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Overview of the Kentucky Geological Survey No. 1 Hanson Aggregates Well, Carter County, Kentucky

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Our Mission

The Kentucky Geological Survey is a state-supported research center and public resource within the University of Kentucky. Our mission is to support sustainable prosperity of the commonwealth, the vitality of its flagship university, and the welfare of its people. We do this by conducting research providing unbiased information about geologic resources, environmental issues, and natural hazards affecting Kentucky.

Earth Resources—Our Common Wealth

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Technical Level

Statement of Benefit to Kentucky

The KGS No. 1 Hanson Aggregates well was drilled in northern Carter County to learn about the underground carbon dioxide storage capacity of rocks underlying eastern Kentucky. Information from this well will be used to evaluate the feasibility of commercial carbon-storage reservoirs in eastern Kentucky if industrial CO_2 emissions are regulated in the future.

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Overview of the Kentucky Geological Survey No. 1 Hanson Aggregates Well, Carter County, Kentucky

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Abstract

The Kentucky Geological Survey drilled the No. 1 Hanson Aggregates well in northern Carter County, Ky., to assess the carbon dioxide storage capacity and confining intervals in the Middle Cambrian–Upper Ordovician section in the southern Appalachian Basin, north of the Rome Trough. The well was drilled to a total depth of 4,835 ft, penetrating the Mississippian–Middle Cambrian Paleozoic section and 120 ft of Neoproterozoic Grenville granite gneiss. Steel casing was cemented to the surface at 350 ft and 2,944 ft to isolate the deep wellbore from the near-surface aquifer and provide anchors for pressure-control equipment. Eight cores totaling 453 ft and 30 rotary sidewall cores were cut, and an extensive suite of geophysical logs, including imaging logs, was run in the borehole. Core plugs were analyzed in the laboratory to determine porosity and permeability, triaxial rock mechanical strength, and capillary entry pressures for shale core plugs; thin sections were taken of sandstone and carbonate reservoir rocks. From these data, three intervals were selected for formation-water sampling, step-rate pressure testing to determine in-situ rock strength, and determining reservoir porosity and permeability parameters: the Maryville sand–Basal sand section, middle Copper Ridge Dolomite, and Rose Run Sandstone. Although CO_2 injection testing was cost-prohibitive, the project has otherwise successfully delivered the high-quality data required to assess CO_2 storage capacity and subsurface confinement in the southern Appalachian Basin of northeastern Kentucky.

Introduction

The Kentucky Geological Survey drilled the No. 1 Hanson Aggregates stratigraphic research well in northern Carter County, Ky., to test reservoir and rock properties in the southern Appalachian Basin for potential as deep saline reservoirs for carbon dioxide storage in the subsurface (Bowersox and others, 2013) (Fig. 1). A cooperative landowner, Hanson Aggregates, provided the location inside the Eastern Kentucky Coal Field boundary, as mandated by the legislation that enabled KGS's carbon storage research. Budget limitations necessitated a well located where all strata above Precambrian basement could be penetrated at a total depth less than 5,000 ft, however. Because the No. 1 Hanson Aggregates was a one-time research well, all possible geological, geophysical, and petroleum engineering data were collected within the budget constraints. As a result, a unique data set, one unlikely to be reproduced in its entirety by future research wells, has been assembled. This data set is available through the KGS Oil and Gas Records Database.

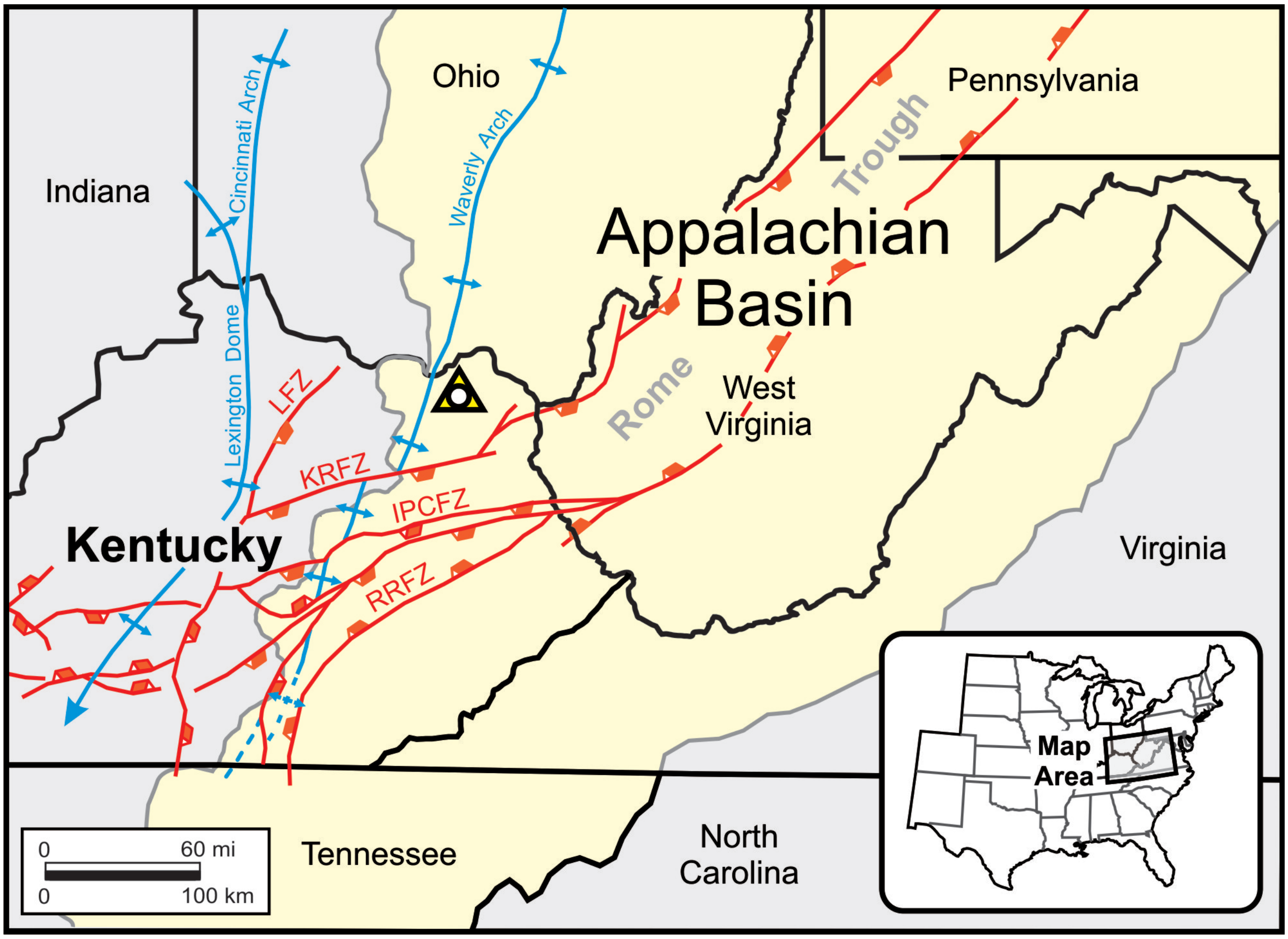


Figure 1. Location of the Kentucky Geological Survey No. 1 Hanson Aggregates well, Carter County. Yellow triangle = well. LFZ = Lexington Fault Zone. KRFZ = Kentucky River Fault Zone. IPCFZ = Irvine–Paint Creek Fault Zone. RRFZ = Rockcastle River Fault Zone. The well is located on the western flank of the Waverly Arch, 22 mi north of the Kentucky River Fault Zone.

Characterization of the Well Site

The No. 1 Hanson Aggregates well was drilled in northern Carter County, near the western margin of the southern Appalachian Basin (Fig. 1). After the landowner, Hanson Aggregates, was contacted and a site-use agreement was negotiated, we conducted a preliminary environmental site assessment to identify any issues that might have prevented using the site, an abandoned tobacco field. The site proved to be environmentally acceptable, and the well was constructed on about 1 acre of sloping ground, which required a highwall cut on the southwest side of the site. Limestone aggregate was trucked in to fill and level the well pad, control erosion and dust, and safely support the weight of the drilling rig. All well-site drainage was channeled away from a nearby creek by silt fences surrounding the well pad. Pits for holding drilling fluid and cuttings were lined with heavy plastic to prevent waste-fluid infiltration. After the well site was abandoned and remediated, the gravel, drill cuttings, and pit liners were removed to a licensed landfill, the surface was recontoured, and the site was hydroseeded for erosion control.

Geologic Summary

The No. 1 Hanson Aggregates well was drilled about 22 mi north of the Kentucky River Fault Zone and Rome Trough, a Cambrian structural extensional basin in eastern Kentucky underlying the Appalachian Basin (Hickman and others, 2015) (Fig. 1). This location was chosen so that we could test potential injection and storage intervals encountered in nearby wells; these intervals included the Knox Group carbonates and Rose Run Sandstone, and sandstones in the Conasauga Group and Basal sand intervals. The well site was constructed on the Cowbell Member of the Borden Formation (Philley and Chaplin, 1976) and drilled to a total depth of 4,835 ft, penetrating the entire Middle Cambrian–Mississippian section and 120 ft of Neoproterozoic Grenville granite gneiss (Fig. 2) (Bowersox and others, 2013). Depths of the tops of stratigraphic units encountered in the No. 1 Hanson Aggregates well are listed in Table 1. In the region around the No. 1 Hanson Aggregates well, north of the Kentucky River Fault Zone the Knox is near-horizontal, dipping about 1° east-southeast, whereas in the Rome Trough, it dips about 4° southeast (Figs. 3, 4A, B). Although many wells have been drilled to Precambrian basement in Carter and adjacent counties, no oil or gas has been reported in the Knox and deeper formations.

Operational Overview

The No. 1 Hanson Aggregates research well was drilled in northern Carter County to test reservoir and rock properties in the central Appalachian Basin for certain intervals' potential as deep saline reservoirs for geosequestration of carbon dioxide in the subsurface. KGS, as the well operator, designed and permitted the well, developed the programs for drilling, coring, geophysical logging, testing, plugging and abandonment, and surface remediation, and contracted services through the University of Kentucky. The well design and operations, including well abandonment, were in compliance with Kentucky Division of Oil and Gas regulations, Hanson Aggregates safety policy, Federal Environmental Protection Agency and Occupational Safety and Health Administration regulations, as well as Federal Mine Safety and Health Administration regulations (because the well was located on Hanson Aggregates quarry property).

Preconstruction Preparations and Well-Site Construction

Before construction began, a phase I environmental site assessment was conducted in October 2012 by Smith Management Group, a Lexington, Ky., environmental consulting firm, to assess prior uses of the proposed well site that might have been detrimental to the suitability of the site for the proposed project (Fig. 5A). No releases or threatened releases of hazardous substances were indicated at the proposed well site. KGS identified domestic water wells within a mile of the proposed well site before drilling commenced in order to address any community concerns about the potential for groundwater contamination. Water wells were located southeast of the well site in residential areas bracketing the AA Highway (Ky. 9). We informed 20 nearby residents about the proposed project and asked for permission to conduct baseline groundwater sampling from their domestic water wells. In the end, two landowners consented to the sampling. At the time wells were sampled, we also sampled Grassy Creek at two locations bracketing the well site in order to have baseline surface-water samples. A public meeting was held in Grayson, Ky., in December 2012 to present background information about subsurface carbon storage and how the project would proceed. The meeting was well publicized in print media, on a local radio station, and on the University of Kentucky website, but it was poorly attended, probably because of heavy rainfall that evening. The information was well received by those in attendance, however.

A 1-acre well site and access road were constructed on the Hanson Aggregates property fronting the AA Highway in January 2013 (Figs. 5B–F). Construction required cutting into the hillslope on its south side, leaving a highwall on the southwest side of the well pad (Figs. 5B, D–F). For safety, a fence and warning signs were placed along the top of the cut to warn any visitors to the well site of the slope cut below. The well pad was covered with gravel to mitigate any erosion or stormwater runoff, and provide a working surface for heavy machinery used during the project (Fig. 5C). We ensured that soil and groundwater were protected from leaking drilling and testing fluids, well cuttings, and any collected stormwater by constructing plastic-lined, fenced mud pits (Figs. 5C, D).

Well Permitting

The Kentucky Geological Survey's project plan was to drill, test, and permanently plug and abandon the No. 1 Hanson Aggregates research well. Accordingly, the well was permitted with the Kentucky Division of Oil and Gas as a stratigraphic test well—the most appropriate category

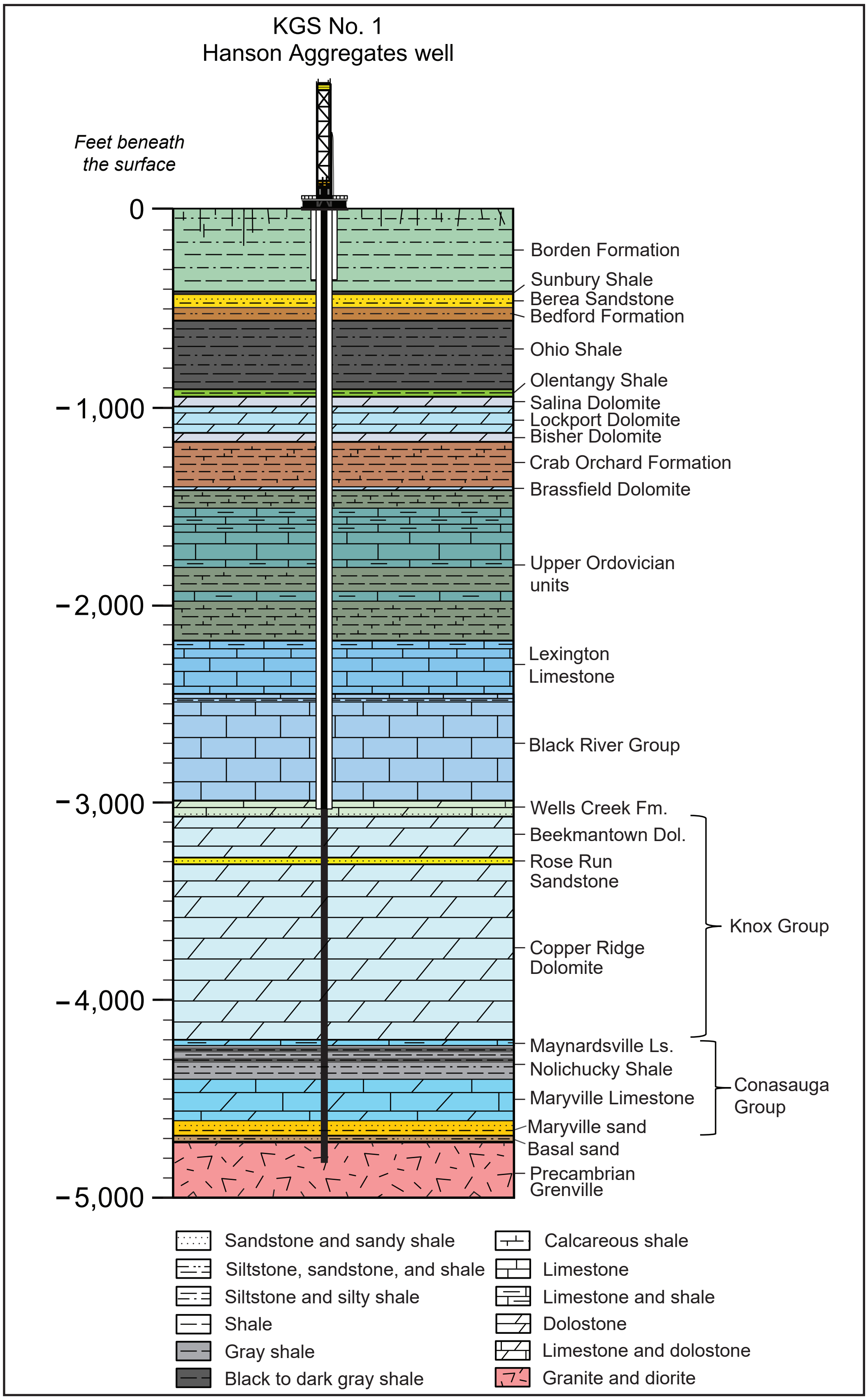


Figure 2. Generalized stratigraphy and lithology of strata penetrated by the No. 1 Hanson Aggregates well.

