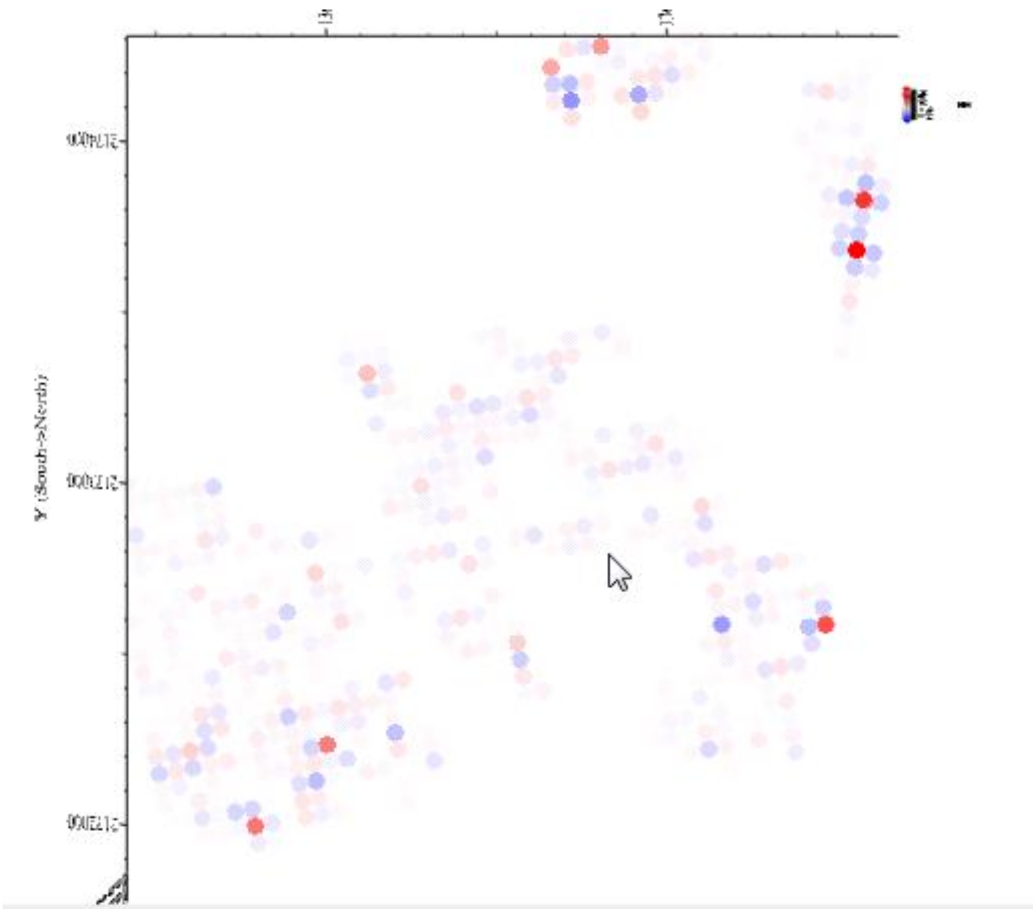

Figure 35. Statics difference map on source locations, same color scale as in Fig. 34. Some statics discrepancies at the rim of the source pattern only. Interior is largely consistent.

3.8 Wave Field Separation

Figures 36-37 show the wave field after noise suppression and deconvolution, while Figures 38-46 show the separated and enhanced up-going wave fields. Since the survey geometry is dominated by near vertical reflection geometry, the separation has been carried out using a median filter, in combination with a Radon filter to pass up-going P-wave reflections only.

These up-going wave fields contain the reflected P-wave field. Although the processing steps were identical for Baseline and Monitor surveys, there are differences visible in the up-going wave fields. Wave field differences can be caused by changing noise conditions and would manifest themselves ultimately in variations in the up-going wave fields.

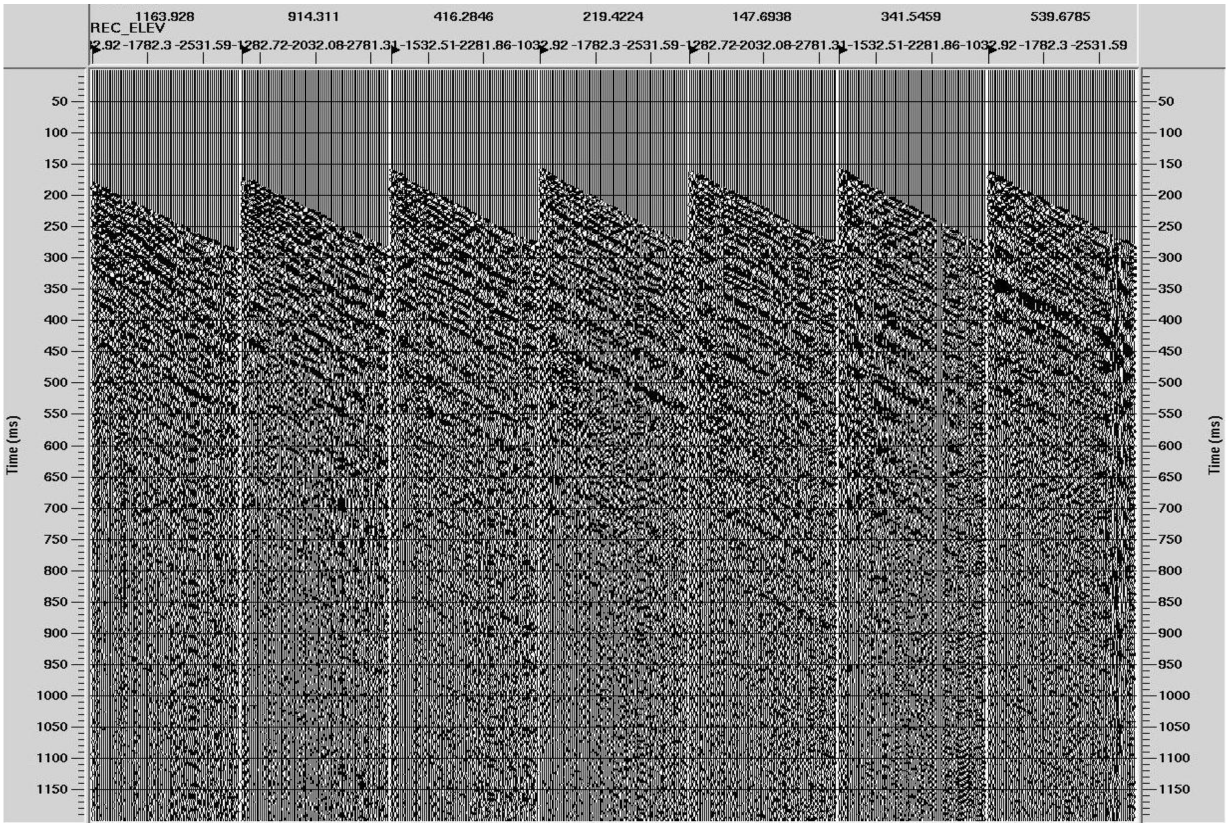

Figure 36. Baseline gathers after noise suppression and deconvolution (west-east).

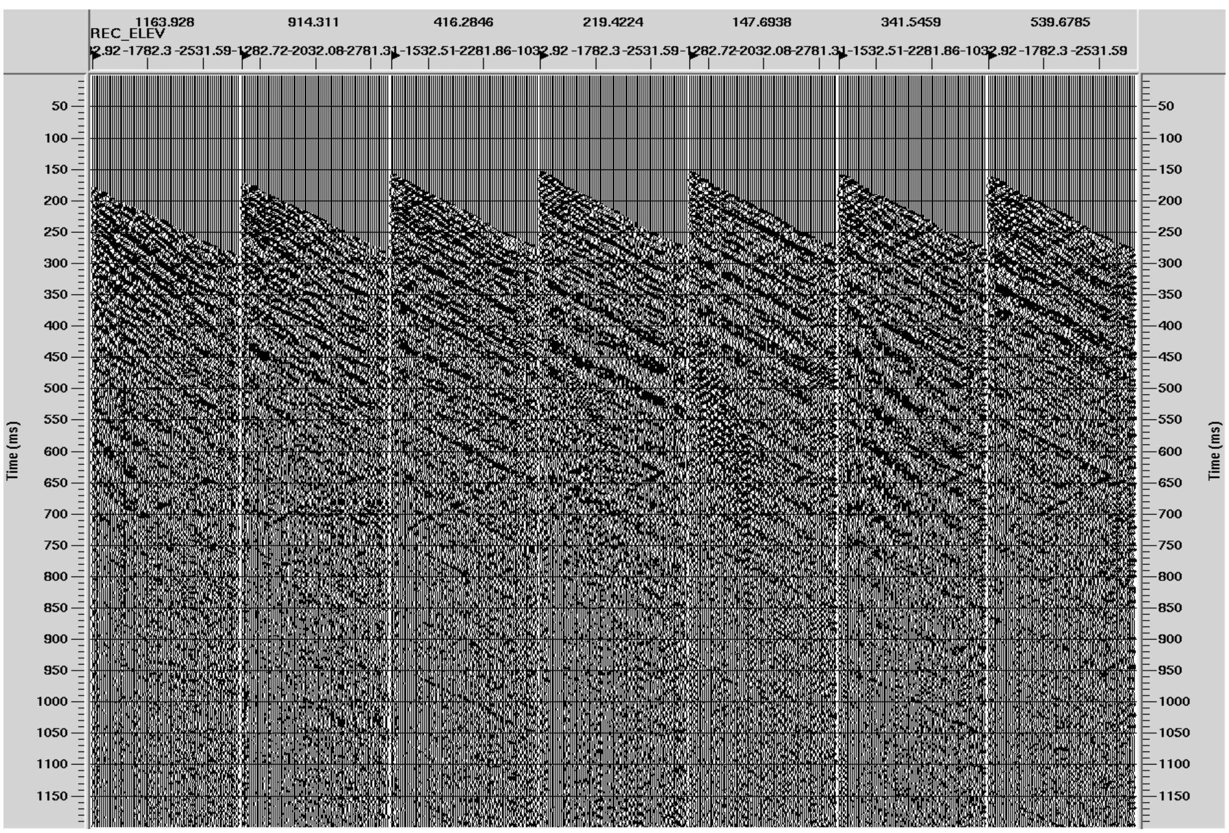

Figure 37. Monitor gathers after noise suppression and deconvolution (west-east).