Table 1. Formation tops, drill depth, and subsea elevation of strata penetrated by the No. 1 Hanson Aggregates well.

Stratigraphic Unit	*Comment*	*Depth (ft KB)*	*Subsea (ft)*	*Lithology*
Borden Formation		Surface	0	Siltstone and shale, gray to green, silty, calcareous; may have pyrite and phosphates.
Sunbury Shale		412	341	Shale (clays and quartz silt): black to brown, organic-rich, some pyrite (possible source rock for natural gas and oil).
Berea Sandstone		427	326	Sandstone and siltstone: quartz sand grains with quartz, calcite, and dolomite cement.
Bedford Formation			753	Siltstone and shale: gray, silty to sandy, quartz grains with calcite and dolomite cement.
Ohio Shale		559	194	
Cleveland Member	Possible source rock for natural gas and oil	559	194	Shale (clays and quartz silt): black to brown, organic-rich, some pyrite.
Three Lick Bed	Possible source rock for natural gas and oil	633	120	Shale and siltstone: dark gray to black, organic-rich (overall less organic-rich than above and below), some pyrite.
Upper Huron Member	Possible source rock for natural gas and oil	666	87	Shale (clays and quartz silt): black to brown, organic-rich, some pyrite.
Middle Huron Member	Possible source rock for natural gas and oil	732	21	Shale and siltstone: dark gray to black, organic-rich (overall less organic-rich than above and below), some pyrite.
Lower Huron Member	Possible source rock for natural gas and oil	808	–55	Shale (clays and quartz silt): black to brown, organic-rich, some pyrite.
Olentangy Formation		908	–155	Shale and siltstone: light gray and silty, calcareous (not organic-rich as above).
Corniferous	Drillers' term for Salina and Lockport Dolomites	946	–193	
Salina Dolomite		946	–193	Dolomite (magnesium carbonate): gray to tan, some calcite, minor pyrite.
Lockport Dolomite		1,114	–361	Dolomite (magnesium carbonate): gray to tan, some calcite, minor pyrite (anhydrite sulfates possible).
Keefer Sandstone	Big Six sandstone; not well developed	1,124	–371	Dolomite (magnesium carbonate), sandy: gray to tan dolomite with sand grains possible, some calcite, minor pyrite (anhydrite sulfates).
Crab Orchard Formation	Clinton Formation	1,170	–417	Shale: red, brown, gray, and green, some silty, calcareous, minor pyrite.
Brassfield Formation		1,399	–646	Dolomite (magnesium carbonate): gray to orange.
Upper Ordovician (undifferentiated)		1,410	–657	Shale and limestone (calcareous carbonate): gray shale, silty to calcareous, interbedded with thin limestone beds.
Lexington Limestone		2,177	–1,424	Limestone and shale: gray, crystalline to fossiliferous limestone, calcareous.

Table 1. Formation tops, drill depth, and subsea elevation of strata penetrated by the No. 1 Hanson Aggregates well.

Stratigraphic Unit	*Comment*	*Depth (ft KB)*	*Subsea (ft)*	*Lithology*
Mud Cave Bentonite marker bed		2,478	–1,725	Shale, bentonitic: green-gray clay shale.
High Bridge (Black River) Group		2,478	–1,725	Limestone: gray to cream, calcareous, locally silty; and some local pyrite.
Pencil Cave Bentonite marker bed		2,559	–1,806	Shale, bentonitic: green-gray clay shale.
Pecatonica Limestone		2,865	–2,112	Limestone: gray to cream, calcareous, locally silty; some local pyrite.
Wells Creek Formation		2,994	–2,241	Dolomite and limestone: gray, cream, and green, calcareous.
St. Peter Sandstone		3,074	–2,321	Dolomite and sandstone: thin interbeds of sandstone and sandy dolomite with dolomite.
Knox Group		3,078	–2,325	
Beekmantown Dolomite		3,078	–2,325	Dolomite, white, cream, and gray; some calcite and some local pyrite and chert nodules.
Rose Run Sandstone		3,282	–2,529	Sandstone: quartz sand grains in dolomite and quartz cement.
Copper Ridge Dolomite		3,314	–2,561	Dolomite: white, cream, and gray; some calcite and some local pyrite and chert nodules.
Conasauga Group			753	
Maynardsville Limestone		4,200	–3,447	Dolomite and shale: gray dolomite, some silty, interbedded with underlying shale toward base.
Nolichucky Formation		4,243	–3,490	Shale, siltstone, and dolomite: dark and medium gray shale interbedded with brown to gray siltstones and dolomites; shales are pyritic and calcareous.
Maryville Limestone		4,402	–3,649	Dolomite, siltstone, and shale: gray dolomite, some silty, interbedded with siltstones and thin shales; may have some pyrite and anhydrite (sulfate).
Maryville sand		4,610	–3,857	Sandstone and dolomite: sandstone, quartz, with quartz and dolomite cement, interbedded with dolomite as above.
Basal sand	Possible Mount Simon correlative	4,683	–3,930	Shale, siltstone, and sandstone: interbedded shale, siltstone, and sandstone, very bioturbated, calcareous to dolomitic.
Granite Wash		4,720	–3,967	Granite and diorite, metamorphosed: feldspar, quartz, hornblende, biotite, and other minerals.
Precambrian basement	Grenville granite gneiss	4,721	–3,968	Granite and diorite, metamorphosed: feldspar, quartz, hornblende, biotite, and other minerals.

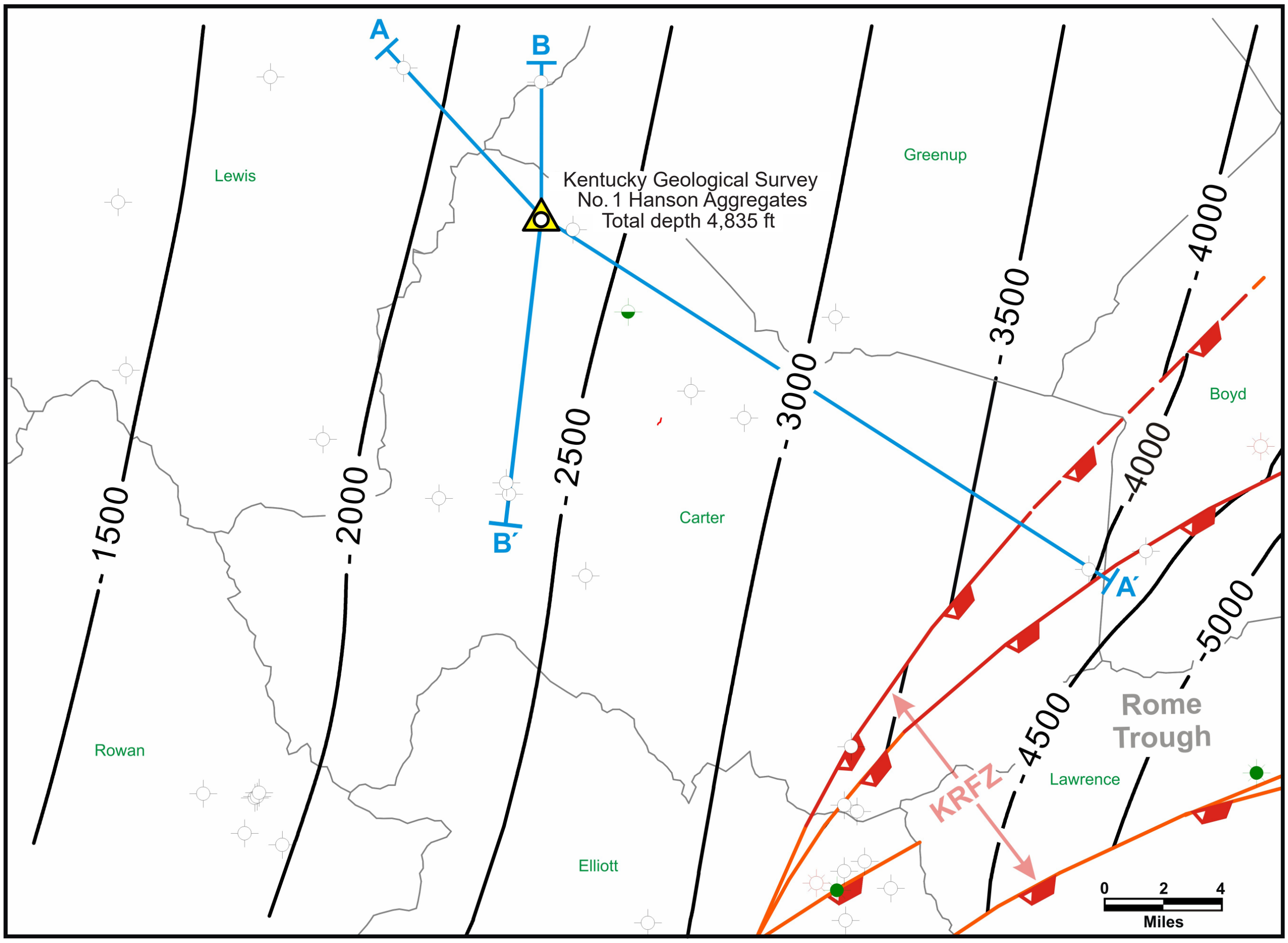
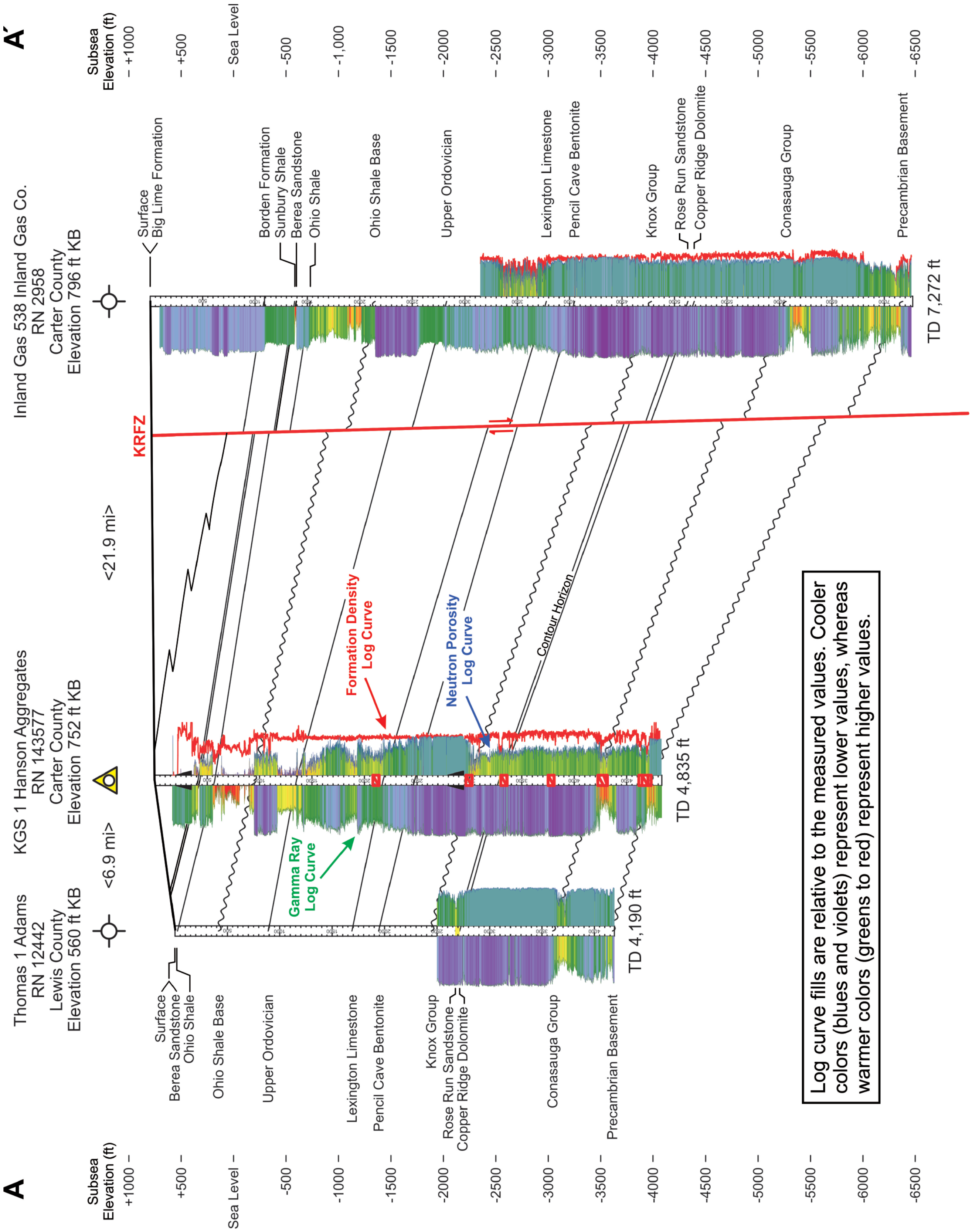


Figure 3. Subsurface structure on top of the Knox Group, in feet below sea level, and index to cross sections A–A' and B–B' (blue). Dip at the top of the Knox north of the Kentucky River Fault Zone is about 1° east-southeast and in the Rome Trough is about 4° southeast and greater.

for the goals of the project. A stratigraphic test well is one in which data are collected to determine subsurface structural, stratigraphic, and formation rock properties, but the well is not completed for oil or gas production. The intent is that the test well will ultimately be permanently plugged and abandoned at the conclusion of data collection. As with all oil and gas wells drilled in Kentucky, the permit for the No. 1 Hanson Aggregates required an abandonment bond to ensure there would be funds available to the Kentucky Division of Oil and Gas to abandon it if the operator defaulted on the abandonment requirement. The abandonment bond requirement for the No. 1 Hanson Aggregates well was satisfied by the Kentucky Geological Survey's then-current blanket abandonment bond.

Well Design

The No. 1 Hanson Aggregates well was designed in accordance with Kentucky Division of Oil and Gas regulations for groundwater protection and wellbore pressure control during drilling, coring, and testing (Fig. 6), and to minimize surface environmental impact. The drilling contractor optimized the well design to improve operational efficiency. The design ensured that groundwater would be protected by cementing 9⅝-in. steel casing from 355 ft to the surface, in accordance with state regulations, then verifying the quality of the cement bond by a geophysical cement bond log, followed by approval by a Kentucky Division of Oil and Gas inspector. Subsurface pressure control while drilling and coring to the well's total depth was ensured by attaching blowout-preven-



Log curve fills are relative to the measured values. Cooler colors (blues and violets) represent lower values, whereas warmer colors (greens to red) represent higher values.

Figure 4. Subsurface structural cross sections through the No. 1 Hanson Aggregates well (Fig. 3). Northwest-southeast cross section A–A' crosses a strand of the Kentucky River Fault Zone with about 250 ft of dip offset.

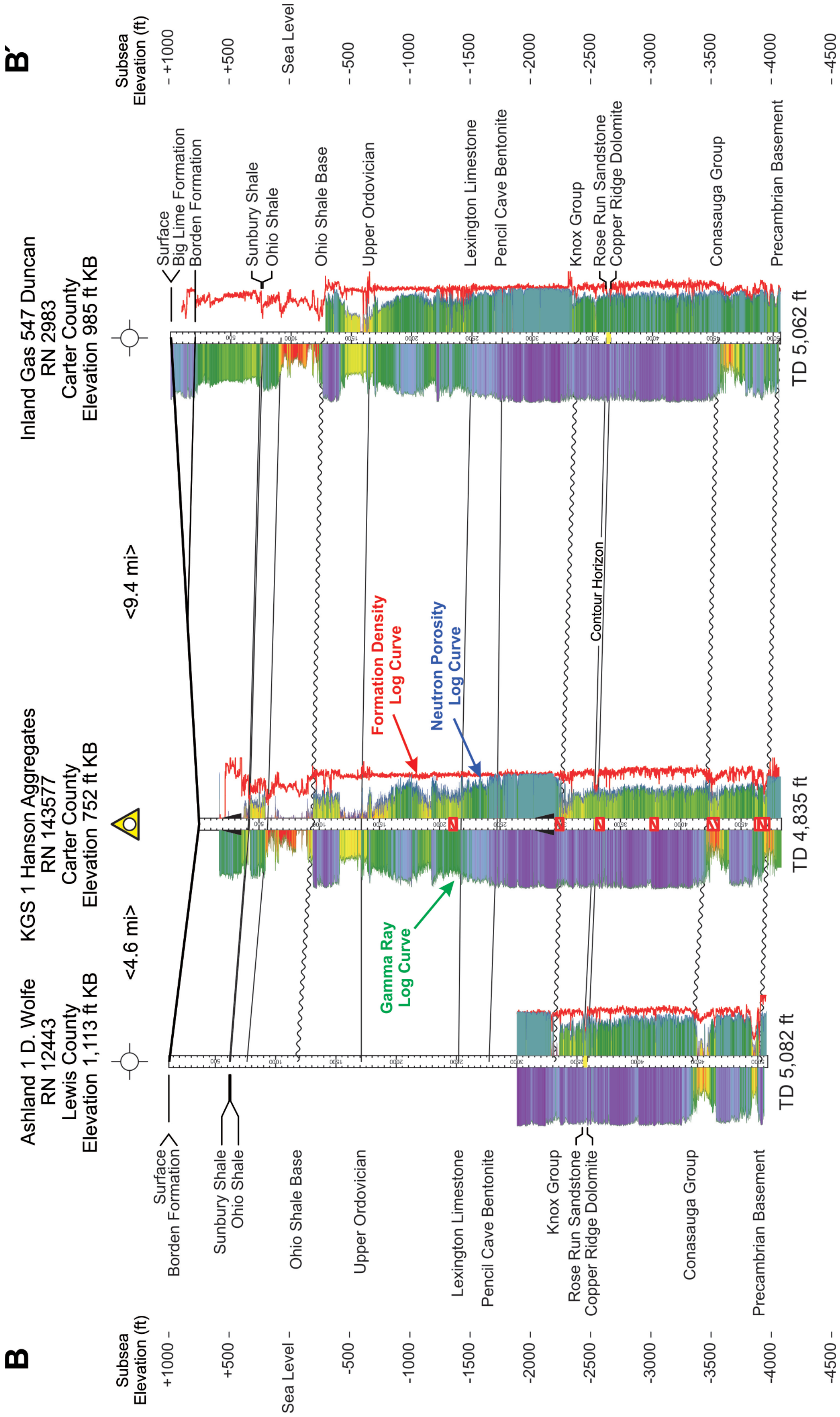


Figure 4. See caption on previous page.

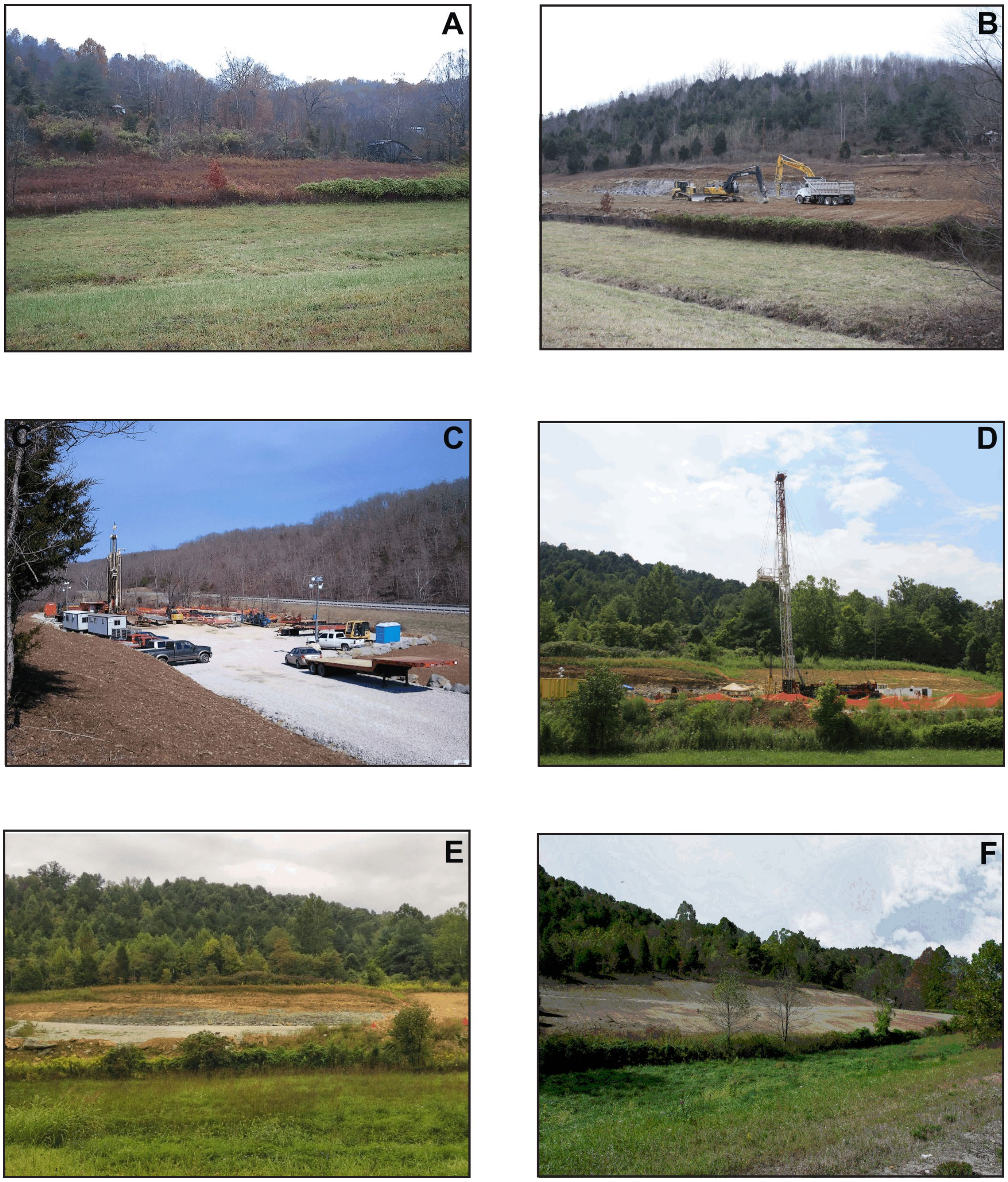


Figure 5. Construction, operations, and remediation of the No. 1 Hanson Aggregates well site. (A) Preconstruction view of the well site on Dec. 12, 2012. The well site is in the overgrown field behind the mowed AA Highway right-of-way. An abandoned tobacco barn is in the background on the right and an abandoned house on the left at the tree line. View is from the AA Highway. (B) Well-site construction on Jan. 14, 2013. The well site covered about 1 acre and was leveled to accommodate the drilling rig. A highwall was cut into the Cowbell Member of the Borden Formation at the back of the site to provide enough room for the drilling rig, water tanks, and trucks delivering equipment and supplies. The highwall was fenced with orange heavyweight plastic fencing for safety. View is from the AA Highway. (C) The drill site during the retrieval of core 8 on April 17, 2013. The access road is in the lower right corner of the photo and the AA Highway is in the background. (D) The service rig on the well site during the step-rate test in the Copper Ridge Dolomite on Aug. 11, 2013. View is from the AA Highway. (E) The well site viewed from the AA Highway on Sept. 18, 2013, before surface remediation. (F) The remediated well site viewed from the AA Highway on Oct. 10, 2013.

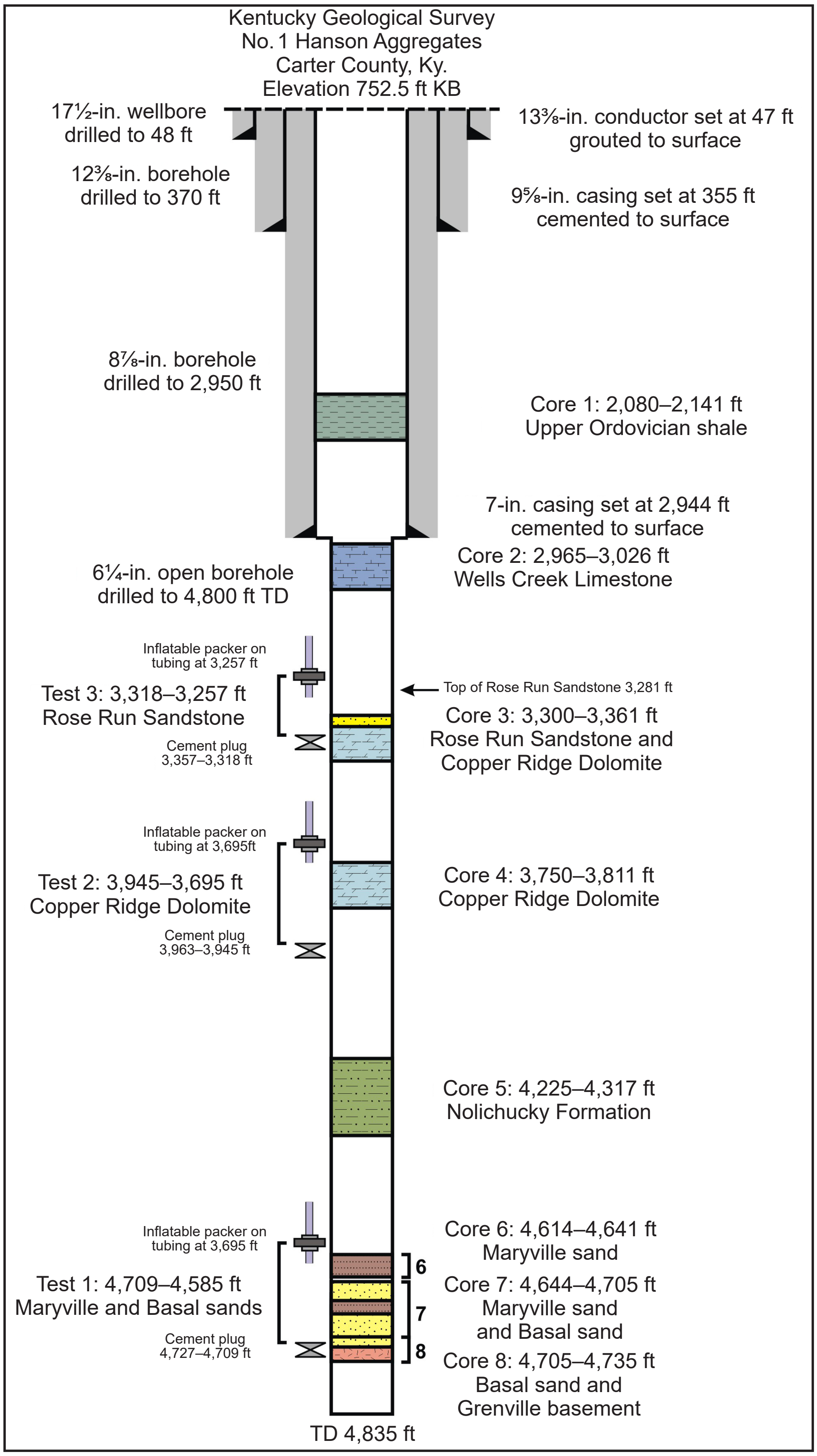


Figure 6. Design of the KGS No. 1 Hanson Aggregates well, showing as-drilled casing depths, cores, and step-rate test intervals. Core 1 was cut using a conventional mud system whereas cores 2 through 8 were cut with fresh water in the wellbore. All testing was conducted in the open, uncased wellbore.

tion equipment to 7-in. steel casing, which was cemented from 3,000 ft to the surface. Once again, the quality of the cement bond between the casing and wellbore was verified by a geophysical cement bond log, followed by approval by a Kentucky Division of Oil and Gas inspector.