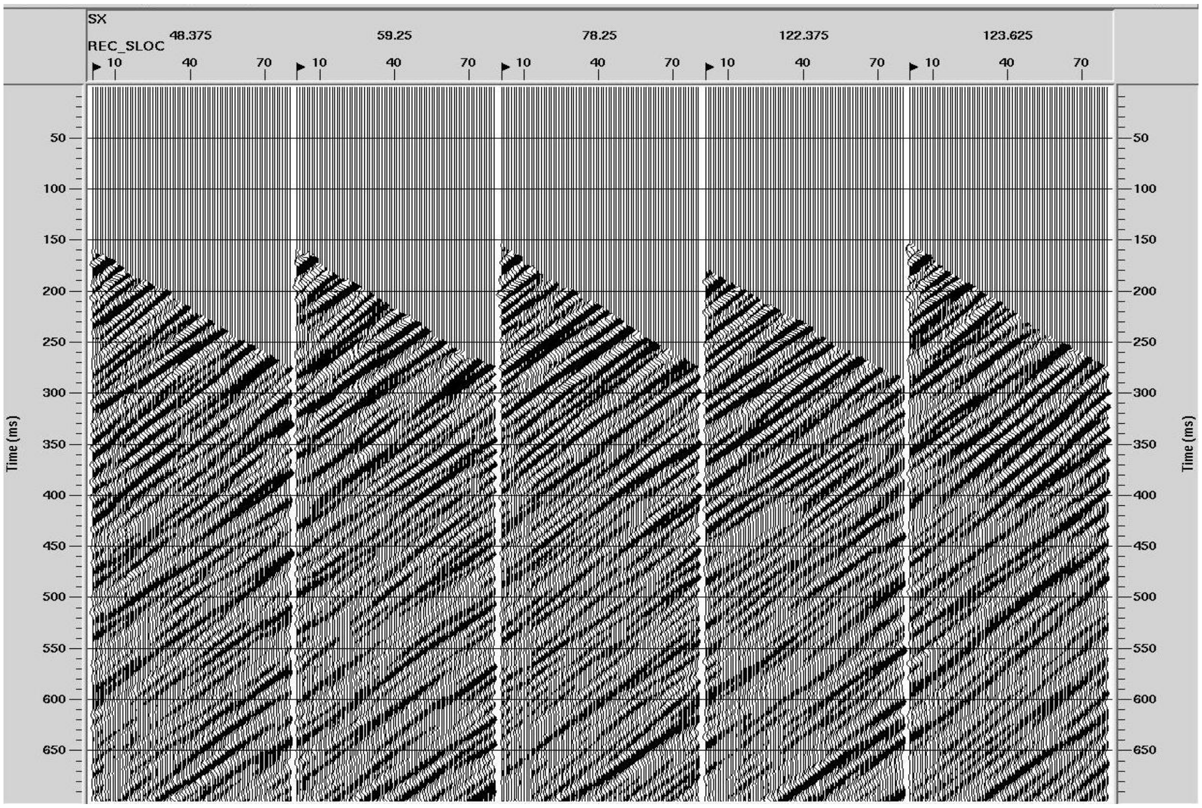

Figure 38. Upgoing baseline gathers East of well.

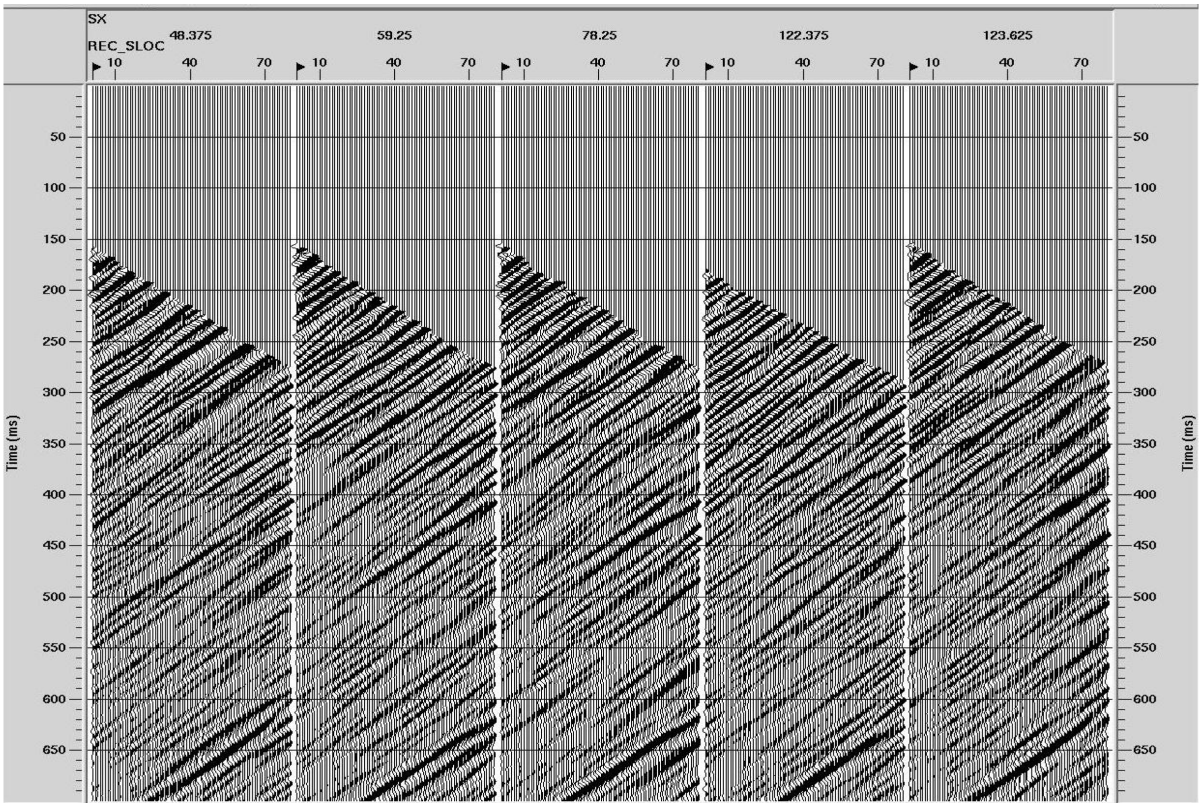

Figure 39. Upgoing monitor gathers East of well.

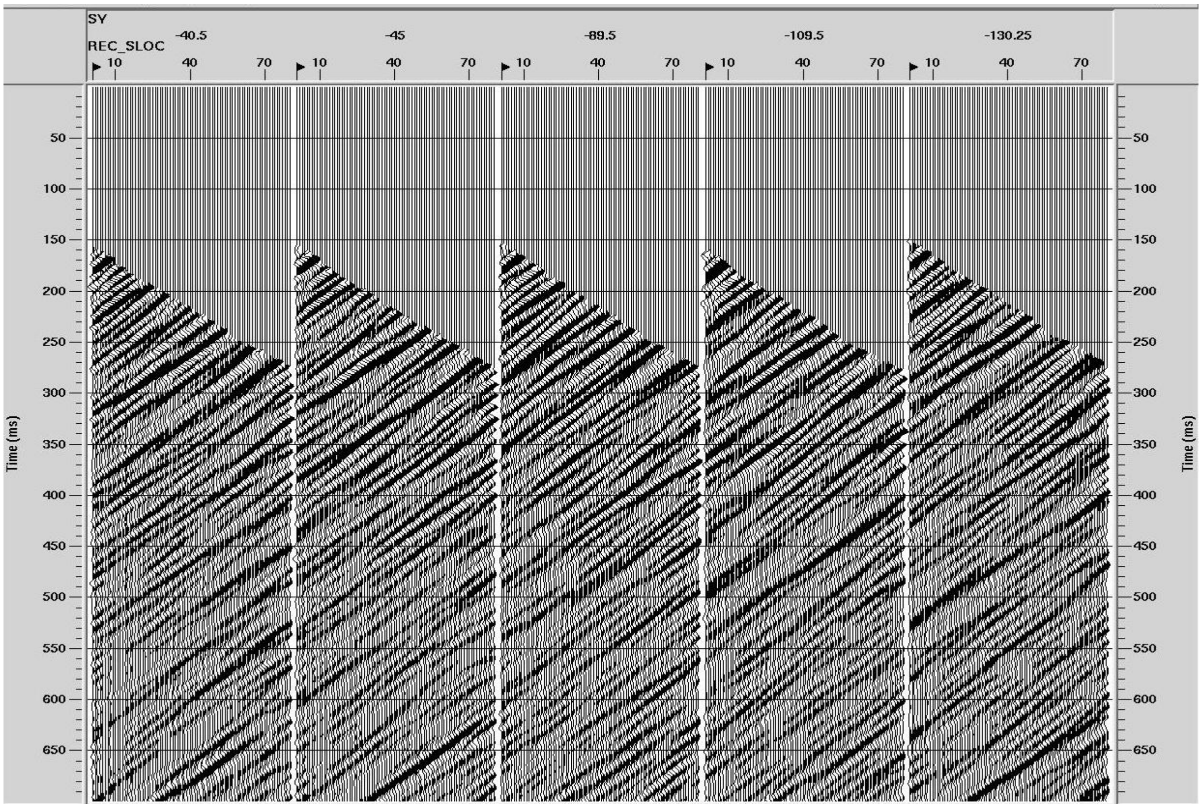

Figure 41. Upgoing baseline gathers South of well.

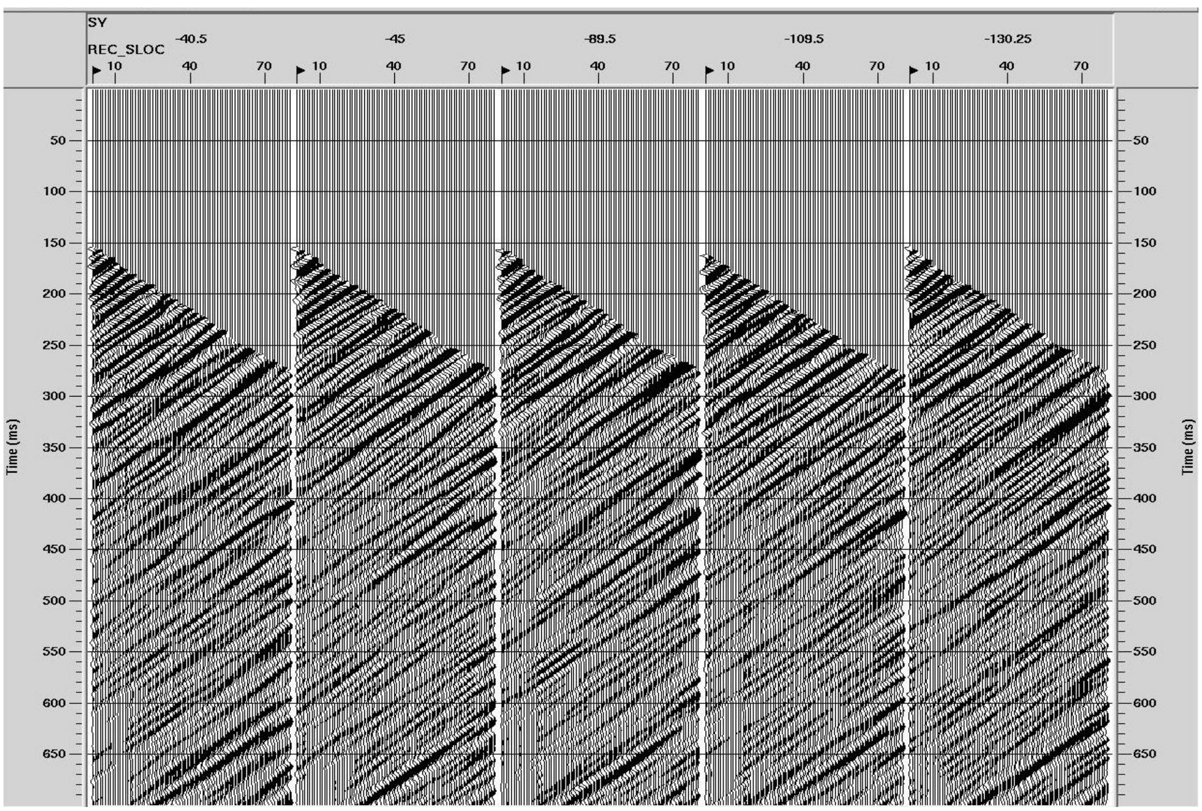

Figure 42. Upgoing monitor gathers South of well.