Drilling and Coring Programs

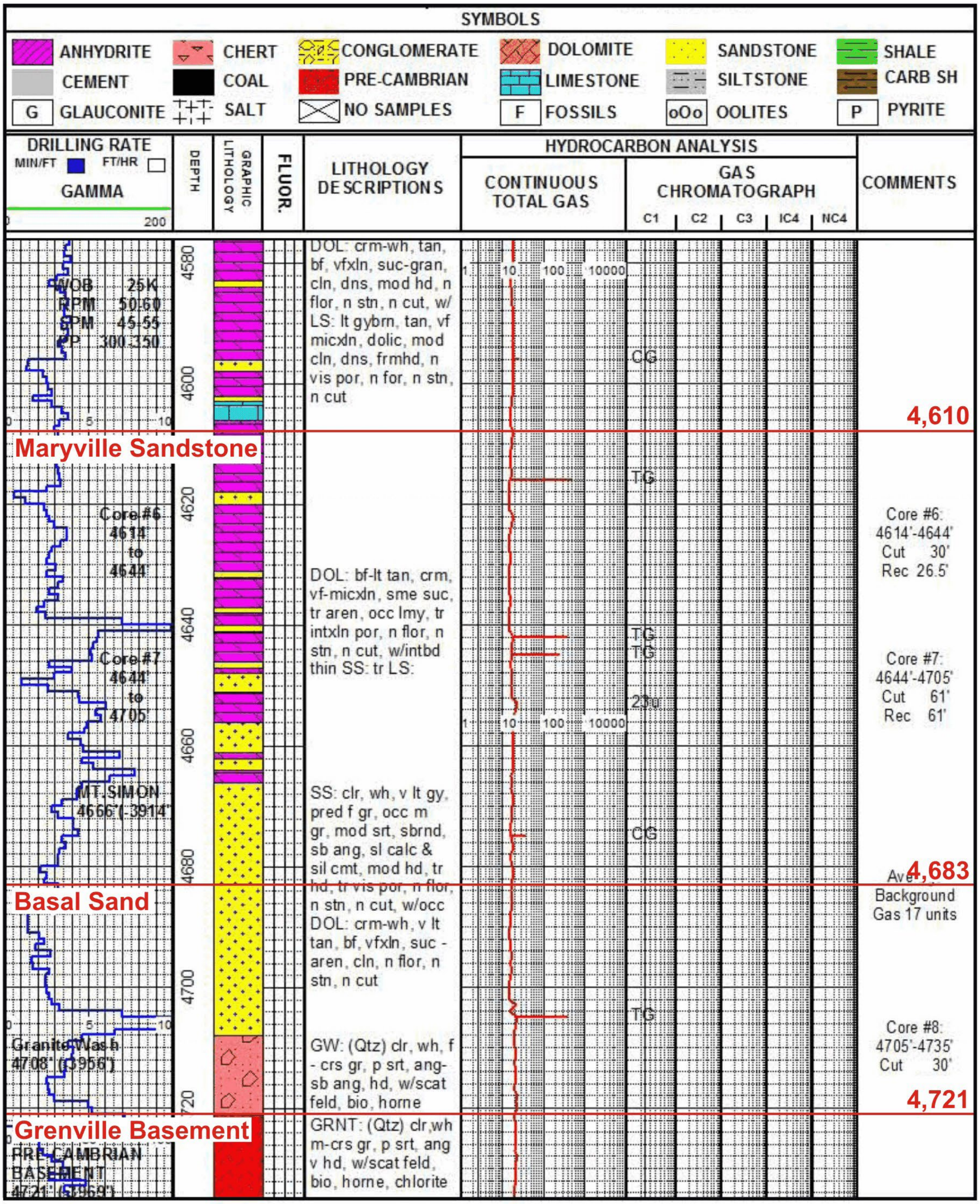
The well was drilled with a hydraulic air-rotary/top-drive drilling rig, rated to drill a vertical borehole to 6,000 ft (Fig. 5C). Kelly bushing height above the ground surface of this drilling rig was 6.5 ft, and all work in the borehole was conducted in reference to KB. Figure 6 is the as-drilled wellbore diagram. The final well construction ensured subsurface pressure control and isolation of the test interval by cementing 7-in. casing from 2,944 ft to the surface, slightly shallower than the design depth of 3,000 ft; the cement bond quality was verified by a geophysical cement bond log, followed by approval by the Kentucky Division of Oil and Gas, and installation of blowout prevention equipment. Whole-diameter conventional cores would be collected from zones in the several potential confining intervals and saline reservoirs in order to determine chemistry, mineralogy, and permeability of possible caprocks and reservoirs. Coring was conducted by Cor-Pro, a coring contractor from Houston, Texas. The original coring program called for cutting six cores (five 60-ft cores and one 90-ft core) in the Upper Ordovician shale, Beekmantown Dolomite, Rose Run Sandstone, Copper Ridge Dolomite, and Basal sand (Table 2).

Mud Logging and Geophysical Logging

The No. 1 Hanson Aggregates well was mud-logged and geophysically logged in the open, uncased wellbore from immediately below the shallow surface casing at 355 ft to the well's total depth. The mud log (Fig. 7) provides lithologic descriptions of cuttings from the wellbore in 5-ft intervals, prepared by experienced geologists, and also reports the drilling penetration rate of the well, any oil shows in the cuttings, and natural gas in the drilling fluid. From these data, preliminary depths of formation tops can be estimated and used to pick core points, and a qualitative estimate of hydrocarbons encountered in the well can be made. Several downhole geophysical logs (electric logs or logs) were run by Schlumberger to characterize the electrical, nuclear, and acoustic properties of rock units in the subsurface (Figs. 8–9, Table 3), as well as to record continuous images of the wellbore. All of these logs were digitally recorded, and both digital data and raster log images are available online through the KGS Oil and Gas Records Database. Measurements from these logs are used to determine petrophysical and reservoir rock properties of subsurface strata, including porosity, lithology, formation-fluid resistivity and saturation, wellbore drilling-fluid invasion, and geomechanical properties of strata penetrated by the wellbore, and to

Table 2. Core intervals, recovery, and coring rates.

Core	*Formation*	*Core Diameter (in.)*	*Cored Interval*		*Coring Results*		*Recovery (percent)*	*Coring Rate*	
			Top (ft KB)	*Base (ft)*	*Cut (ft)*	*Recovered (ft)*		*(min/ft)*	*(hr/core)*
1	Upper Ordovician shale	4.0	2,080	2,141	61.0	61.0	100.0	1.7	1.7
2	Wells Creek Limestone	3.5	2,965	3,026	61.0	61.0	100.0	2.0	2.0
3	Rose Run Sandstone Copper Ridge Dolomite	3.5	3,300	3,361	61.0	61.0	100.0	2.0	2.0
4	Copper Ridge Dolomite	3.5	3,750	3,811	61.0	60.8	99.7	4.6	4.7
5	Nolichucky Formation	3.5	4,225	4,317	92.0	92.0	100.0	4.7	7.2
6	Maryville sandstone	3.5	4,614	4,641	27.0	26.5	98.1	3.8	1.7
7	Maryville sand Basal sand	3.5	4,644	4,705	61.0	61.0	100.0	2.9	2.9
8	Basal sand Grenville basement	3.5	4,705	4,735	30.0	28.5	95.0	14.7	7.4
				Total	**454.0**	**451.8**	**99.5**	**3.9**	**29.6**



DOL: crm-wh, tan, bf, vfxln, suc-gran, cln, dns, mod hd, n flor, n stn, n cut, w/ LS: lt gybrn, tan, vf micxln, dolic, mod cln, dns, frmhd, n vis por, n for, n stn, n cut

DOL: bf-lt tan, crm, vf-micxln, sme suc, tr aren, occ lmy, tr intxln por, n flor, n stn, n cut, w/intbd thin SS: tr LS:

SS: clr, wh, v lt gy, pred f gr, occ m gr, mod srt, sbrnd, sb ang, sl calc & sil cmt, mod hd, tr hd, tr vis por, n flor, n stn, n cut, w/occ DOL: crm-wh, v lt tan, bf, vfxln, suc - aren, cln, n flor, n stn, n cut

GW: (Qtz) clr, wh, f - crs gr, p srt, ang-sb ang, hd, w/scat feld, bio, horne

GRNT: (Qtz) clr, wh m-crs gr, p srt, ang v hd, w/scat feld, bio, horne, chlorite

Figure 7. Mud-log section from the No. 1 Hanson Aggregates well, showing the variety of information collected.

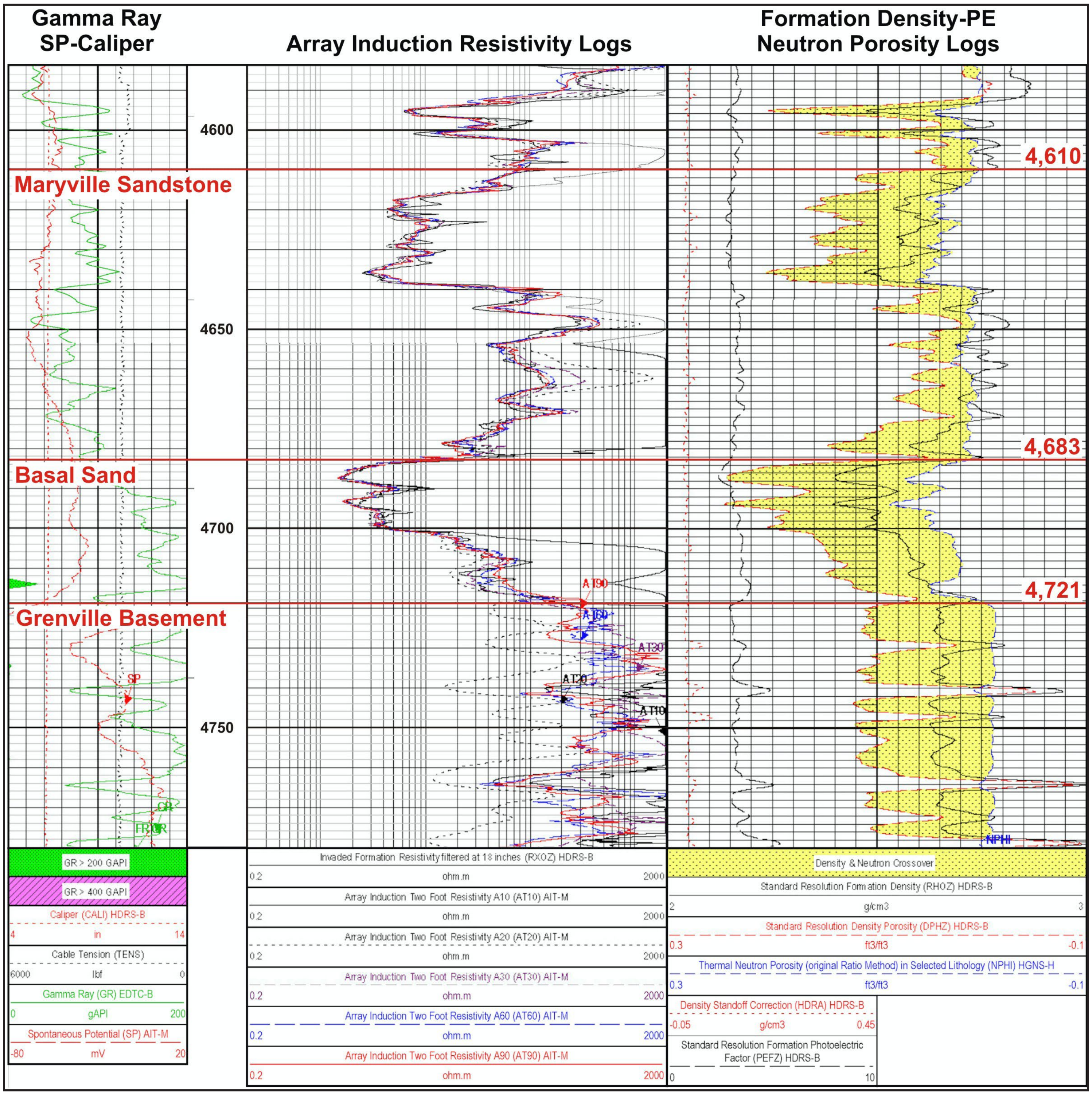


Figure 8. Log section of the gamma-ray/SP, array-resistivity, and formation-density/neutron-porosity logs run in the No. 1 Hanson Aggregates well. Amphibolite bands in the Grenville granite gneiss below 4,721 ft appear as thin, high-density spikes on the formation-density log.

identify naturally fractured intervals in the subsurface (Table 3). After the wellbore was logged at 4,835 ft, 30 rotary sidewall cores were collected to supplement data from the whole-diameter cores (Table 2).

Spectral Gamma-Ray, Sonic Scanner, and Elemental Analysis Logs

The spectral gamma-ray log (Fig. 9) differentiates the gamma-ray contribution of potassium, uranium, and thorium in the total gamma-ray readings. These data can be useful for determin-

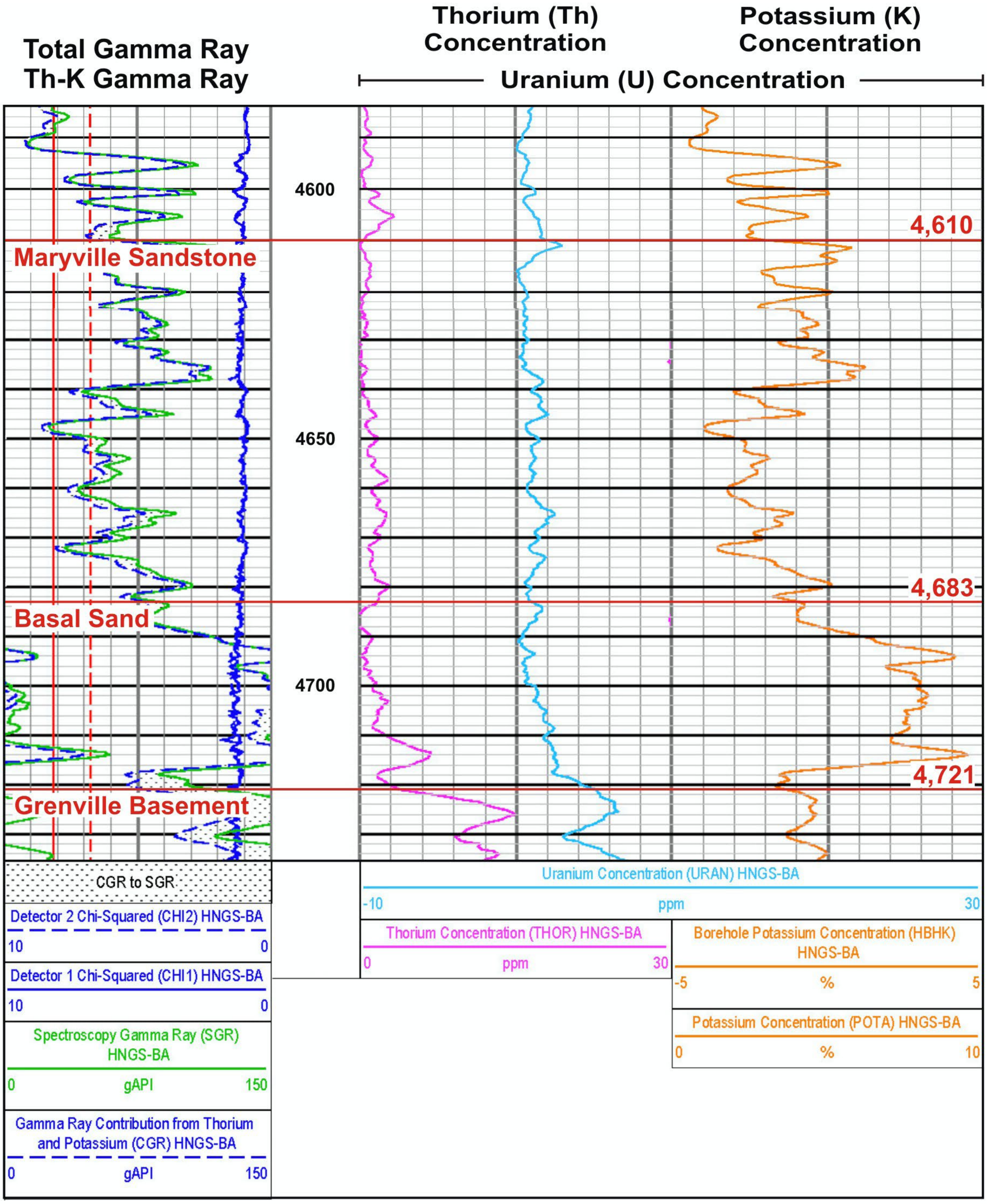


Figure 9. Spectral gamma-ray log section from the No. 1 Hanson Aggregates well. Total gamma-ray log value is most influenced by the uranium-thorium content of the rock; however, the high potassium content in the section from 4,690–4,716 ft causes a high gamma-ray value on the log.

Table 3. Geophysical logs run in the KGS No. 1 Hanson Aggregates well. In addition to gamma-ray, formation-density, neutron-porosity, caliper, and array-resistivity logs, several enhanced geophysical logs were used. The spectral gamma-ray log differentiates the contribution of potassium, uranium, and thorium from standard gamma-ray readings. These data can be useful for distinguishing elemental compositions of clays in shales or sand downhole. Schlumberger's Sonic Scanner (compressional and shear) log emits an acoustic wave through strata and inherent fluids and measures DT (delta time) compression wave, DT shear wave, compressional wave velocity, shear-wave velocity, and Poisson's ratio downhole. These data can be useful for future completion designs, comparison to seismic profiles, microseismic analyses, and rock physics evaluations. The ELAN log is useful for downhole petrophysical analysis. It calculates the percentage of free fluids versus bound water in strata, and estimates the gross mineralogy (illite, montmorillonite, chlorite, quartz, K-feldspar, calcite, and dolomite). Examples are shown in this report.

Electric Log Run	*Logged Interval*		*Wellbore Fluid*	*Drill Bit Size (in.)*	*Bottomhole Temperature (°F)*	*Geophysical Logs*	*Use*
	Top (ft)	*Bottom (ft)*					
1	356	2,950	fresh water	8¾	80	neutron-porosity	porosity, fluid saturation, lithology
						litho-density	porosity, fluid saturation, lithology, correlation
						gamma-ray	lithology, correlation
						caliper	borehole diameter and rugosity
						high-resolution Laterlog array	formation resistivity profile, fluid resistivity and saturation, correlation
						spectral gamma-ray	lithology, correlation
						Sonic Scanner	geomechanical properties, porosity, lithology
						four-arm caliper	borehole diameter and rugosity, wellbore breakout identification
						directional survey	wellbore inclination and deviation, subsurface position of the wellbore
2	2,942	4,832	fresh water	63	100	neutron-porosity	porosity, fluid saturation, lithology
						litho-density	porosity, fluid saturation, lithology, correlation
						gamma-ray	lithology, correlation
						caliper	borehole diameter and rugosity
						high-resolution Laterlog array	formation resistivity profile, fluid resistivity and saturation, correlation
						spectral gamma-ray	lithology, correlation
						four-arm caliper	borehole diameter and rugosity, wellbore breakout identification
						Sonic Scanner	acoustic compressional and shear waves, lithology, geomechnical properties
						Formation MicroImager Log	microresistivity tool used to calculate a continuous wellbore image
						Ultrasonic Borehole Imager Log	ultrasonic tool used to calculate a continuous wellbore image
Computed	356	4,832	fresh water	–	–	Elemental Log Analysis (ELAN)	petrophysical analysis of logs for mineralogy, porosity, permeability index, and fluid saturations
	2,983	4,883	fresh water	–	–	Formation MicroImager Log (FMI)	wellbore image for identifying porosity, including vugs, fracturing, strata dip, wellbore breakout
	2,942	4,826	fresh water	–	–	Ultrasonic Borehole Imager Log (UBI)	wellbore image for identifying fracturing, borehole stress, strata dip; not influenced by wellbore fluid

ing mineralogical compositions of clays in shales or sand encountered in the wellbore. Schlumberger completed two computed logs of petrophysical properties of strata for the KGS No. 1 Hanson Aggregates well (Table 3): Sonic Scanner (Fig. 10) and elemental log analysis (ELAN) (Fig. 11). The Sonic Scanner measures both compressional and shear-wave transit time through the wellbore strata and displays the full waveforms of these measurements (Schlumberger, 2005). From these measurements and the litho-density log measurement, continuous Poisson's ratio (a geomechanical elastic property; see the discussion in Gercek [2007] and Peng and Zhang [2007]) of strata penetrated by the wellbore are calculated (Fig. 10). The same data can be used to calculate the Young's modulus, bulk modulus,

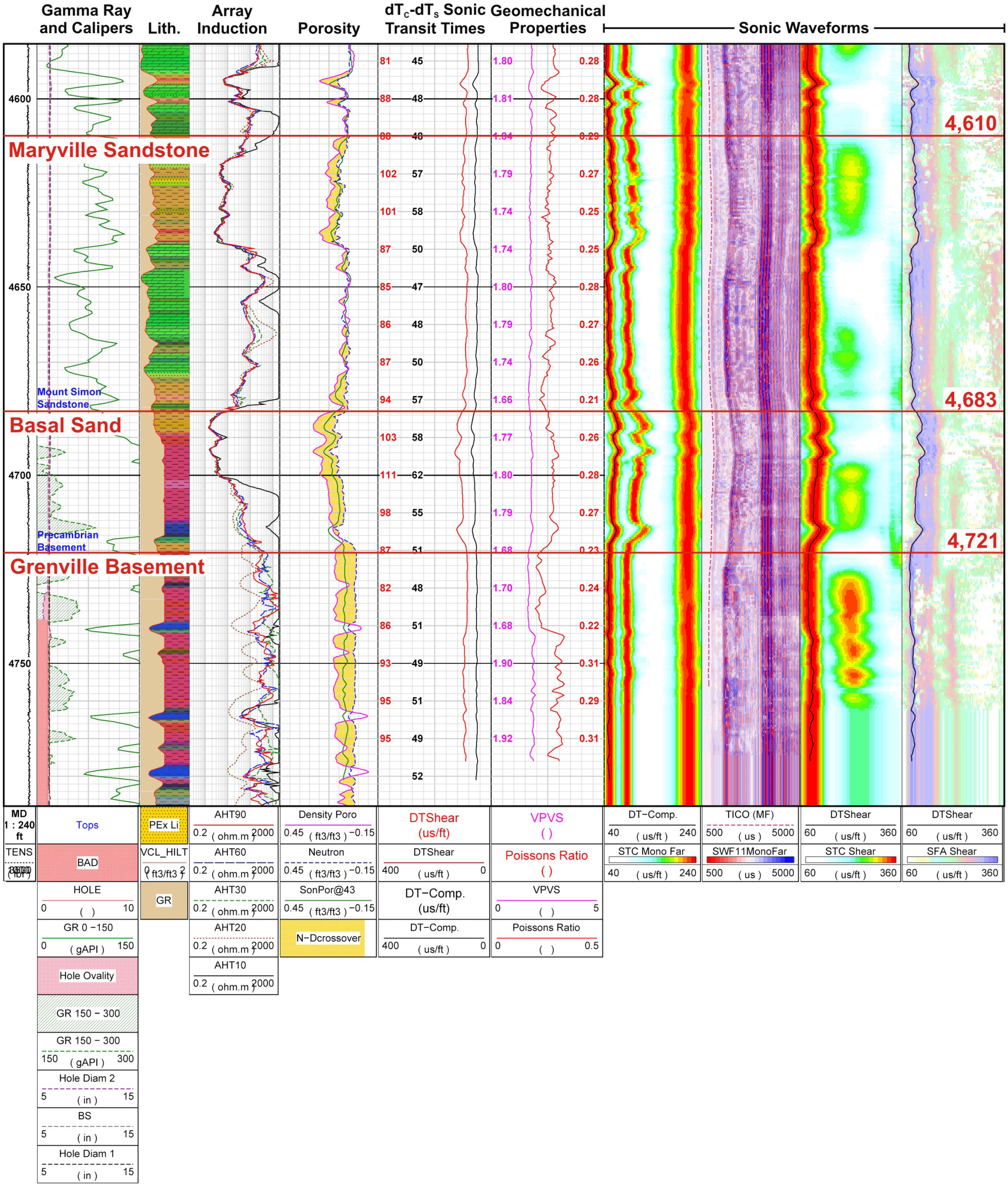


Figure 10. Example of Sonic Scanner analysis (Tamara Oliver, Schlumberger, 2013, personal communication). This log can be used to calculate elastic geomechanical properties of the strata penetrated by the wellbore. Stress-induced anisotropy in a wellbore causes breakouts, identified by the four-arm caliper log and frequency slowness dispersion graphs.

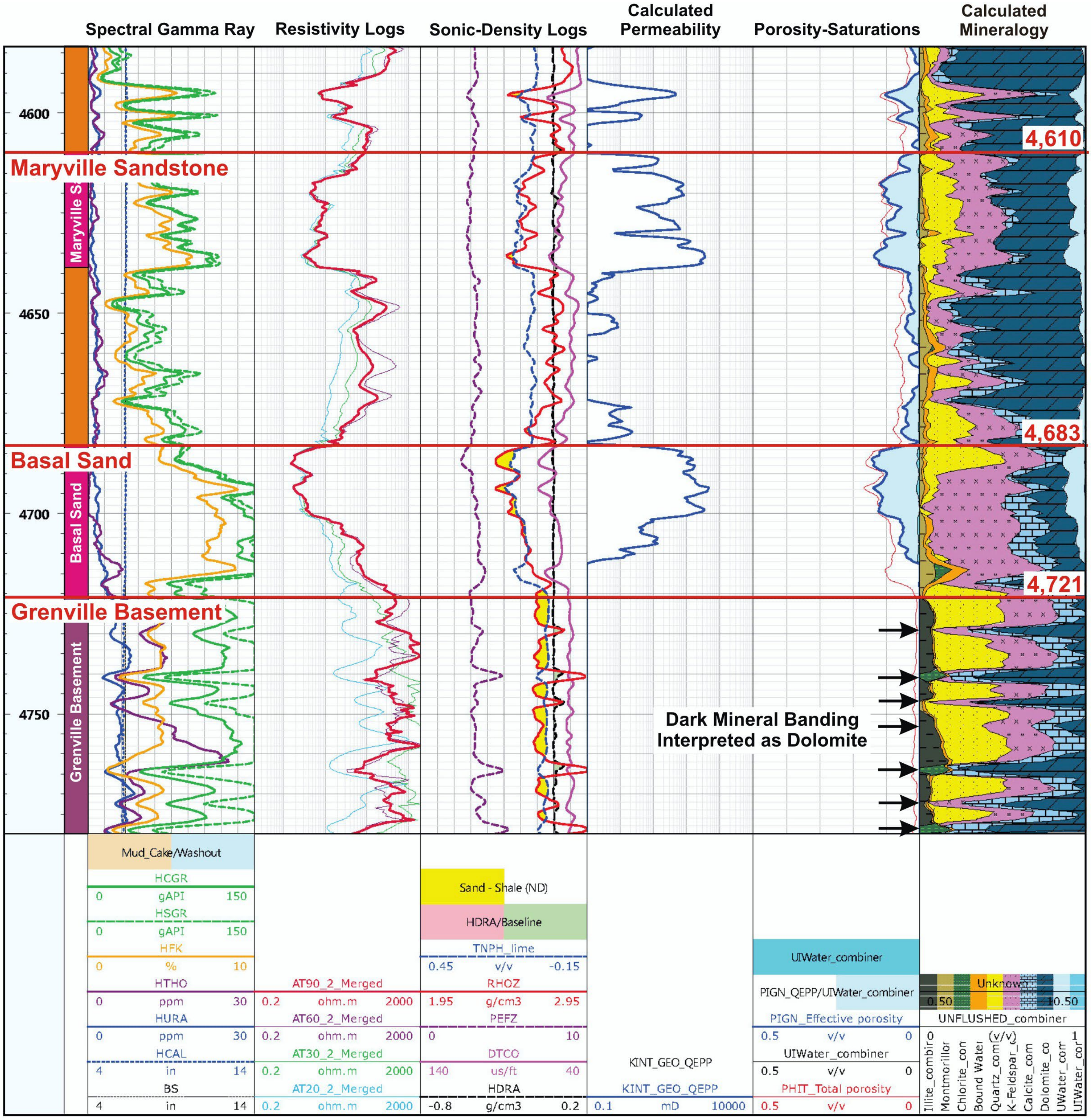


Figure 11. The ELAN log is an analysis of the spectral gamma-ray, array-resistivity, neutron-porosity, and litho-density log suite to create a model of the mineralogical composition, porosity, fluid saturations, and permeability index of strata penetrated by the wellbore (Darling and others, 1991). In this image the high formation density of amphibolite (dark mineral) banding in the Grenville granite gneiss is interpreted by the ELAN analysis as dolomite.

and shear modulus elastic geomechanical properties of the wellbore strata (PetroWiki, 2016). The Sonic Scanner data are also used to identify shear-wave anisotropies in the data from fractures and borehole breakouts in response to the local tectonic stress (Brie and others, 1998). These data can be useful for future completion designs, comparison to seismic profiles, microseismic analysis, and rock physics evaluation. ELAN is a petrophysical analysis of the spectral gamma-ray, array-resistivity, neutron-porosity, and litho-density log suite, used to model mineralogical composition, porosity, fluid saturations, and an index of permeability of strata penetrated by the wellbore (Darling and others, 1991) (Fig. 11). By modeling spectral gamma-ray data, ELAN can differentiate clays from potassium feldspars, which is important for distinguishing clastic lithologies in wellbore intervals without cores (Darling and others, 1991).

Formation MicroImager and Ultrasonic Borehole Imager Logs

Formation MicroImager and Ultrasonic Borehole Imager logs were run as part of the second log run after the well reached its total depth, and only covered the wellbore below casing at 2,944 ft (Fig. 12, Table 3). The Formation MicroImager log displays a continuous geo-oriented wellbore image computed from microresistivity measurements (Schlumberger, 2002a). This image provides a near-full wellbore view of stratification that can be used to determine sedimentary structures, vugular porosity, bedding, and structural features including fractures and faults (Schlumberger, 2002a) (Fig. 12). The Formation MicroImager image aids log-to-core comparisons, which improve our understanding of the geology of the reservoir and confining strata and make coring the entire wellbore unnecessary (discussed below). Because the image is geo-oriented, bed, fracture, and fault orientations can be interpreted (Fig. 13). As a microresistivity log, however, the FMI response is affected by any conductive minerals in the rock, most notably pyrite. Pyritic intervals will appear to be vugular, although if cored, these intervals may prove to actually be dense limestone and dolomite (Bowersox and Williams, 2014). Thus, additional information is needed to determine and describe vugular intervals in carbonate rocks: commonly from the formation-density, neutron-porosity, and sonic logs. In addition, the Ultrasonic Borehole Imager log can be run independently to provide a visualization of vugular porosity.

The Ultrasonic Borehole Imager log is conceptually similar to the Formation MicroImager log in that it provides a geo-oriented image of the wellbore, but unlike the FMI, it makes wellbore images from ultrasonic sound pulses (Schlumberger, 2002b). The value of the UBI is largely that its imaging is independent of the drilling fluid in the wellbore (Schlumberger, 2002b), and, as a sonic log, it is unaffected by conductive minerals in the rock. The UBI log thus supplements the FMI log and can be used to visualize porosity, analyze fractures and the natural stress regime in the borehole, and study borehole stability. The UBI produces a lower-resolution image that loses much of the finer detail displayed in the FMI log through the same wellbore interval, however (Fig. 12). That is, some features visible on the FMI may only be inferred from the UBI log. On the other hand, vugs visible on the FMI log can be confirmed by the UBI log (Fig. 12), thus improving reservoir porosity evaluation.