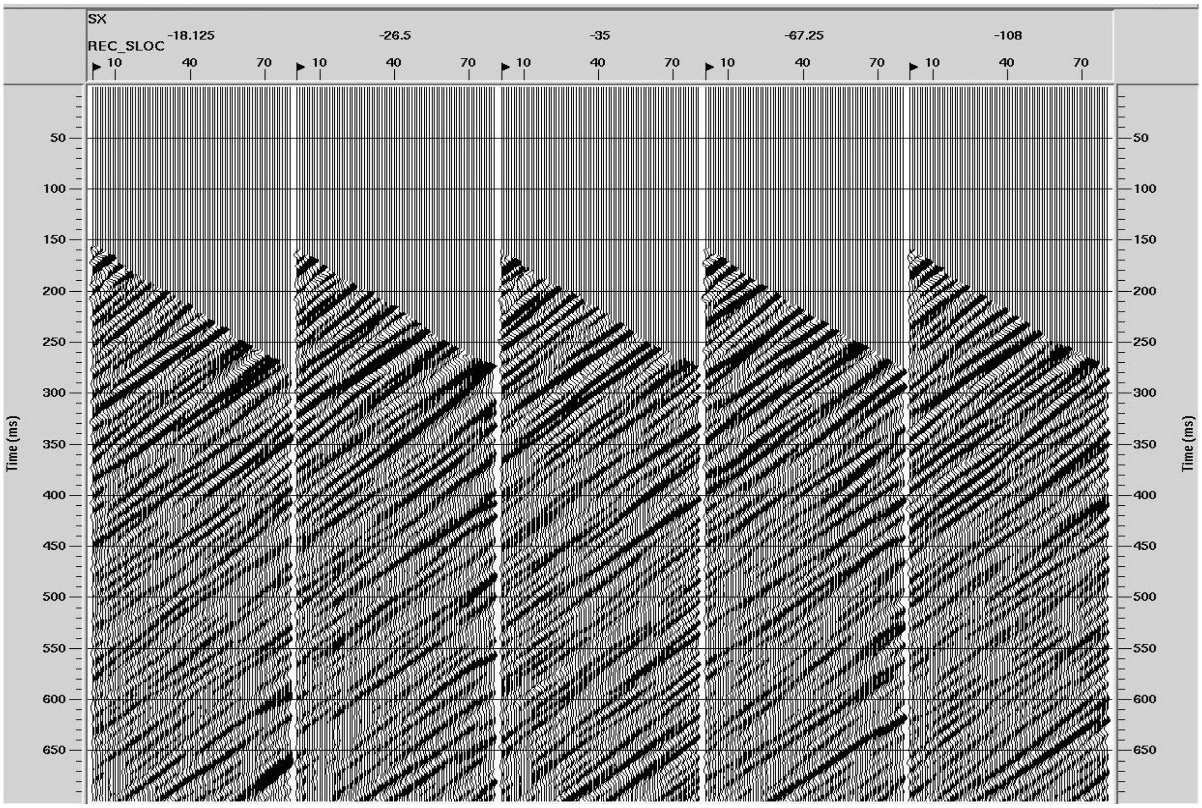

Figure 43. Upgoing baseline gathers West of well.

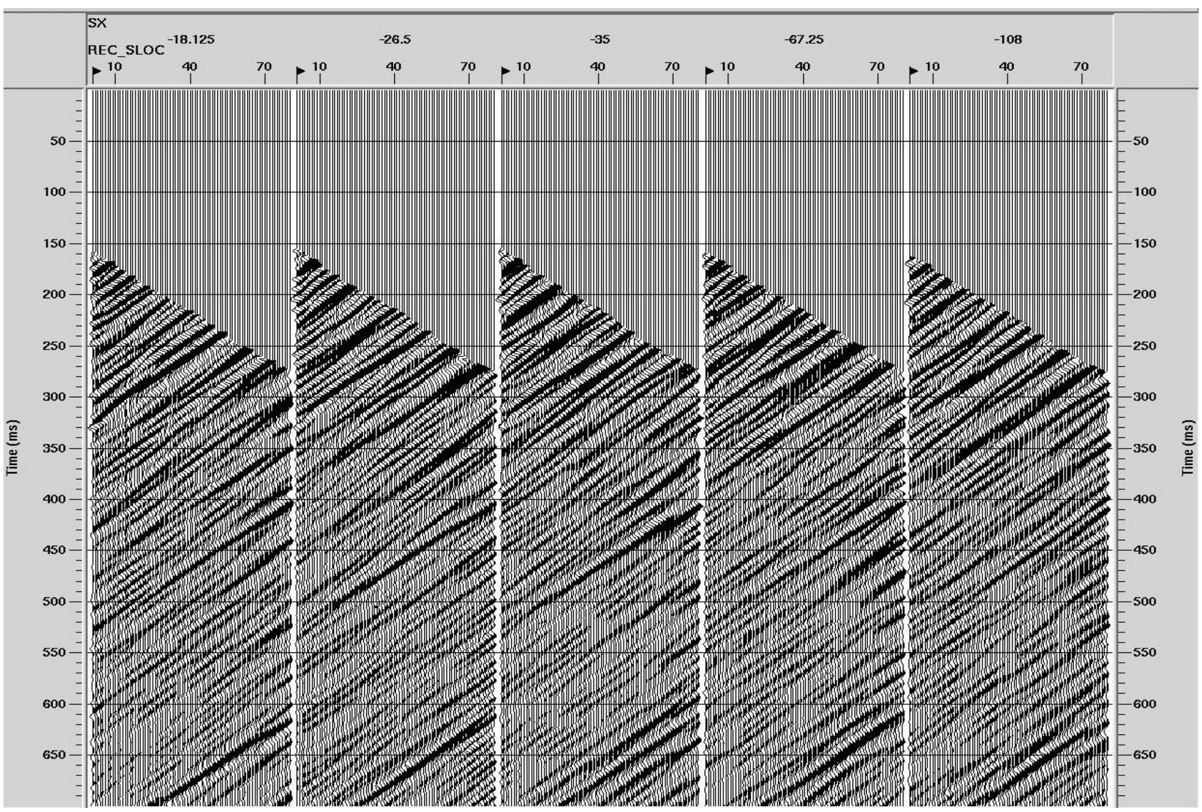

Figure 44. Upgoing monitor gathers West of well.

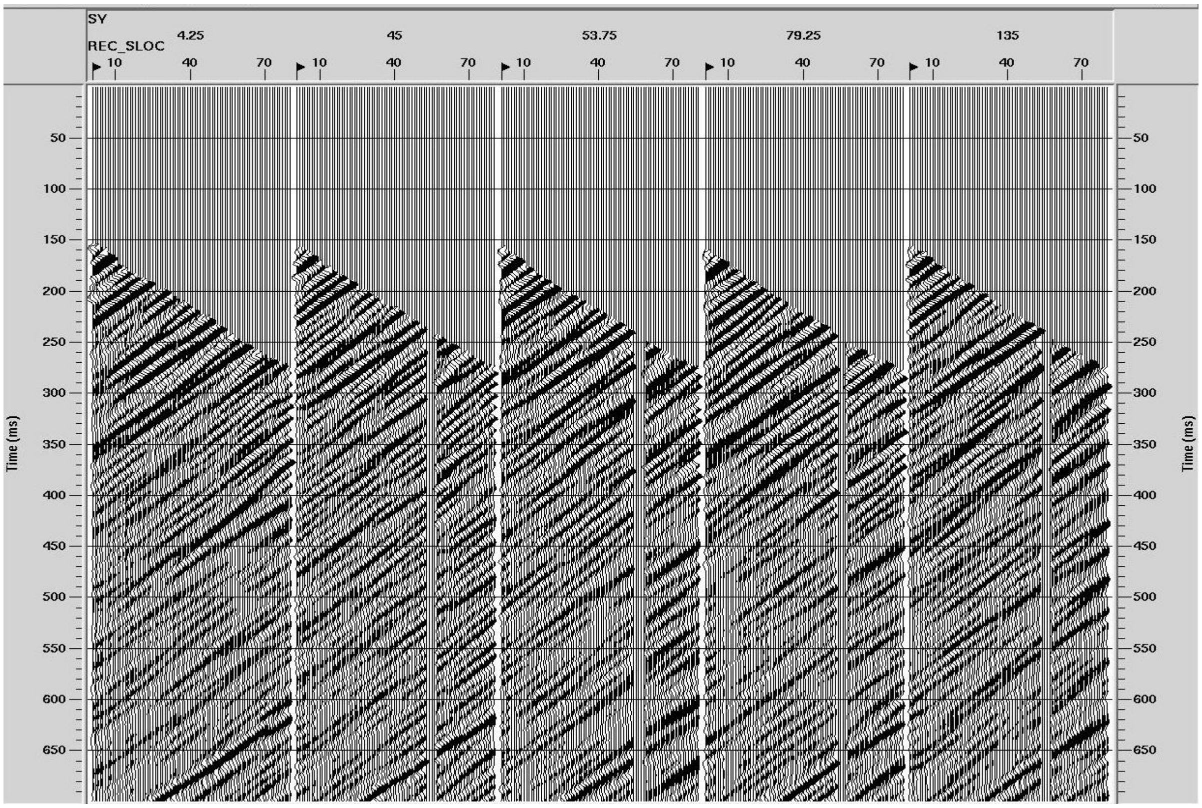

Figure 45. Upgoing baseline gathers North of well.

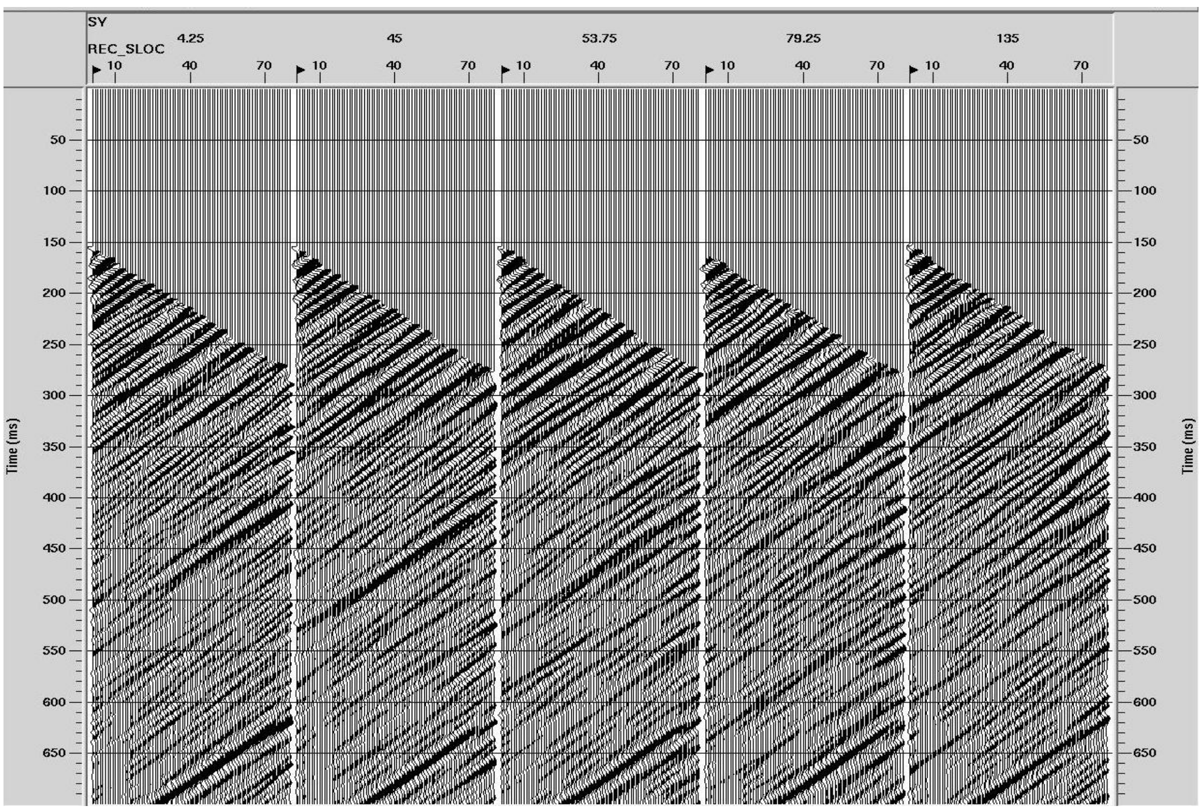

Figure 46. Upgoing monitor gathers North of well.

3.9 Imaging

All up-going wave field data, at coincident source point locations both Baseline and Monitor, were pre-stack depth migrated using an amplitude preserving Pre-stack Kirchhoff Depth Migration algorithm using the identical velocity model, as shown in Figure 31.

The depth migration was conducted with the following set of parameters:

- Maximum incidence angle: 45 degrees
- Maximum operator dip: 10 degrees
- True-amplitude compensation
- Maximum length: 8500ms
- Baseline and Monitor use only identical source locations

The resulting image volumes are depth volumes where the reference top elevation is given as 750 ft AMSL. The images are limited by the available source pattern. The source location impact is visible on both Baseline and Monitor images. However since both footprints are identical for Baseline and Monitor survey, we can still attempt to extract the relative time-lapse change. Amplitudes are preserved in the migration algorithm and amplitude values are normalized, such that low and high fold areas show consistent amplitudes. Both Baseline and Monitor data use the same velocity for depth migration.

Figure 47 shows an up-going wave field with the expected reflection time and depth labeled. Such as reflection signal will map into a subsurface depth image with amplitude and character changes.

Figures 48-51 show West-East and South-North image slices of the Baseline and Monitor through the borehole location. When comparing Baseline and Monitor images the shallow and deep marker horizons are clearly visible and correlatable. Key features match in Baseline and Monitor as they should, while detailed responses vary due to different noise conditions during Baseline and Monitor survey. Such noise conditions can cause variations of smaller scale reflection responses. Although the velocity model did not incorporate any subsurface dip in the vicinity of the borehole, a very small general up-dip to the North East is visible on all those slices.

Figure 52 and 52 show slices in the time domain and incorporate Zero Offset corridor Stacks. However, the nearest offset shot that was used to generate the corridors tended to have tube wave and other noise present which impacts the correlation of reflectivities with the images. In low noise areas the ties are visible.

The image character above 5000 ft is consistent between Baseline and Monitor, while below 5000 ft differences are more pronounced.

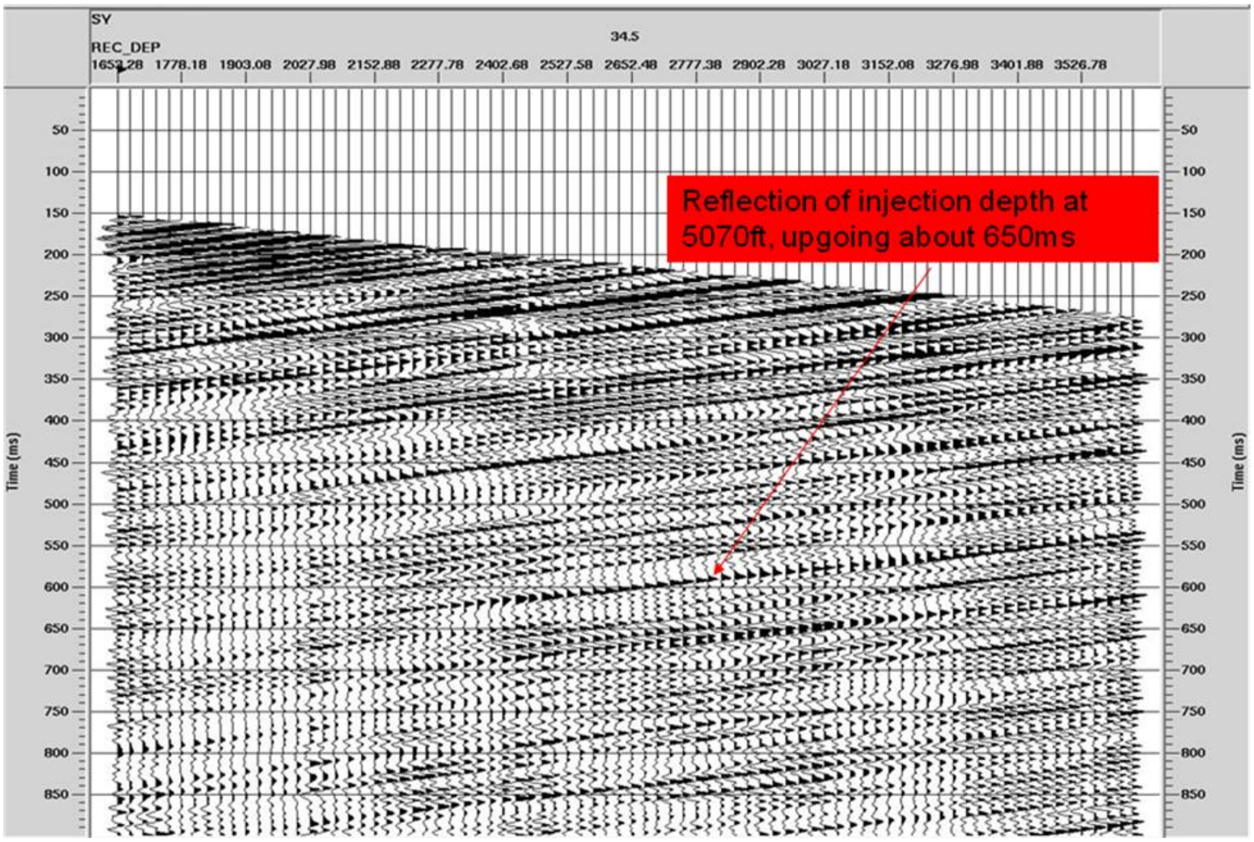

Figure 47. Approximate expected target reflection in monitor gather.

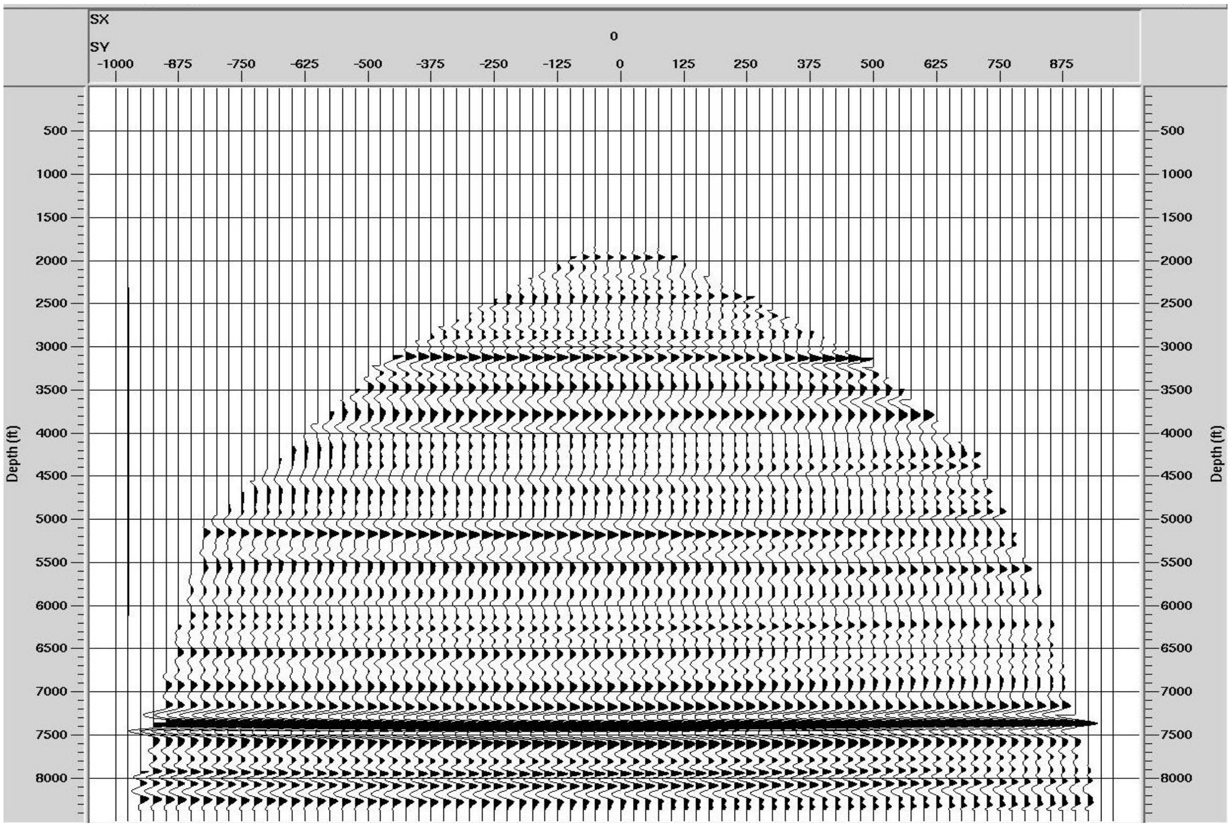

Figure 48. Depth migrated baseline image (South-North).

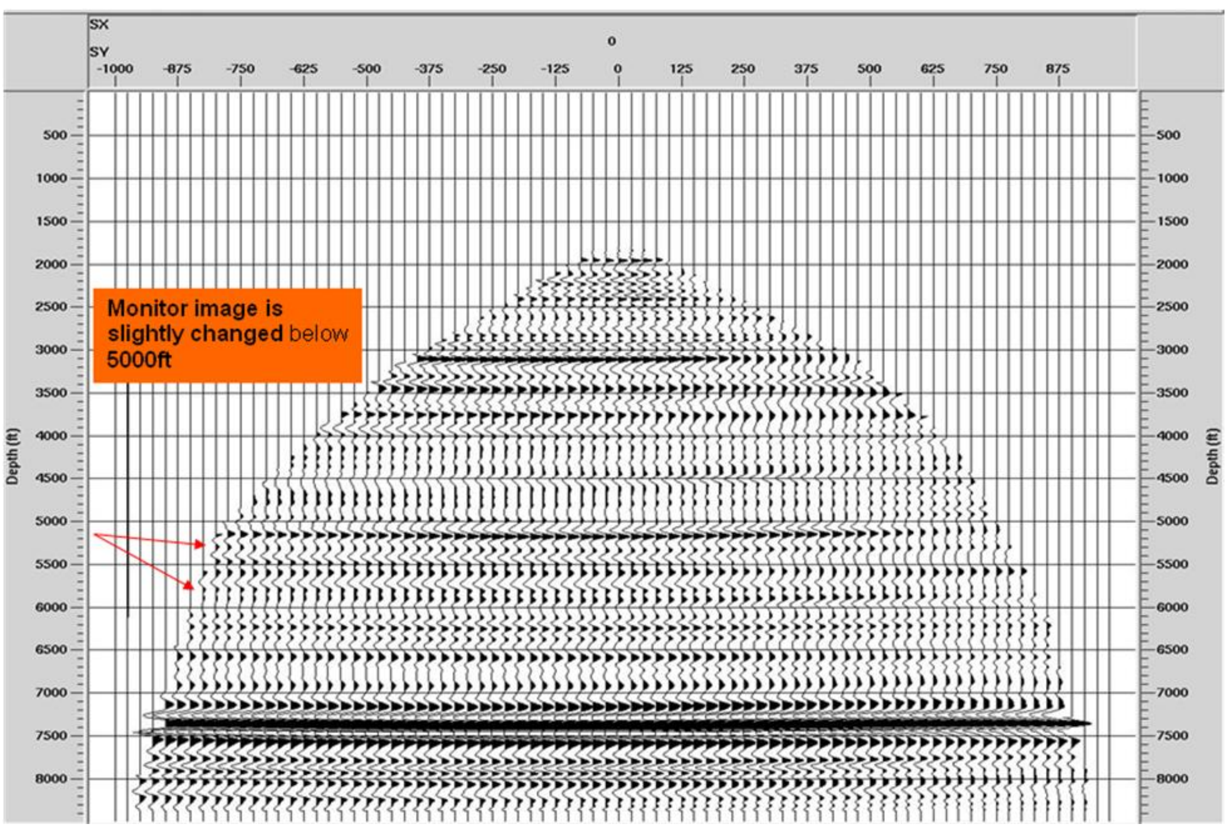

Figure 49. Depth migrated monitor image (South-North).