Drilling Operations

KGS was entirely in charge of the drilling of the No. 1 Hanson Aggregates well; contractors at the well site reported to KGS during active drilling and testing. Major operational decisions during drilling, coring, logging, and testing were made by KGS. After the permits were approved, the well was drilled without incident in the spring of 2013. Operations on the well site commenced on March 17, 2013, and were completed on schedule on April 10 (Fig. 14). The well's location, approximately midway between two dry exploratory test wells, was selected, in part, to avoid encountering hydrocarbons during drilling and testing (Fig. 3).

The well was drilled using an air hammer (Fig. 15) to the first core point at 2,080 ft, at which time the wellbore was filled with a 2 percent potassium chloride–based drilling fluid, whose viscosity and water-loss control properties were optimal for coring the Upper Ordovician shale. The purpose of the drilling fluid was to mitigate shale sloughing into the wellbore, which could cause the core barrel to stick. After the first core was recovered, the drilling fluid was displaced from the wellbore and stored in mud pits. Subsequent drilling to 2,944 ft, where 7-in. casing was cemented to the surface, then to 3,520 ft, was by air hammer, after which the influx of formation brine from the Rose Run into the wellbore exceeded the capacity of the air-drilling compression to displace it from the wellbore. Drilling from 3,520 ft to the well's total depth of 4,835 ft used conventional 6¼-in. tricone rotary drill bits and a wellbore fluid system of formation brine and fresh water. Drilling and coring operations, includ-

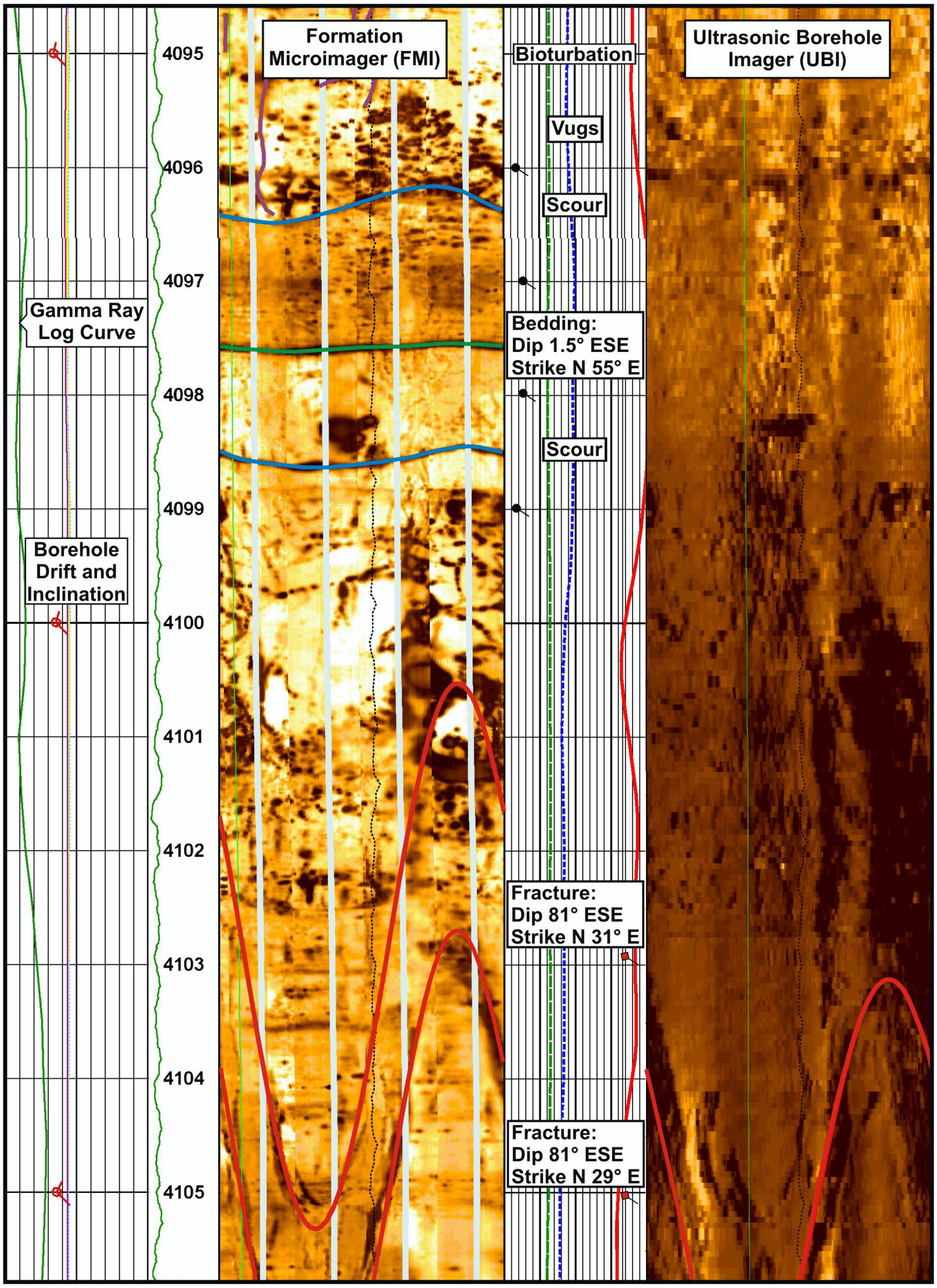


Figure 12. Interpretation of the Formation MicroImager and Ultrasonic Borehole Imager image log sections from the Copper Ridge Dolomite, showing vugular porosity (dark spots on the FMI log), bedding, and fractures. The FMI is a microresistivity log and is thus sensitive to the amount of disseminated conductive pyrite in the rock. Pyrite-enriched spots will appear to be vugs. The low-resolution UBI log, from an ultrasonic tool, is not sensitive to pyrite content and will show a more accurate distribution of vugular porosity.

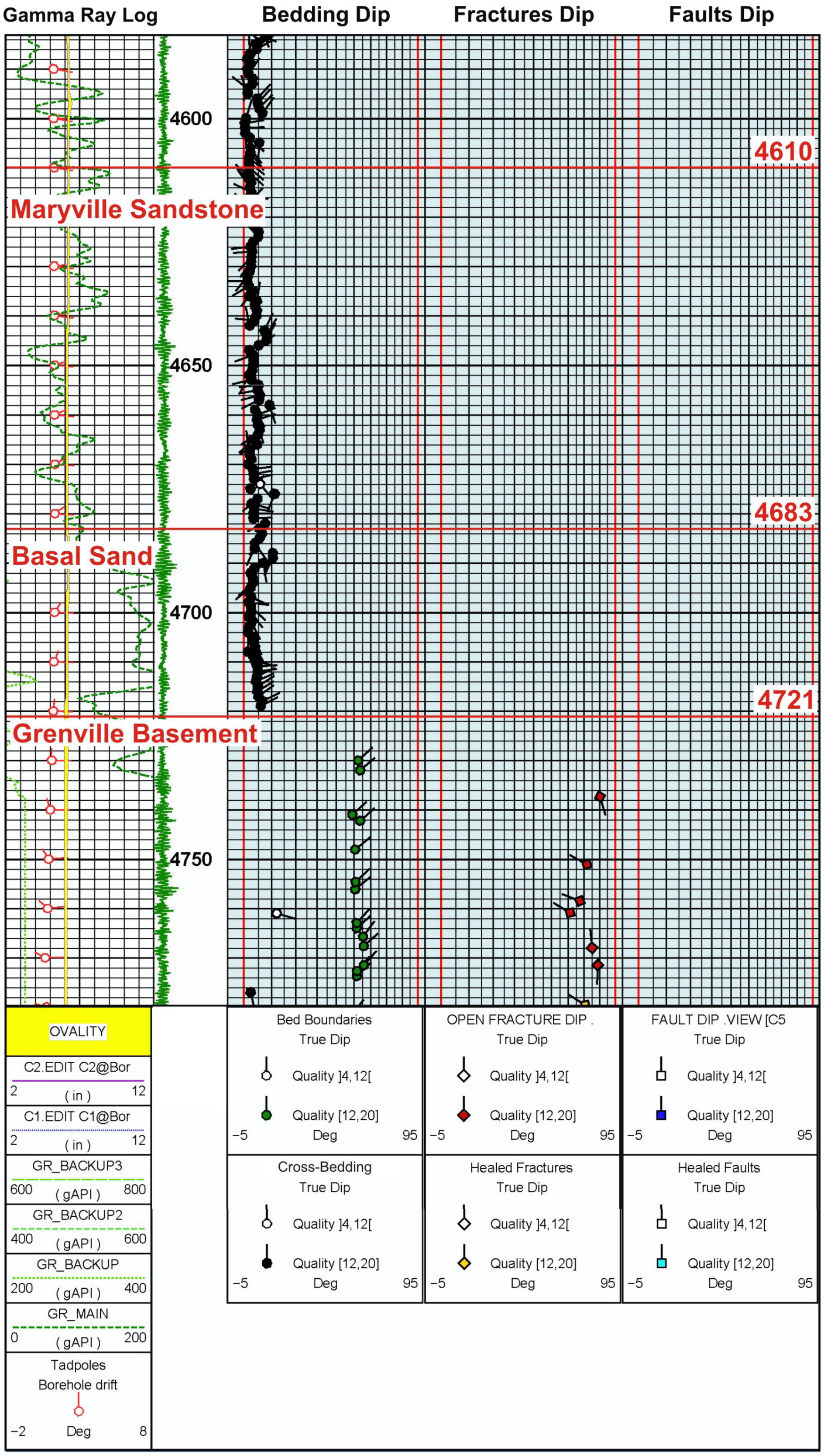


Figure 13. Dipmeter interpretation of bedding and fracturing and faulting features recorded by the Formation MicroImager log. Bedding dip in the Grenville is interpreted from the orientation of the amphibolite bands. Filled colored circles are posted at the depth and dip angle from horizontal of the feature, 0 to 90°(where vertical), and the black lines pointing away from the circles show the compass azimuth of the feature's dip direction (0 at north, then clockwise to 360°).

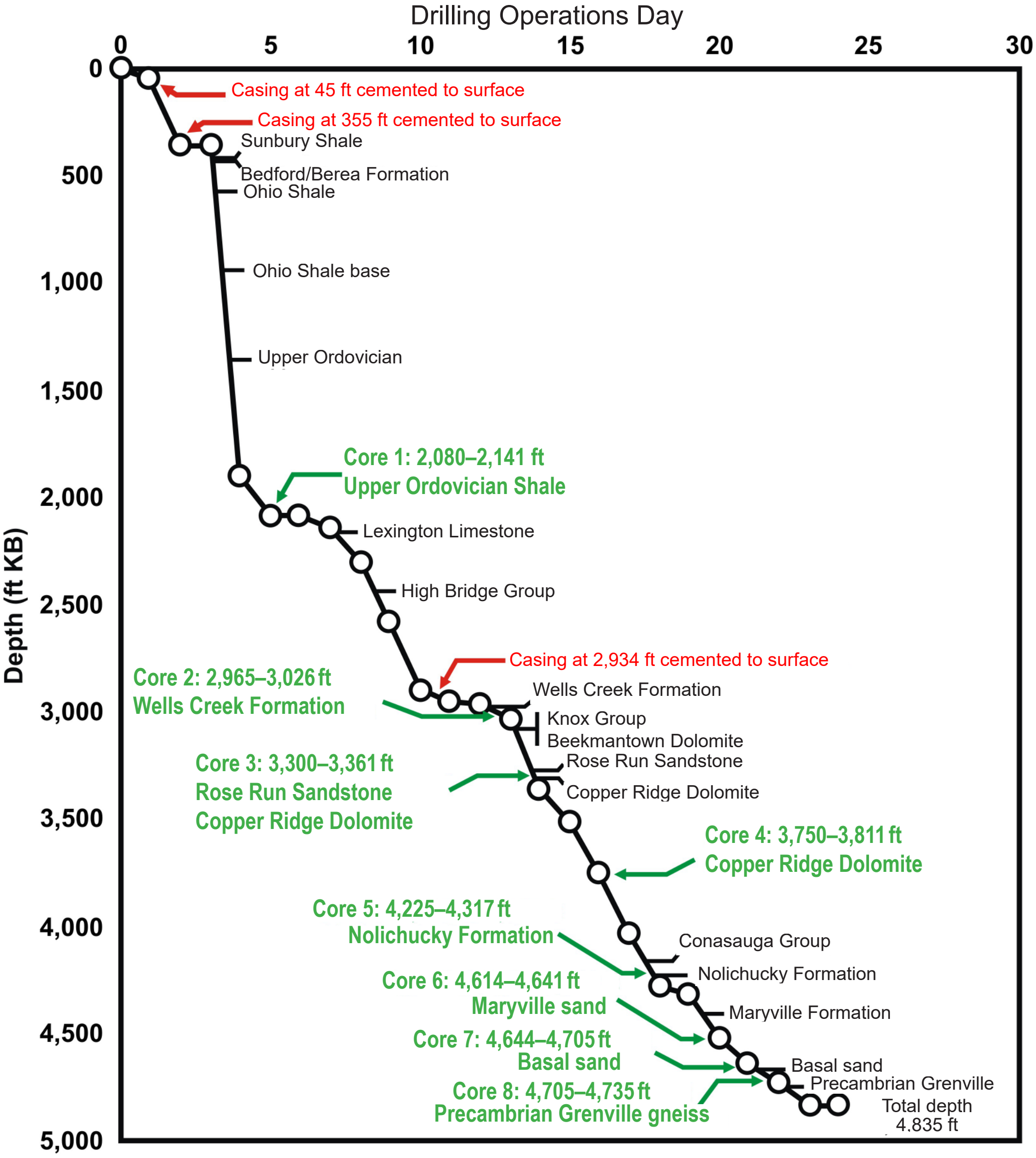


Figure 14. Drilling progress of the No. 1 Hanson Aggregates well, annotated with formation tops, core intervals, and casing depths.

ing geophysical well logging, were completed on schedule and within budget in 24 days (Fig. 14).

A minor natural-gas flow was encountered during drilling with air into the Rose Run at 3,267 ft. After the gas flow spiked at 3,300 ft, the gas influx to the wellbore was killed in 30 min by pumping fresh water into the wellbore. Surface blowout-prevention equipment ensured that there was no risk of losing well control while kill water was being pumped into the well. Because of subsequent formation-brine influx to the wellbore from the Rose Run, however, drilling below 3,300 ft was by conventional rotary drilling, with water in the borehole to the well's total depth. No further hydrocarbon shows were encountered during the remainder of the drilling and coring. No hydrogen sulfide was encountered at any time during drilling, coring, and testing.