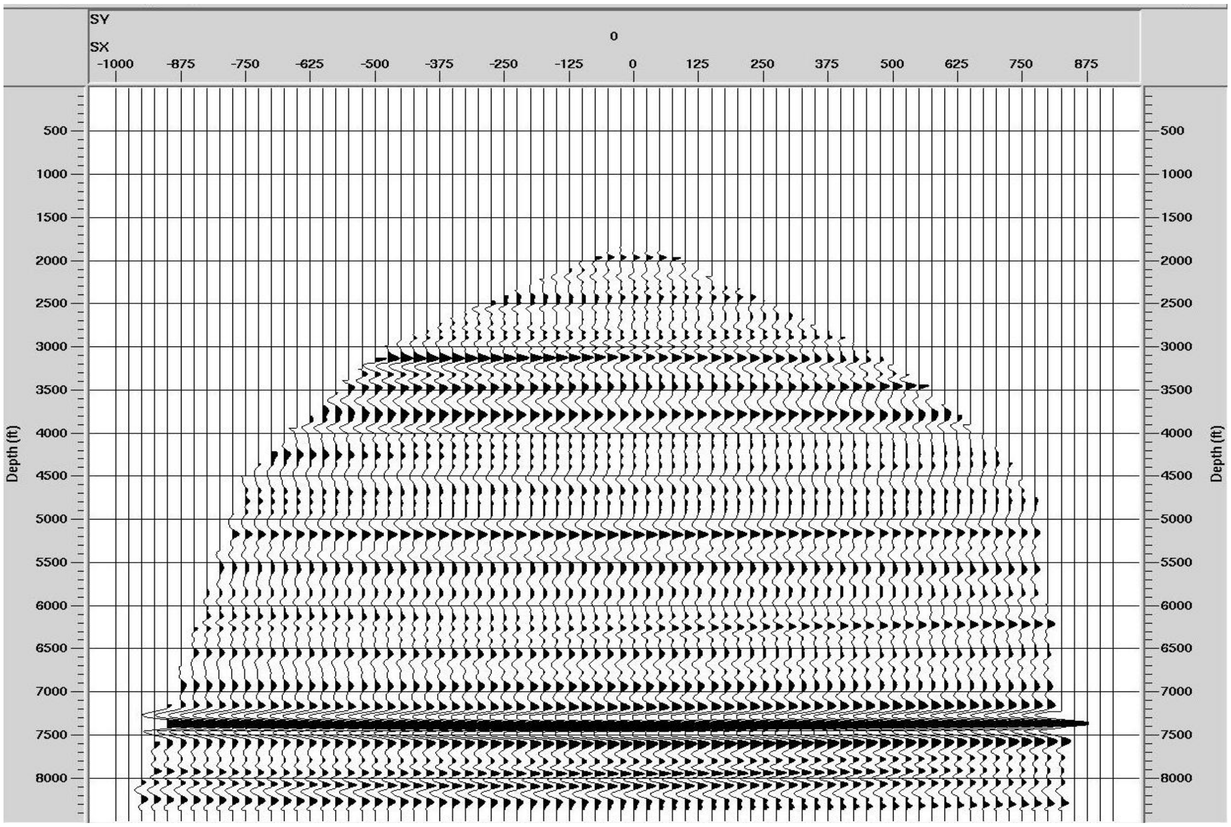

Figure 50. Depth migrated monitor image (West-East).

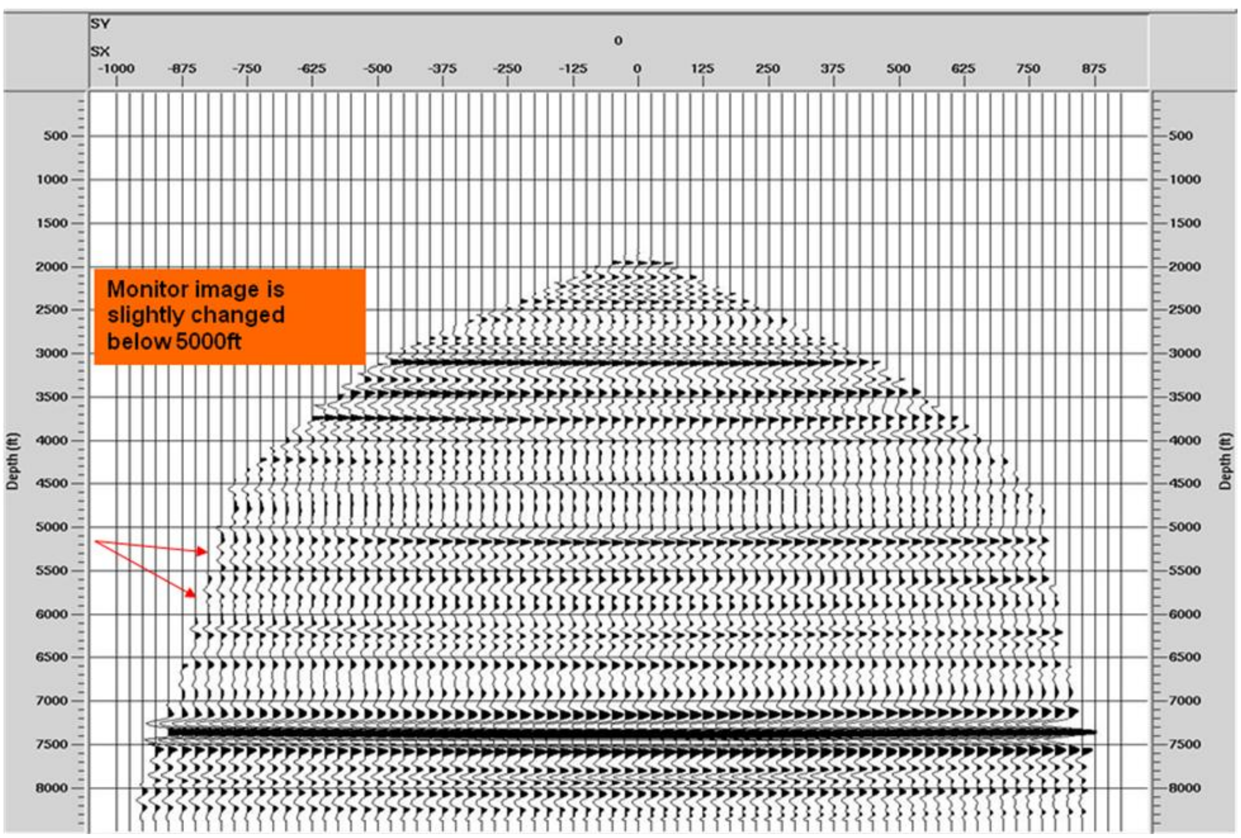

Figure 51. Depth migrated monitor image (West-East).

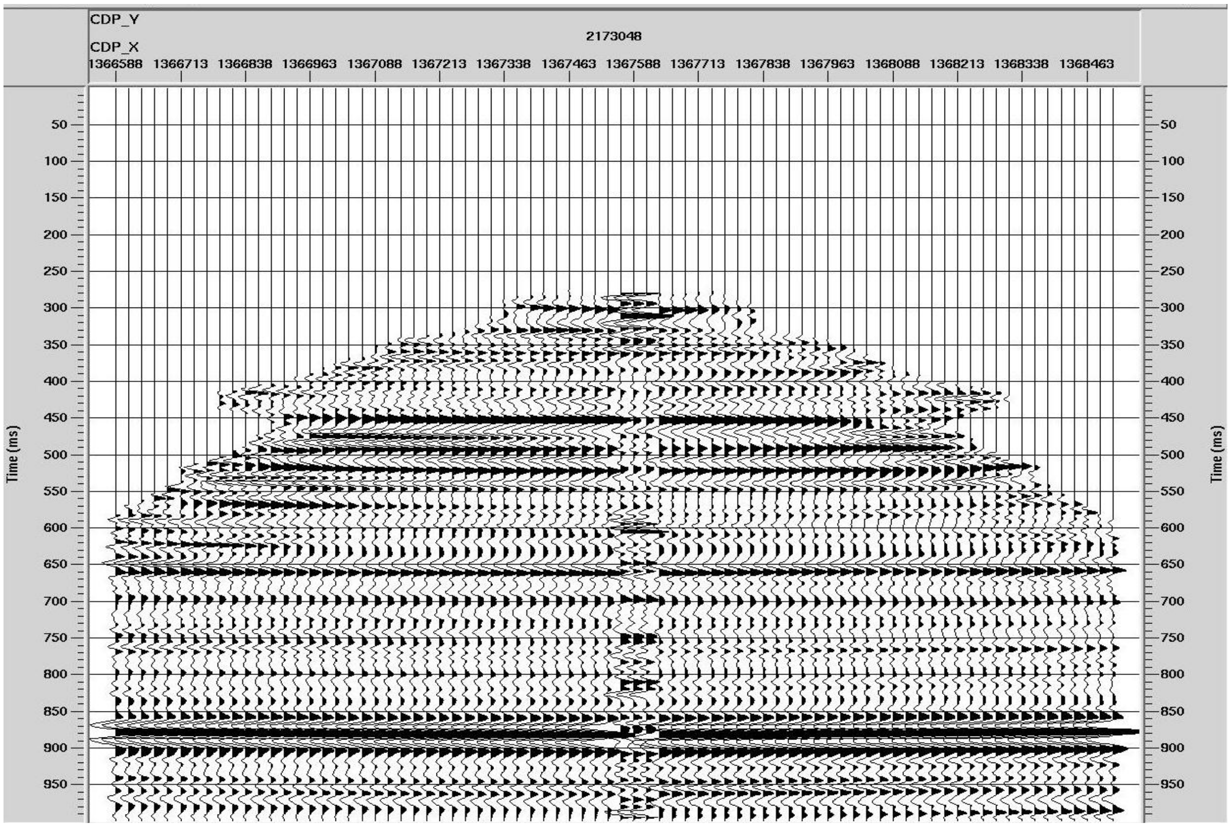

Figure 52. Depth migrated baseline image in time with corridor stack.

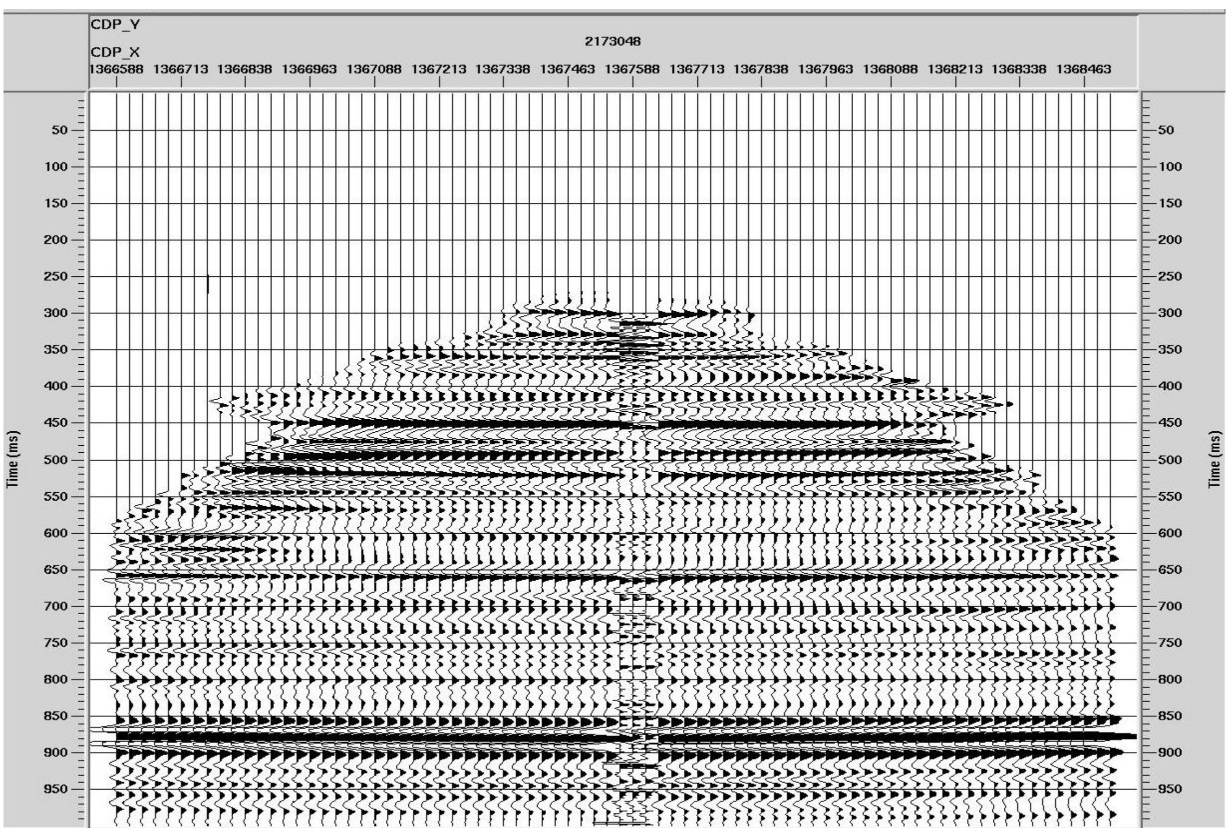

Figure 53. Depth migrated monitor image in time with corridor stack.

4.0 Time-Lapse Observations

During the deconvolution process we had applied the optimum deconvolution operator as estimated on the Baseline and the Monitor individually. The following Figure show the deconvolution operators for an identical set of the source points in comparison for Baseline and Monitor. As Figure 54 shows below, in general the Baseline source deconvolution operators (left) exhibit a greater variability than the Monitor deconvolution operators (right). Slight variations in deconvolution filter responses are visible for corresponding Baseline and Monitor pairs, but generally are consistent as applied.

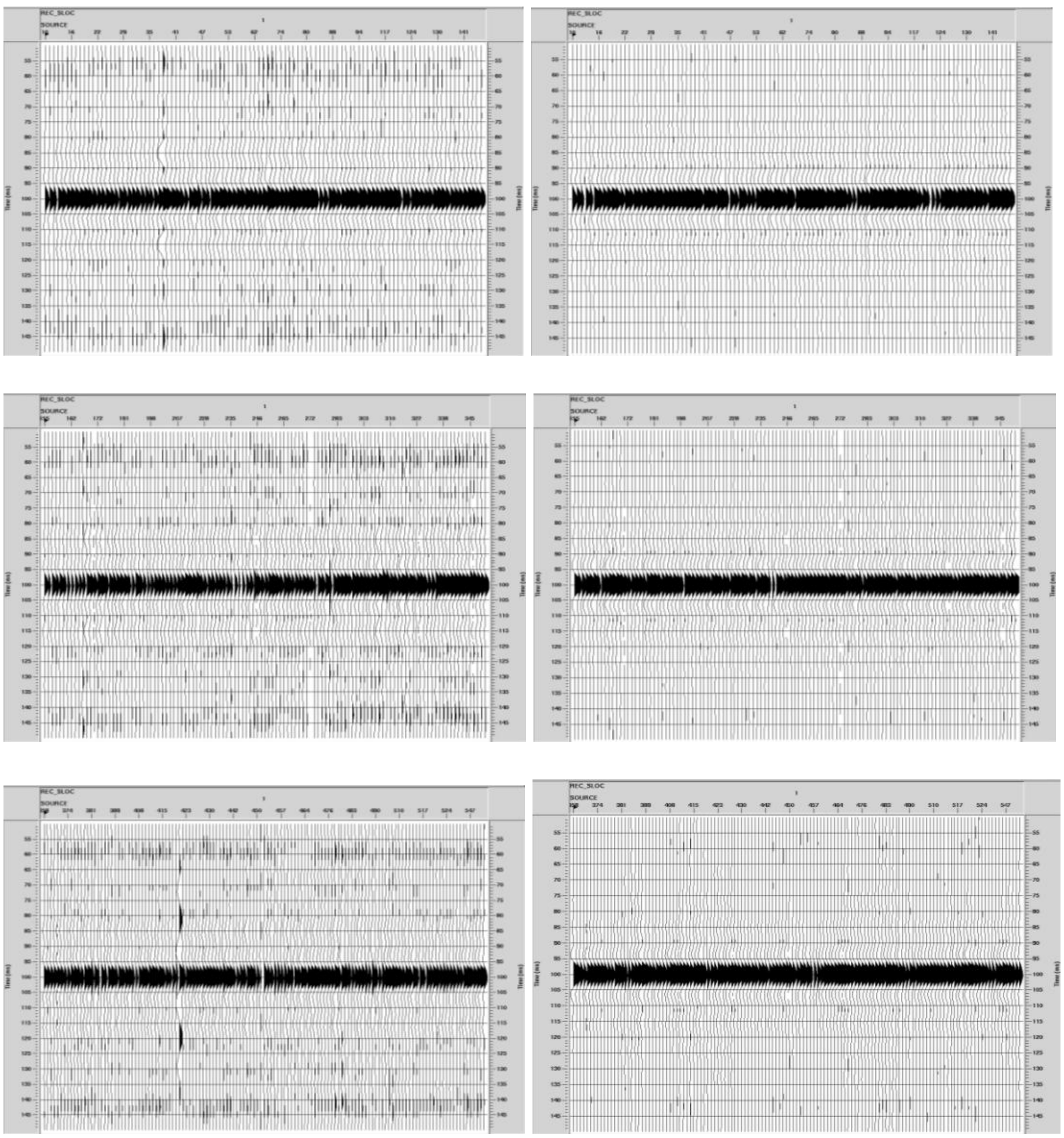

Figure 54. Decon operators for left) Baseline right) Monitor for each individual source location.

In an attempt to alleviate amplitude differences that might arise due to different noise patterns, source or near surface conditions, both Baseline and Monitor depth images were equalized by normalizing their RMS differences in a marker window above the injection zone. The estimated scale was applied to the Monitor, and subsequently the Baseline was subtracted from the Monitor. An additional residual image static shift was estimated, but the correlation based approach did not find any significant applicable shifts to be necessary to get a more accurate Baseline to Monitor image alignment.

While the previous Figures 48-53 show the overall slices, the following Figures focus on a smaller image window that includes the injection zone. Amplitude responses are continuous in the interior region of the image. As the edges of the images are approached, the low fold and limited source distribution causes inconsistent amplitudes at the edges. This is particularly visible on the left and right hand side of the difference image slices in Figure 57 and 60. Figure 55-57 show image slices extending from South to North, while Figures 58-60 show the corresponding West to East slices. The well is located at x=1367587 and y=2173048, roughly in the center of the slices.

After image subtraction the near-well amplitude residual extends in the north–easterly direction away from the injection well. The feature is highlighted on Figure 55-60 and corresponds to the depth slice as extracted at approx. depth 5170 in Figure 61, in close proximity to the CO2 injection interval.

Due to having limited and non-uniform source layout around the injection well due to permitting, environmental and logistical restrictions, and due to the receiver array restrictions to be placed safely high in the well, the incidence angle range for the depth imaging was limited. The depth image is constructed using near vertical reflection responses, and thus limits the lateral resolvability. The vertical resolution however is maintained.

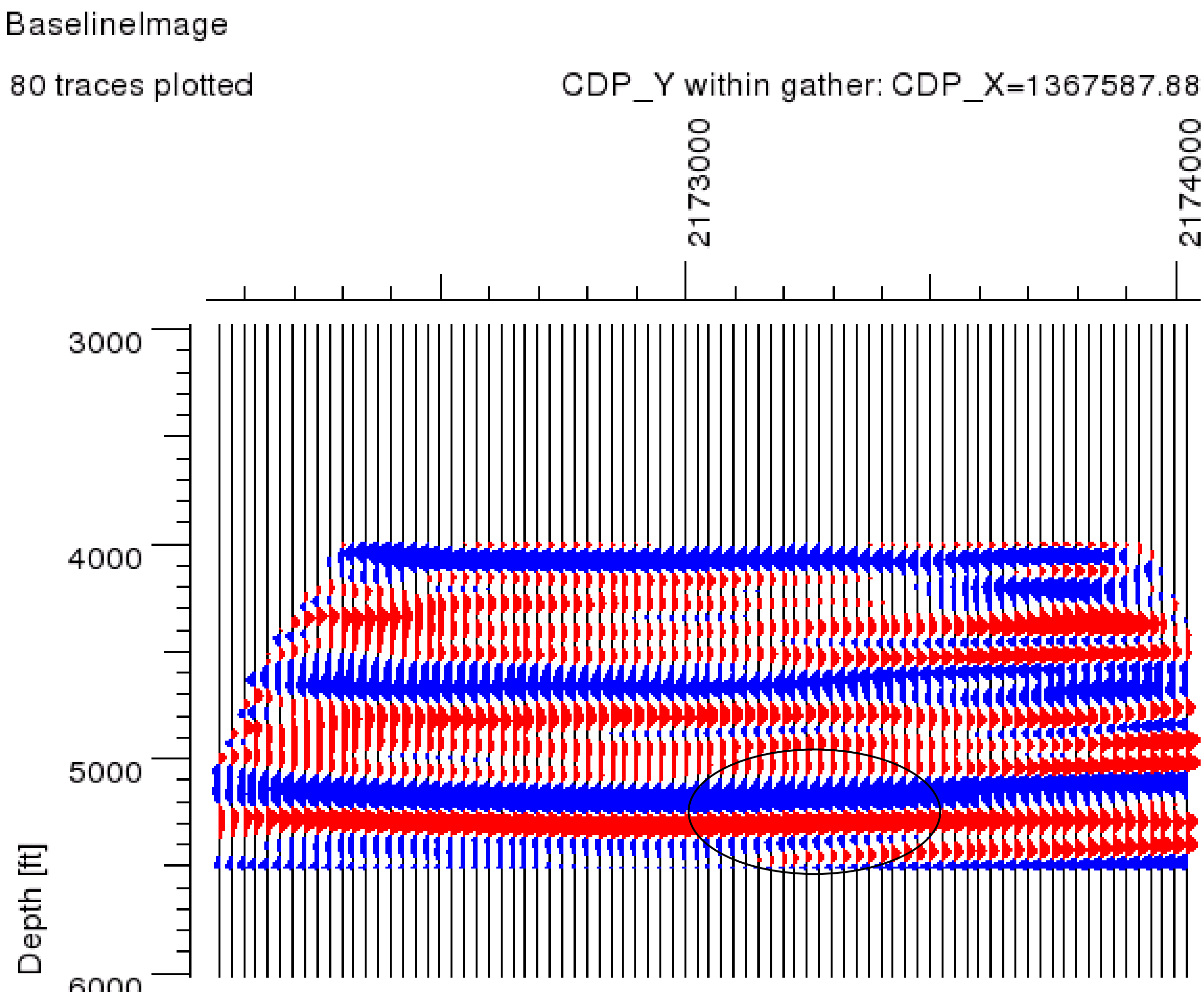

Figure 55. Depth migrated baseline image South-North slice in depth.