Better-than-expected program costs during drilling allowed us to extend the coring program, and an additional 124 ft of cores was cut. A total of 454 ft of whole-diameter conventional cores was cut in the No. 1 Hanson Aggregates well, with an average core recovery of 99.5 percent at an average rate of 3.9 min/ft (Table 2) and average cost of $800/ft (direct coring contractor costs plus the cost

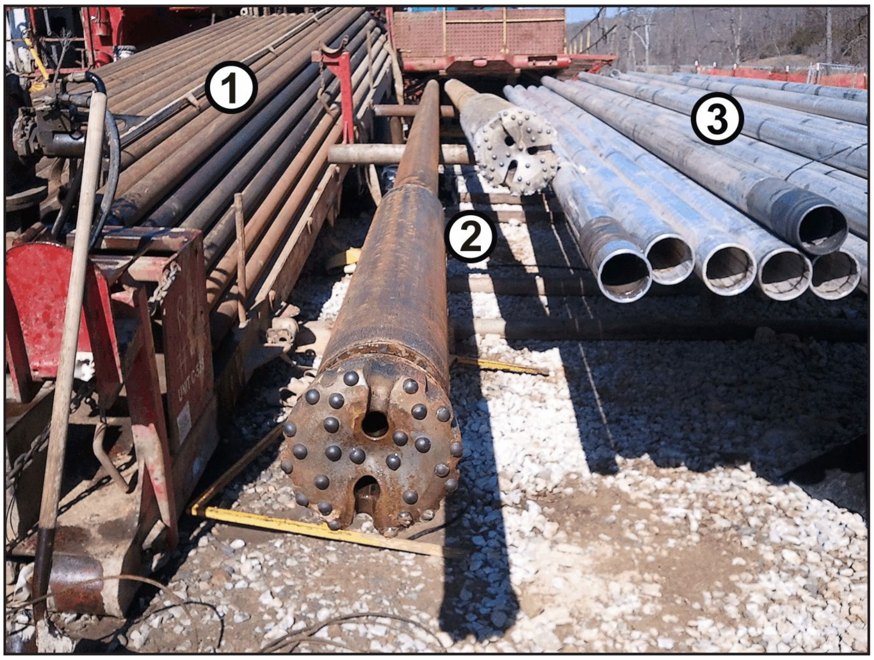


Figure 15. Drilling tools and tubular materials on racks beside the drilling rig, where they were easily accessible to the rig crews during drilling. (1) Drill pipe. (2) Hammer-drill heads. (3) Aluminum core sleeves.

of the drilling rig-time). The Upper Ordovician shale core, from the 8⅞-in. borehole above the casing point at 2,944 ft, had a diameter of 4 in., whereas the seven cores cut in the 6¼-in. borehole, below casing cemented at 2,944 ft, had a diameter of 3½ in. These were the largest-diameter cores that could be cut in the well, considering the expense of drilling and casing larger-diameter boreholes. To maximize the length of the cored intervals, considering the cost of coring, five cores were approximately 60 ft long, two were 30 ft long, and one was 90 ft long. Cores were cut using polycrystalline diamond-cutter core bits (Figs. 16A, B) and aluminum sleeves with ¼-in.-thick walls inside the core barrels to ensure core recovery (Figs. 15, 17A). Upon retrieval from the wellbore, cores were cut into 4-ft lengths, the ends of the cut sleeves were capped and sealed, and the cores were stored in transport racks on site until recovery of the last core (Fig. 17B), then transported on a trailer to CoreLab in Houston (Fig. 17C) for photography, reservoir and geomechanical properties analysis, X-ray diffraction mineralogy analysis, and preparation of petrographic thin sections.

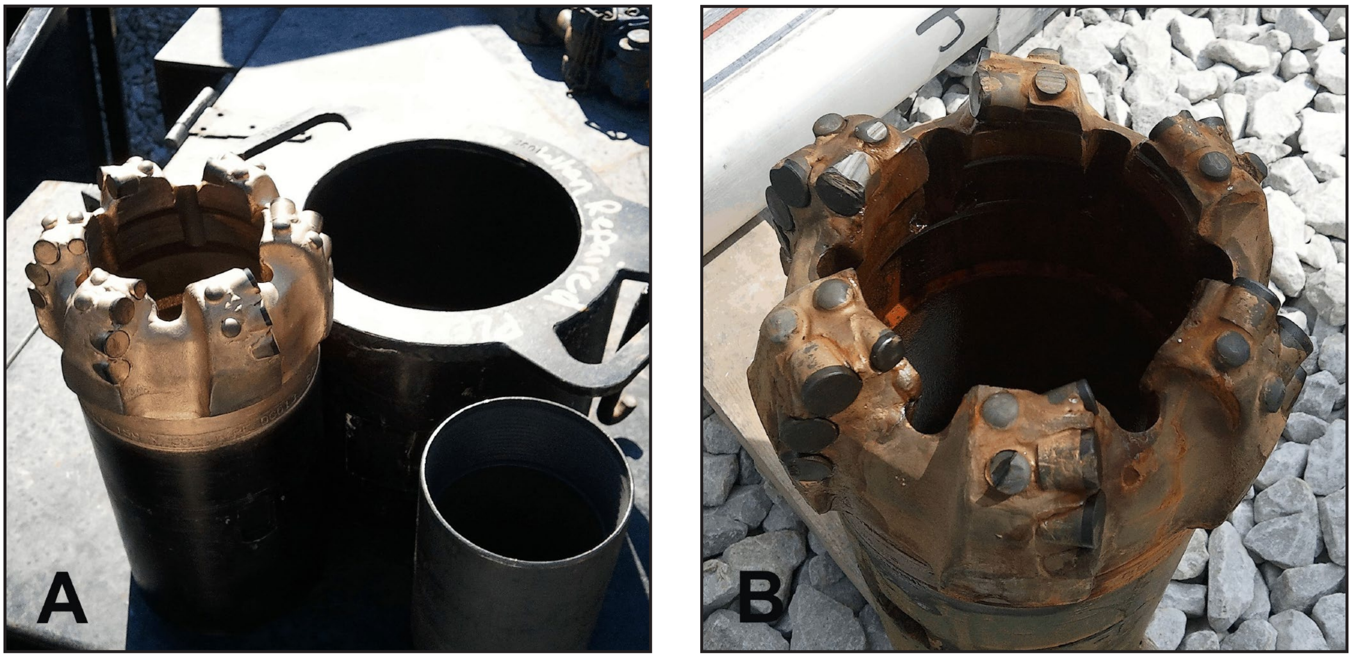


Figure 16. Polycrystalline diamond-cutter core bits used to drill the No. 1 Hanson Aggregates well. (A) A new bit (left), a gage to determine bit wear (center), and core catcher (right) to keep a core inside its aluminum sleeve for recovery. (B) A well-worn core bit after cutting several cores.

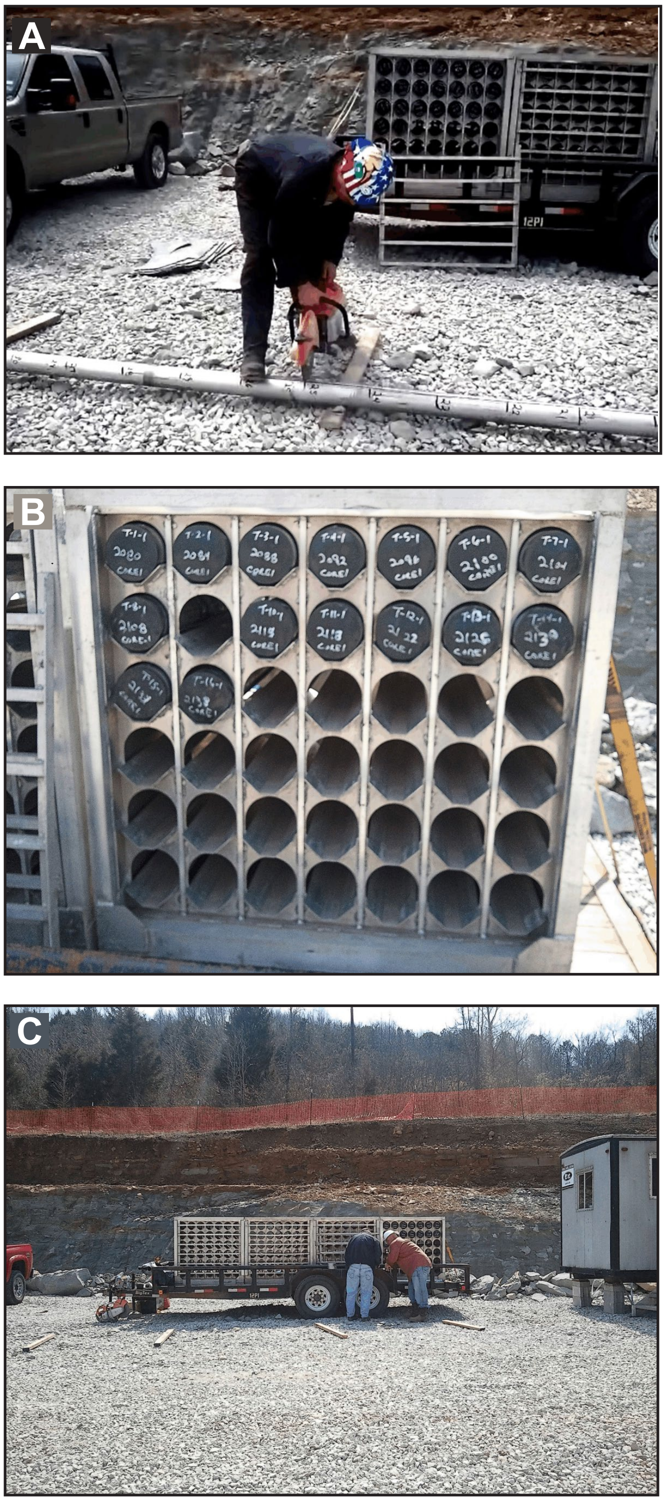


Figure 17. On-site processing of cores. (A) Aluminum core sleeves and cores are cut into sections for shipping, using a diamond-blade concrete saw. (B) Core sections were stored in their capped depth-labeled sleeves in racks for subsequent transport to the lab for analysis. (C) Racks of cores on the trailer to be transported to the lab.

Step-Rate Testing Program

The limited project budget and regulatory requirements precluded testing carbon dioxide injection into the No. 1 Hanson Aggregates well. Thus, a testing program was designed to test in-situ subsurface reservoir rock strength by step-rate testing (Felsenthal, 1974). Step-rate testing determines the maximum pressure at which fluid can be injected into formations before fracture (fracture gradient in psi per foot of depth) because, if the reservoir formation in an injection well is fractured, the associated confining caprock interval may be compromised (U.S. Environmental Protection Agency Region 5, 1994). Because in-situ rock strengths and stresses vary widely in the subsurface, a uniform fracture gradient cannot be applied to all injection wells (U.S. Environmental Protection Agency Region 5, 1994). For example, in EPA Region 5, which encompasses Illinois, Indiana, Michigan, Minnesota, Ohio, Wisconsin, and 35 Native American tribal lands (www.epa.gov/aboutepa/epa-region-5; last accessed 08/22/2018), fracture gradients were found to range from 0.48–0.91 psi/ft. Consequently, in the absence of other data, injection pressures in EPA Region 5 wells completed before 1994 were limited to 0.47 psi/ft in the Mount Simon Sandstone (comparable to the Basal sand in the No. 1 Hanson Aggregates well) and 0.80 psi/ft in the Middle Devonian Dundee Limestone, whereas wells drilled in 1994 and later required site-specific data (U.S. Environmental Protection Agency Region 5, 1994).

Fracture gradients are critical issues for ensuring subsurface CO_2 injection rates, storage, and caprock integrity. The only fracture gradient determined by step-rate testing from comparable strata available to KGS was from the basal Copper Ridge Dolomite in the KGS No. 1 Marvin Blan well, Hancock County (about 200 mi west of the No. 1 Hanson Aggregates well), at 7,180–7,455 ft (Bowersox and Williams, 2014). Geomechanical and sonic-velocity analyses were performed on two sidewall cores and five core plugs from the No. 1 Hanson Aggregates well to determine rock compressive strength, static values of Young's modulus and Poisson's ratio elastic constants, and to simulate the in-situ stress conditions of potential reservoirs. Although these data can be used to calibrate elastic constants calculated from the Sonic Scanner log for advanced reservoir modeling, they cannot provide the critical fracture pressure-gradient data. Thus, the testing focus for the No. 1 Hanson Aggregates well was to determine fracture gradients for potential deep saline storage reservoirs in the Basal sand, Copper Ridge Dolomite, and Rose Run Sandstone.

Step-Rate Test Protocol

The protocol used for the three step-rate tests in the No. 1 Hanson Aggregates well was adapted from the procedure developed by EPA Region 8 (U.S. Environmental Protection Agency Region 8, 1999). A step-rate test can be performed in wells without tubing and a packer, although highly permeable or thick injection intervals may need to be mechanically isolated by some combination of straddle packers (U.S. Environmental Protection Agency Region 5, 1994) and plugs. Fluid is pumped into the mechanically isolated test interval in increasing volumes in predetermined uniform time steps until there is a slope change of the rate-pressure curve or a pressure drop indicates the formation has fractured (U.S. Environmental Protection Agency Region 5, 1994). EPA Region 8 guidelines suggest 30-min time steps for formations with 100 mD permeability and 60-min time steps for formations with 50 mD permeability (U.S. Environmental Protection Agency Region 8, 1999). Fluid pumping is then continued at increasing rates for several more time steps to verify that the fracture gradient of the formation has in fact been exceeded. Maximum permitted injection pressure for the injection well is then set at or below the fracture gradient pressure (U.S. Environmental Protection Agency Region 5, 1994).

Step-rate test intervals in the No. 1 Hanson Aggregates well are shown in Figure 6. All testing in this well was in the open-hole wellbore below the casing cemented at 2,994 ft over a period of 5 days. Test intervals were chosen to bracket intervals in which conventional whole cores had been cut in potential reservoir rocks. Prior to testing in the wellbore, a gamma-ray correlation log was run to ensure operational depth control. Rather than using straddle packers to isolate test intervals, as would be done where casing was cemented in an injection well, cement plugs were used to isolate the bottoms of test intervals in the No. 1 Hanson Aggregates well and inflatable packers mounted on 2⅜-in. tubing and set in the open-hole wellbore were used to isolate the tops. Prior to each test, we attempted to recover formation water from the isolated test interval (Fig. 18A). Formation water was recovered from the wellbore by swabbing the test interval through the tubing until a stable conductivity was attained (Fig. 18B) for any recovered water. Water samples were collected from the Rose Run Sandstone and Copper Ridge Dolomite, but no fluid could be recovered from the Basal sand–Maryville sand test interval. All three intervals were underpressured, with pressure gradients below 0.465 psi/ft, as would be typical for deep saline reservoirs. Surface-reading pressure-monitoring gages were placed in both the isolated wellbore to monitor for fracturing and in the wellbore annulus above the packer to monitor for fluid leakage during testing. Only drinking water purchased from the Grayson, Ky., municipal water system was used for the step-rate tests.