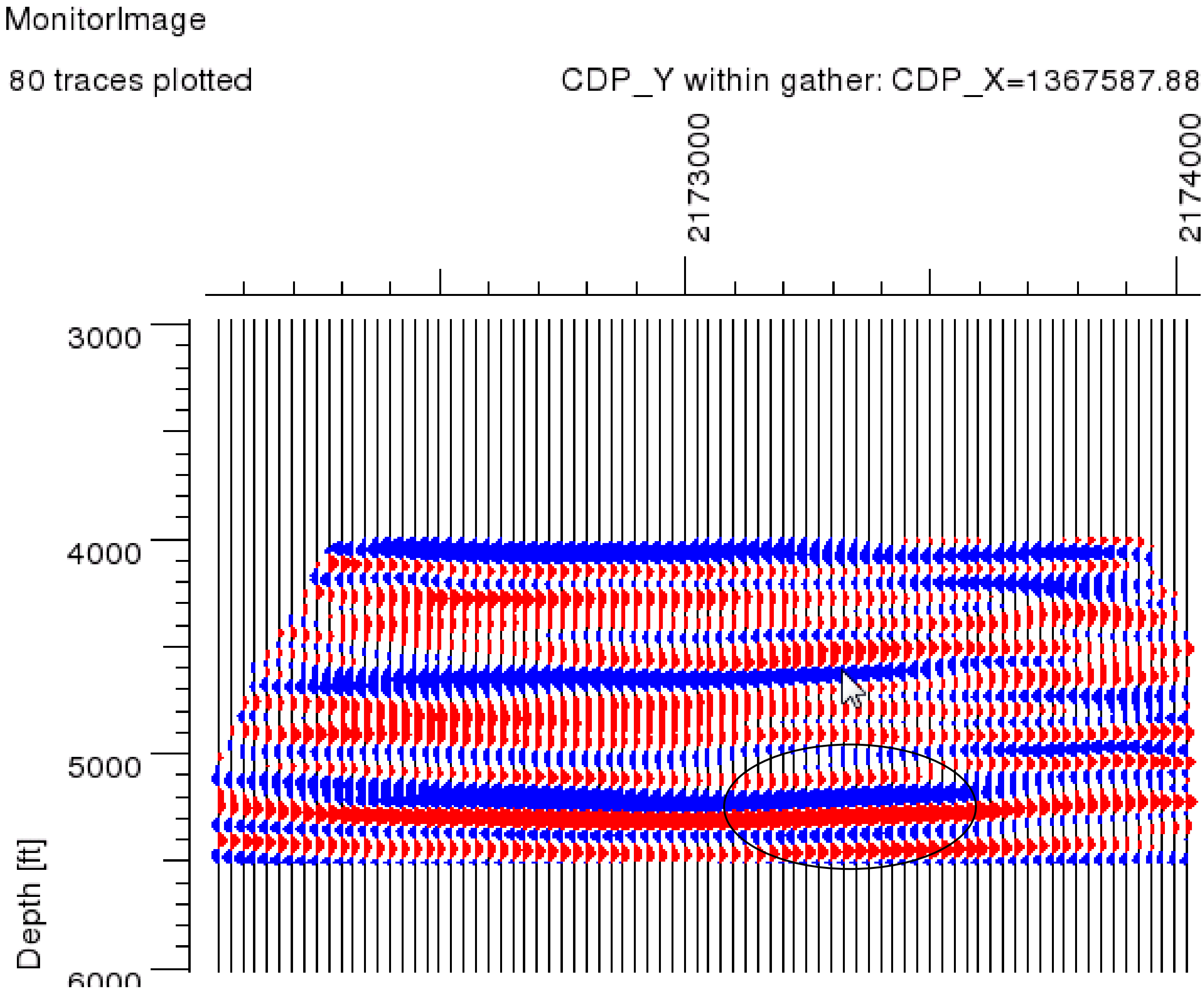

Figure 56. Depth migrated monitor image South-North slice in depth.

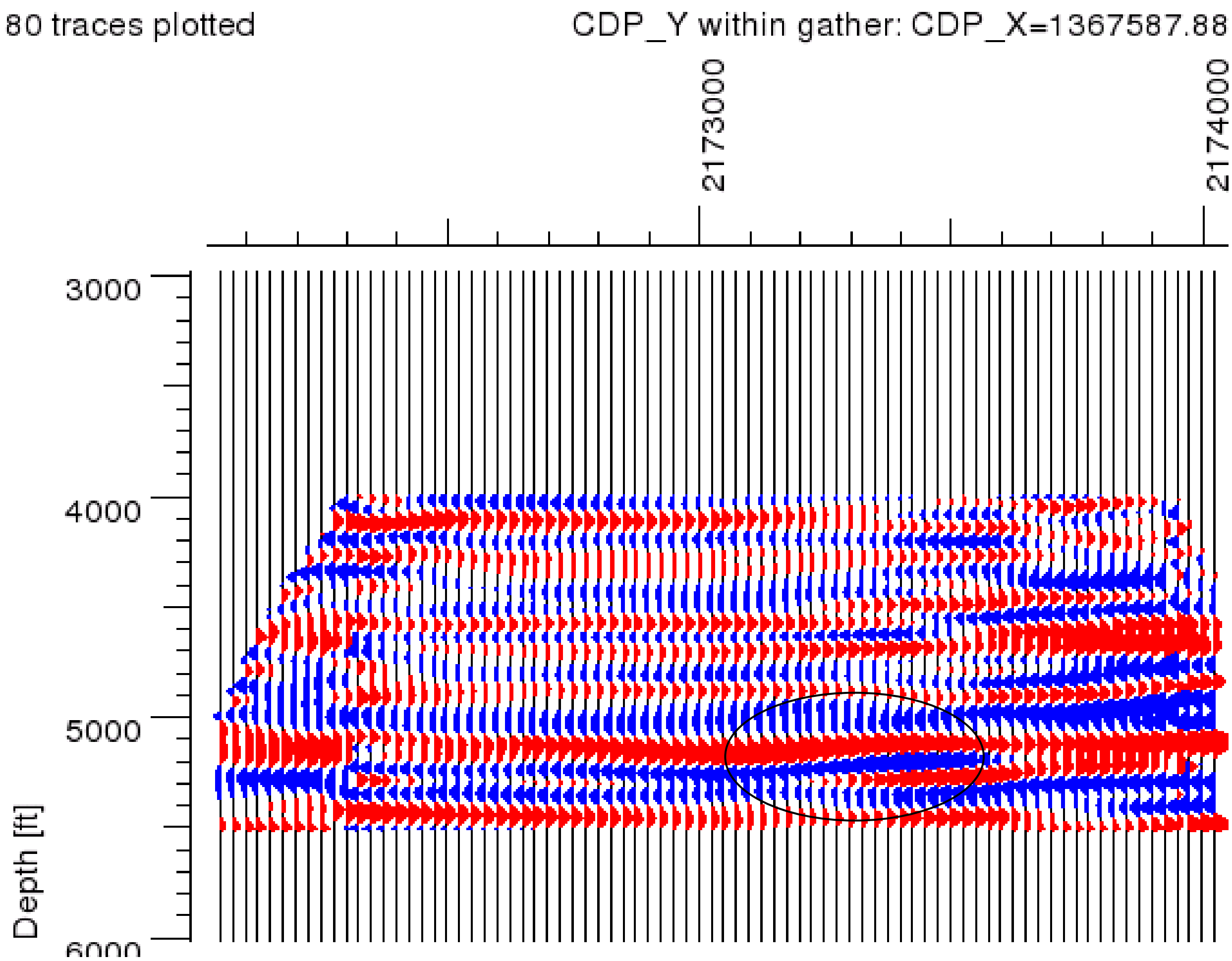

Figure 57. Depth migrated difference image South-North slice in depth.

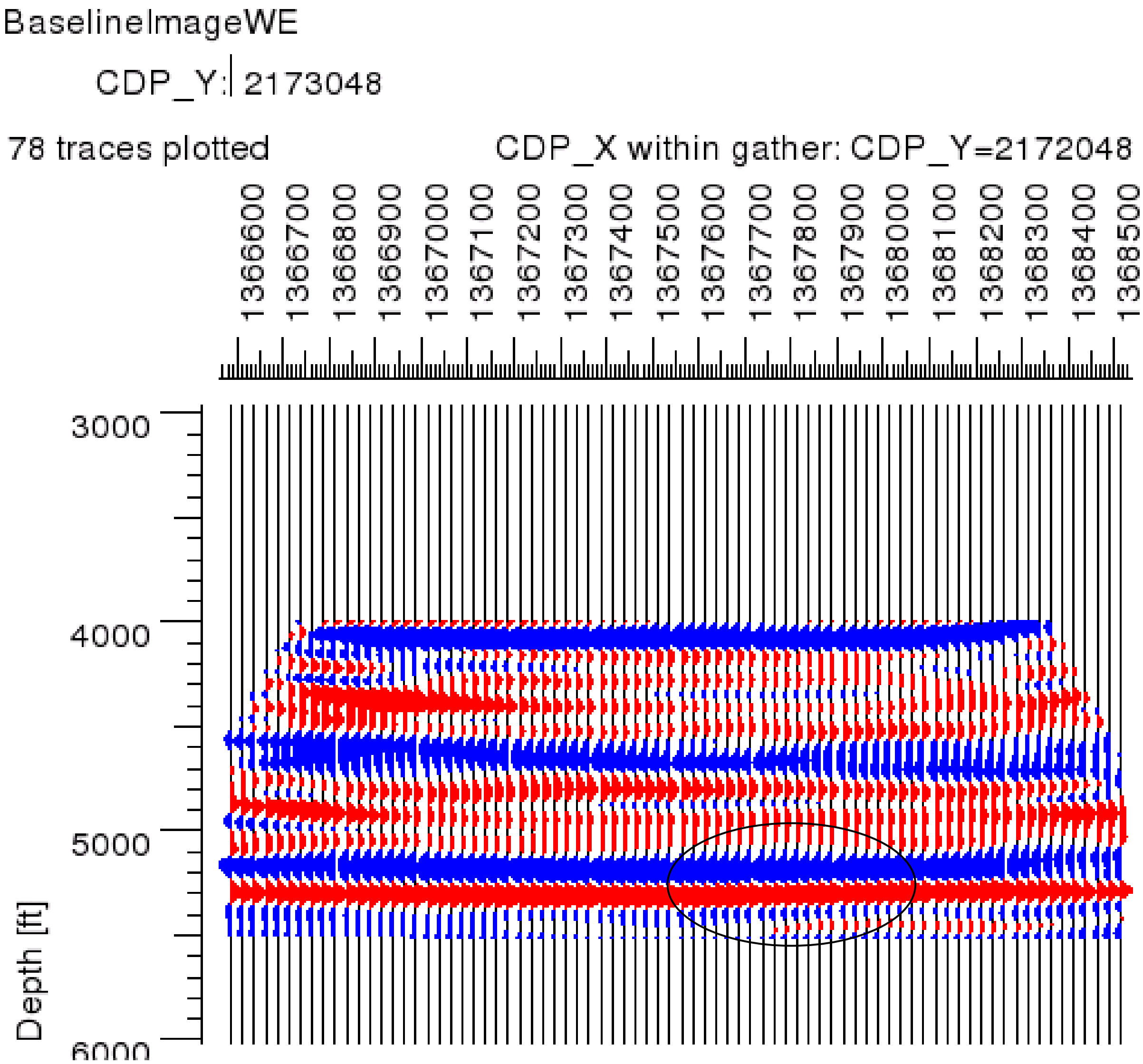

Figure 58. Depth migrated baseline image West-East slice in depth.

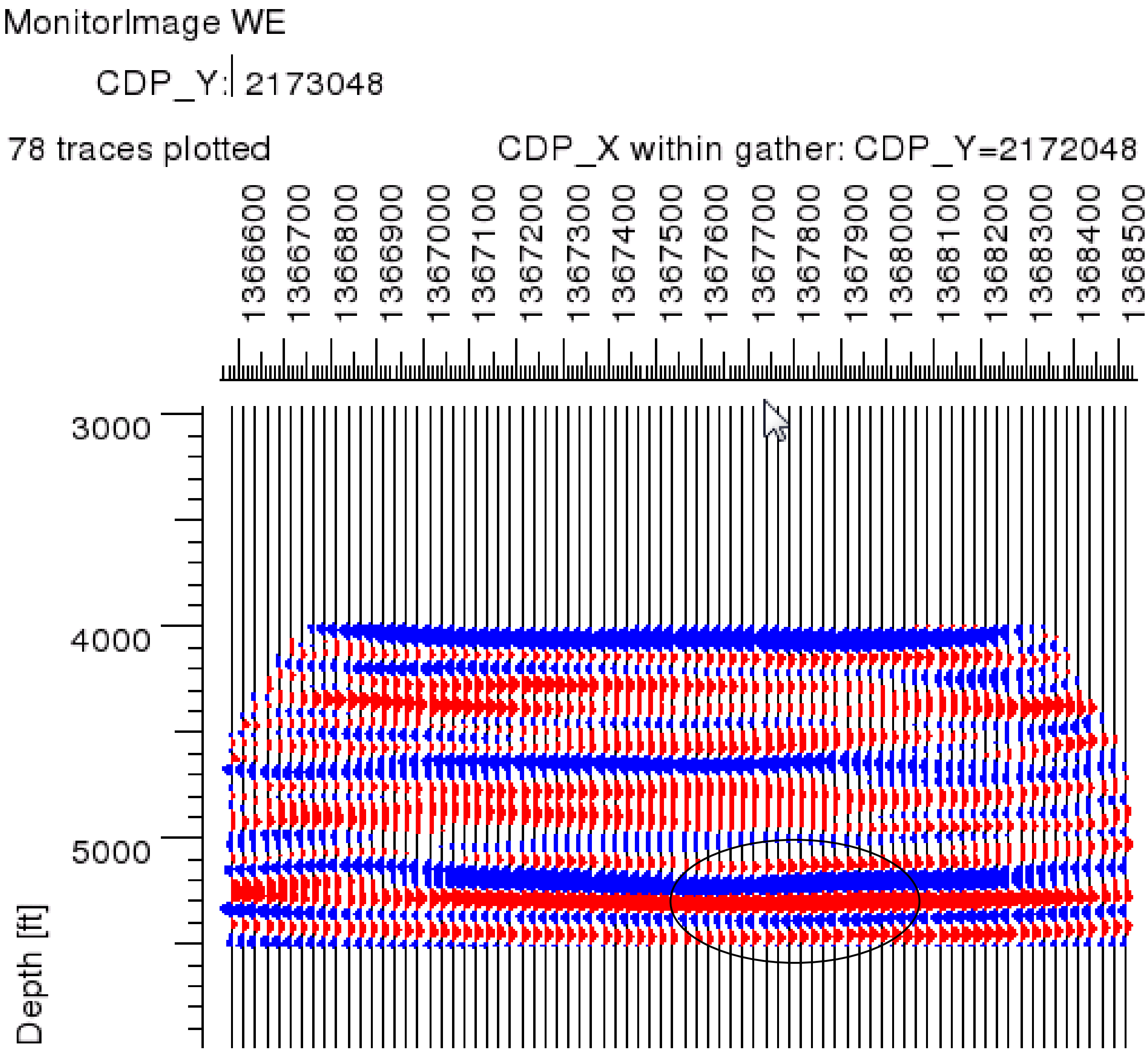

Figure 59. Depth migrated monitor image West-East slice in depth.

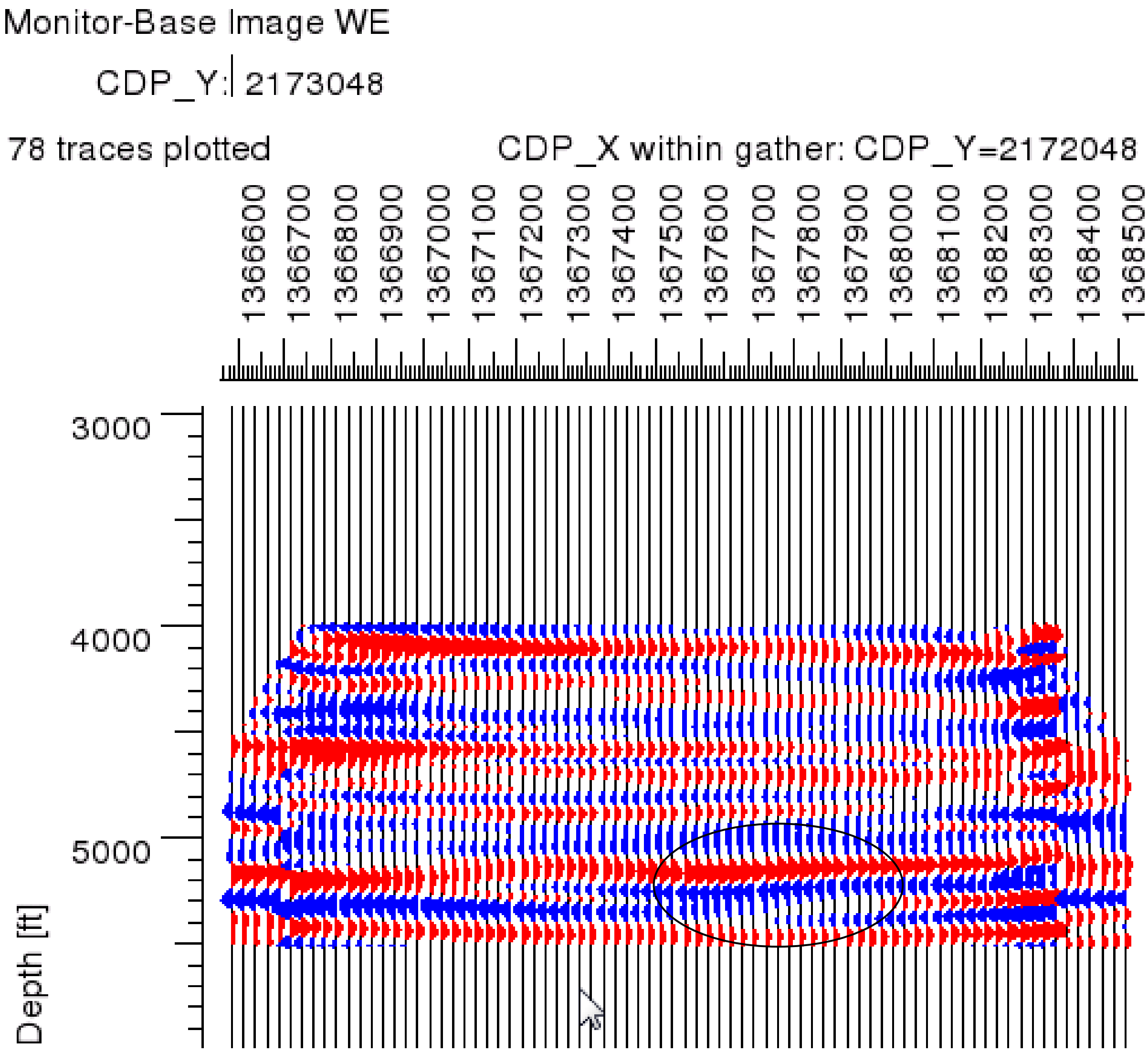

Figure 60. Depth migrated difference image West-East slice in depth.

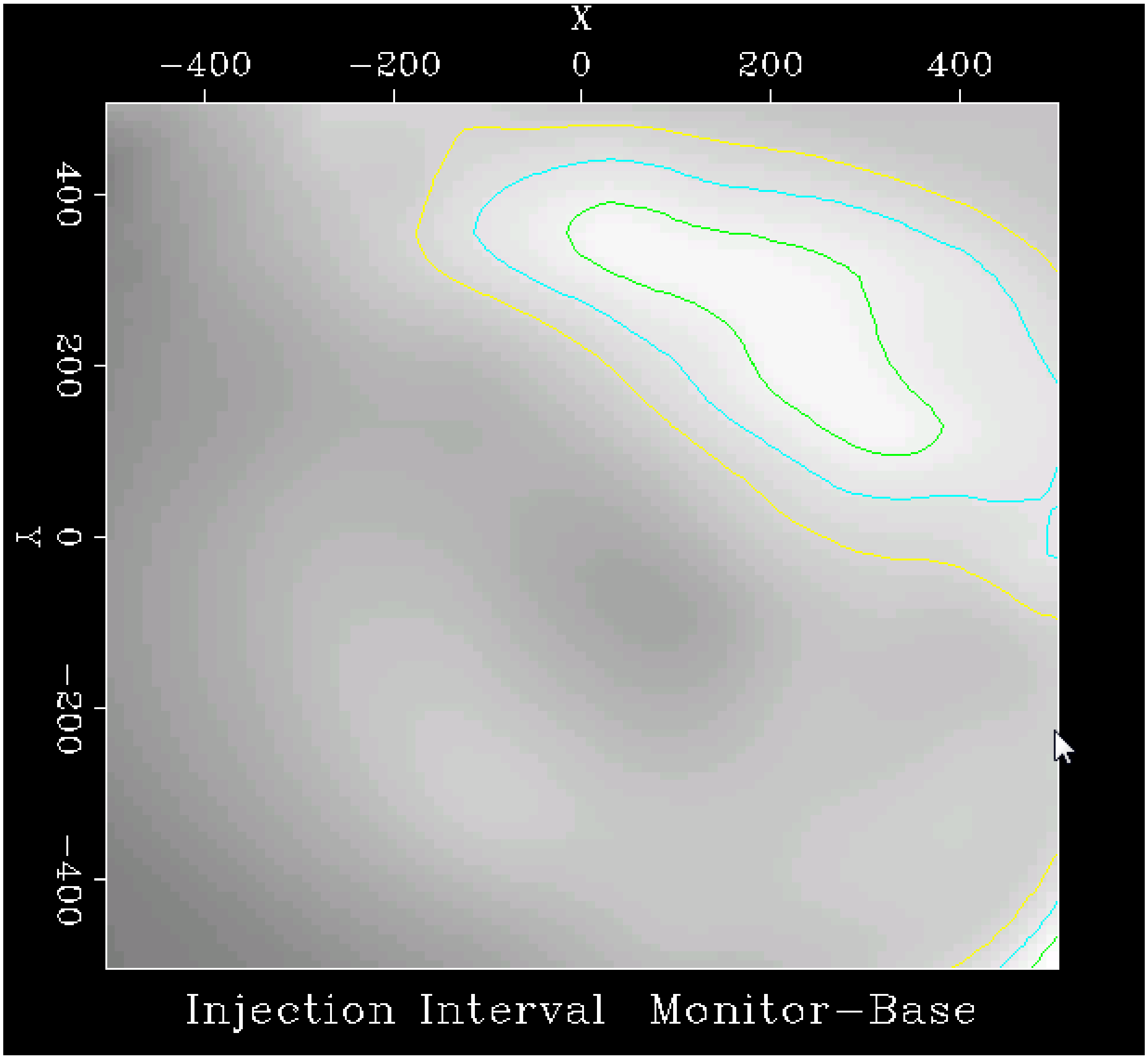

Figure 61. Depth migrated difference image depth slice with a large amplitude difference contour. Local coordinates from injection well (0,0), limited to +/- 500 ft from injection well.

5.0 Conclusions

A spatially limited time-lapse VSP data set was collected before and after CO2 injection into a storage formation. Although the data exhibited noise conditions that were not ideal, the subsequent processing steps tried to minimize those effects and isolated the up-going reflected signal for imaging purposes. Using a consistent 3D velocity model for imaging both the Baseline and Monitor data set ensured that the kinematics of the overburden were identical for the data sets. In and around the injection zone the velocities and thus the images are expected to differ. After imaging both Baseline and Monitor survey, the respective image volumes were normalized based on a marker window above the injection zone, such that RMS amplitude values were consistent between the two data sets. The difference image shows amplitude variations in and around the injection window with a slight up-dip to the NE direction.

Appendix A. Delivered Digital Data.

1) KGS_3DVSP_Blan1_TrueXYZBaseline.segy (Baseline VSP data, SEGY)
2) KGS_3DVSP_Blan1_TrueXYZMonitor.segy (Monitor VSP data, SEGY)
3) Velocity Model (SEGY)
4) KGS_3DVSP_Blan1_Baseline_Depth-122010.segy (Baseline Image, SEGY)
5) KGS_3DVSP_Blan1_Monitor_Depth-122010.segy (Monitor Image, SEGY)

6) Summary Report

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