Test 1: Basal Sand–Maryville Sand. Test 1 was conducted in the Basal sand–Maryville sand interval from 4,585–4,709 ft (Fig. 6). The interval was prepared by setting a cast-iron bridge plug at 4,727 ft and a cement plug at 4,709–4,727 ft to prevent fluid loss during testing to the underlying fractured Grenville basement rock. The interval was swabbed through tubing prior to the step-rate test in an attempt to recover formation water; however, there was no indication of water influx from the Basal sand–Maryville sand interval after swabbing for several hours. We then terminated water sampling, without recovering a formation-water sample, and the step-rate test proceeded. The surface pumping lines and pressure-control lubricator were pressure-tested to 3,000 psi. The logging string, consisting of a surface readout gage and a memory readout gage, was lowered into the wellbore, and the surface readout gage was positioned at 4,630 ft and the memory readout gage at 4,632 ft. Static bottom-hole pressure was measured, followed by the step-rate test. Stable pumping rates were maintained for 15-min steps, continuing until the test interval fractured; fresh drinking water was used as the test fluid. The pumping rate from 0.25 to 2.0 bbl/min and final pump pressure (in psi) at each step were recorded (Fig. 19A). The Basal sand–Maryville sand interval fractured at a pumping rate of 2.0 bbl/min, a rate of about 2,900 bbl

Figure 18. KGS geologists sample formation water swabbed from a step-rate test interval prior to testing. (A) Marty Parris (left) and Steve Webb connect a carboy to collect a water sample. (B) University of Kentucky Department of Earth and Environmental Sciences student Jerry Grider (left) and Marty Parris monitor water-sample conductivity before collecting a sample.

of water/day, and pressure of 2,689 psi, yielding a fracture gradient of 0.58 psi/ft (Fig. 19A), at which time the test was terminated and pressure falloff was monitored for about 12 hr.

Test 2: Copper Ridge Dolomite. Test 2 was conducted in the Copper Ridge interval from 3,695–3,945 ft (Fig. 6), an interval that showed substantial vugular porosity in cores. The interval was isolated at its base by a cast-iron bridge plug set at 3,963 ft and a cement plug at 3,945–3,963 ft to prevent pressure communication and loss of fluids to underlying strata during testing, thus plugging off and abandoning the wellbore below 3,963 ft (Fig. 6). The interval was swabbed through tubing in 19 runs prior to the step-rate test to recover formation water, and 43 bbl of water was recovered from the Copper Ridge. Subsequent analysis of the water sample showed a total dissolved solids residue of 114,900 mg/L. The step-rate test proceeded with pressure testing of the surface pumping lines and pressure-control lubricator to 3,000 psi. The pressure logging string was lowered into the wellbore, and the surface readout gage was positioned at 3,730 ft and the memory readout gage at 3,732 ft. Static bottomhole pressure was measured, followed by the step-rate test. Stable pumping rates for the test were from 0.25 to 5.5 bbl/min for 5-min steps (Fig. 19B). The test was terminated before the Copper Ridge was fractured because the supply of fresh drinking-water test fluid was exhausted. Pumping pressure did not increase above the 3.5 bbl/min rate (about 5,000 bbl of water/day). After the final step, the well was shut-in and pressure falloff was monitored for about 12 hr.

Test 3: Rose Run Sandstone. Test 3 was conducted in the Rose Run Sandstone interval from 3,257–3,318 ft (Fig. 6). The interval was isolated at its base by a cast-iron bridge plug set at 3,337 ft and a cement plug at 3,337–3,318 ft to prevent pressure communication and loss of fluids to underlying strata during testing; the wellbore was plugged and abandoned below 3,318 ft (Fig. 6). The interval was swabbed through tubing in 26 runs prior to the step-rate test to recover formation water, and 53 bbl of water was recovered from the Rose Run. Subsequent analysis of the water sample showed a total dissolved solids residue of 89,773 mg/L. The step-rate test proceeded with pressure testing of the surface pumping lines and pressure-control lubricator to 3,000 psi. The pressure logging string was lowered into the wellbore, and the surface readout gage was positioned at 3,290 ft and the memory readout gage at 3,292 ft. Static bottomhole pressure was measured, followed by the step-rate test. Stable pumping rates for the test were 0.50–8.0 bbl/min for 7-min steps. The test was terminated early because of mechanical problems; however, the Rose Run had fractured at a pumping rate of 2.5 bbl/min (3,600 bbl of water/day) and pressure of 1,966 psi, yielding a fracture gradient of 0.60 psi/ft (Fig. 19C). We observed only minor pressure buildup during the balance of the test following fracturing (Fig. 19C). After the final step, the well was shut-in and pressure falloff was monitored for about 12 hr.

Well Abandonment and Well-Site Remediation

Immediately upon completion of the well-testing program, all equipment and the inflatable packer were removed from the wellbore in preparation for plugging and abandonment. Plugging began on

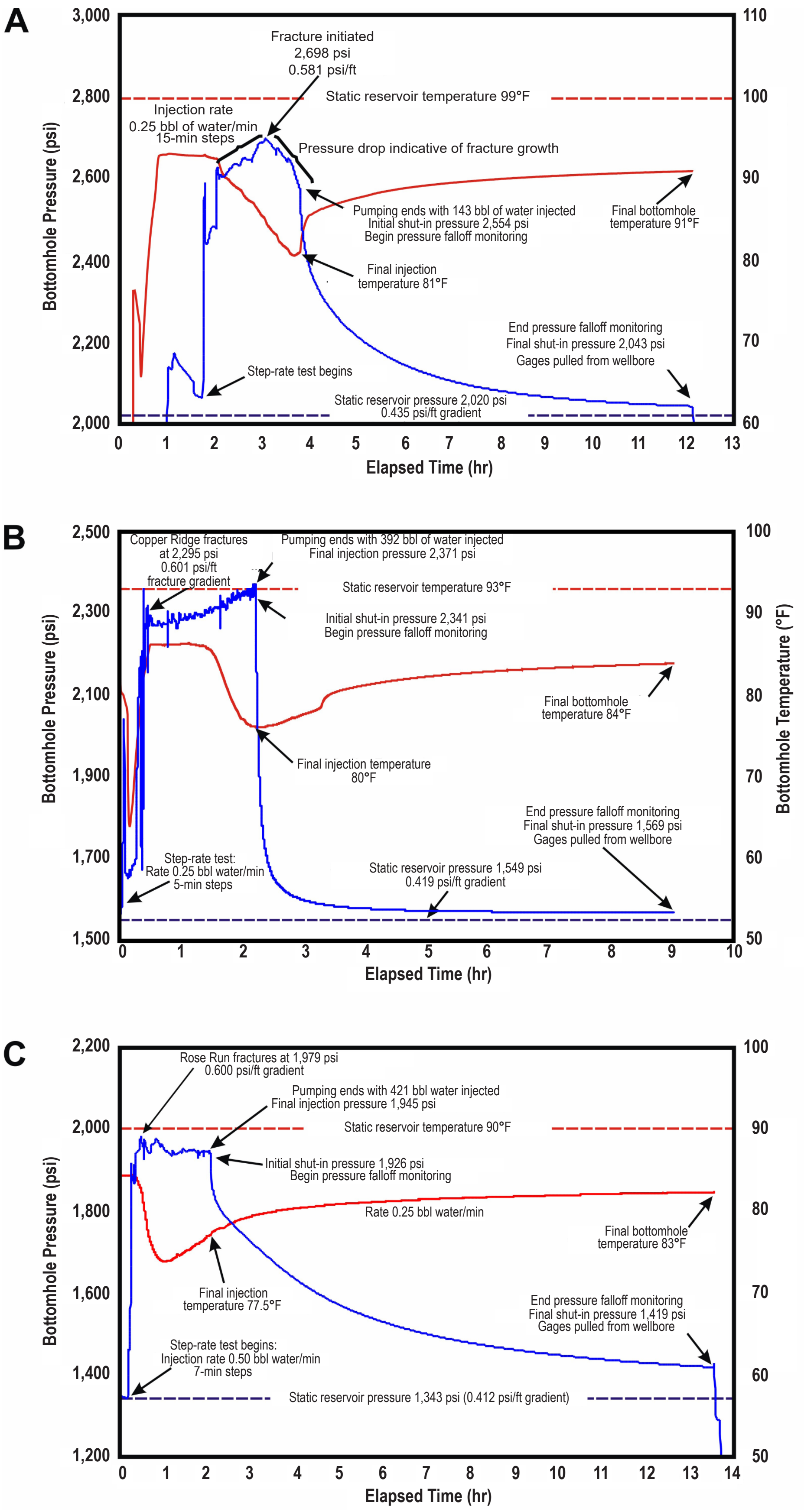


Figure 19. Pressure (blue) and temperature (red) data from the step-rate tests. Injection of water initially cooled the wellbore, but the temperature began to increase because of friction in the test tubing. Only the Maryville–Basal sands fractured; pressure in the Copper Ridge built up during the test, but the unit did not fracture before the water available for testing was nearly depleted and the injection pump was unable to maintain a stable injection rate. Pressure in the Rose Run was stable during injection, varying by less than ±10 psi during the test period, indicating a large reservoir volume with good permeability and porosity. (A) Test 1, Maryville–Basal sands. (B) Test 2, Copper Ridge Dolomite. (C) Test 3, Rose Run Sandstone.

Aug. 14, 2013, and abandonment was completed on Aug. 15. Abandonment plugs were set in the wellbore and casing at 3,108–3,258 ft, 3,108–2,828 ft, 1,403–1,503 ft, 648–748 ft, and 200 ft to the surface. A representative of the Kentucky Division of Oil and Gas witnessed the placement of all plugs. After the plugging was approved, the wellhead was cut off about 3 ft below the surface, and a ⅜-in.-thick steel plate was welded on the casing stub to permanently seal the wellbore. Well-site cleanup was completed in September 2013. Semisolid wet cuttings remaining in the mud pits were nonhazardous, and were safely disposed of in the Green Valley Landfill, Ashland, Ky. The surface of the well site was restored, contoured, and cover-seeded, as specified by Hanson Aggregates; the access road was blocked in October 2013 (Fig. 20). The well completion report and plugging affidavit are available from the online KGS Oil and Gas Records Database.

Discussion and Conclusions

The No. 1 Hanson Aggregates well provided the final data for our CO_2 research that was mandated by the Kentucky legislature under the Incentives for Energy Independence Act of 2007. The well was drilled through the entire Mississippian–Middle Cambrian section in northern Carter County, reaching its total depth in Precambrian basement Grenville gneiss. A total of 453 ft of cores and 30 rotary sidewall cores were recovered, and an extensive suite of geophysical logs was run in the well, including both Formation MicroImager and Ultrasonic Borehole Imager logs. Extensive core analysis was conducted, formation-water samples were collected from the Copper Ridge Dolomite and Rose Run Sandstone, and step-rate tests were run in the Maryville–Basal sands, Copper Ridge Dolomite, and Rose Run Sandstone. In short, the project was an outstanding success in delivering the high-quality data required to assess

Figure 20. The well site was recontoured during remediation, as required by Hanson Aggregates, and obstructed with large stone blocks to hinder trespassing.

the CO_2 storage capacity of the Rose Run, Copper Ridge, and Maryville–Basal sands in northeastern Kentucky and ensure that CO_2 can be confined long-term in the deep subsurface. In addition, the core from the Precambrian Grenville gneiss is providing important information to improve our understanding of the Precambrian crustal history of Kentucky (Moecher and others, 2018).

Because the data set from the No. 1 Hanson Aggregates well is so comprehensive, additional tests related to CO_2 storage are unnecessary for this well. At least one CO_2 injection test would have been ideal, but the arduous permitting and monitoring requirements for CO_2 injection, as well as its prohibitive cost, precluded this. Data from the two CO_2 injection tests in the KGS No. 1 Marvin Blan well, Hancock County (Bowersox and others, 2013, 2016; Bowersox and Williams, 2014), provide clues about what we might have learned from injecting CO_2 into the No. 1 Hanson Aggregates well, although the differences in geology of the target CO_2 storage reservoirs in Hancock County and testing protocols make applying those results to the Carter County project imperfect. The value of the unique data set from the No. 1 Hanson Aggregates well to our ongoing research in eastern Kentucky more than compensates for the lack of CO_2 injection testing, however.

Acknowledgments

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References Cited

Bowersox, J.R., Greb, S.F., Anderson, W.H., and Harris, D.C., 2013, Assessing the CO_2 storage capacity in the central Appalachian Basin: Results of the Kentucky Geological Survey test well, Carter County, Kentucky [abs.]: Geological Society of America, Abstracts with Programs, v. 45, no. 7, p. 99.

Bowersox, J.R., and Williams, D.A., 2014, Geology of the Kentucky Geological Survey Marvin Blan No. 1 well, east-central Hancock County, Kentucky: Kentucky Geological Survey, ser. 12, Report of Investigations 25, 22 p.

Bowersox, J.R., Williams, D.A., and Harris, D.C., 2016, Phase 1 geologic evaluation of the Kentucky Geological Survey Marvin Blan No. 1 deep-saline reservoir CO_2 injection test well, Hancock County, Kentucky: Kentucky Geological Survey, ser. 12, Contract Report 63, 58 p.

Brie, A., Endo, T., Hoyle, D., Codazzi, D., Emersoy, C., Hsu, K., Denoo, S., Mueller, M.C., Plona, T., Shenoy, R., and Sinha, B., 1998, New directions in sonic logging: Oilfield Review, v. 10, no. 2, p. 40–53.

Darling, H., Patten, D., and Schwarze, L., 1991, Single-well data integration: Oilfield Review, v. 3, no. 3, p. 29–35.

Felsenthal, M., 1974, Step-rate tests determine safe injection pressures in floods: Oil and Gas Journal, v. 72, no. 43, p. 49–54.

Gercek, H., 2007, Poisson's ratio values for rocks: International Journal of Rock Mechanics and Mining Sciences, v. 44, p. 1–13.

Hickman, J.B., Harris, D.C., and Eble, C., 2015, Cambrian Rogersville Shale in the Rome Trough, Kentucky and West Virginia: A potential new unconventional reservoir in the Appalachian Basin [abs.]: American Association of Petroleum Geologists, Search and Discovery Article 90216, www.searchanddiscovery.com/abstracts/html/2015/90216ace/abstracts/2103714.html [accessed 06/08/2016].

Moecher, D.P., Bowersox, J.R., and Hickman, J.B., 2018, Zircon U-Pb geochronology of basement rocks (Kentucky, U.S.A.) and implications for late Mesoproterozoic crustal history in the eastern Midcontinent: Journal of Geology, v. 126, p. 25–39.

Peng, S., and Zhang, J., 2007 Engineering geology for underground rocks: Berlin, Springer-Verlag, 319 p.

PetroWiki, 2016, Rock mechanical properties: Society of Petroleum Engineers, petrowiki.org/Rock_mechanical_properties [accessed 01/25/2016].

Philley, J.C., and Chaplin, J.R., 1976, Geologic map of the Wesleyville quadrangle, northeastern Kentucky: U.S. Geological Survey Geologic Quadrangle Map GQ-1305, scale 1:24,000.

Schlumberger, 2002a, FMI: Houston, Texas, Schlumberger, unpaginated.

Schlumberger, 2002b, UBI: Houston, Texas, Schlumberger, unpaginated.

Schlumberger, 2005, Sonic Scanner: Houston, Texas, Schlumberger, unpaginated.

U.S. Environmental Protection Agency Region 5, 1994, Determination of maximum injection pressure for Class I wells : U.S. Environmental Protection Agency, Region 5, Underground Injection Control Section Regional Guidance 7, www.epa.gov/sites/production/files/2015-09/documents/r5-deepwell-guidance7-determination-maximum-injection-pressure-class1-199401-9pp.pdf [accessed 02/2/2016].

U.S. Environmental Protection Agency Region 8, 1999, Step-rate test procedure: U.S. Environmental Protection Agency, Region 8, 6 p., www.epa.gov/sites/production/files/2015-08/documents/r8_guideline_-_step_rate_testing.pdf [accessed 02/2/2016].