

Natural Gas Potential of the Sanford sub-basin, Deep River Basin, North Carolina

By

Jeffrey C. Reid
North Carolina Geological Survey

and

Kenneth B. Taylor
North Carolina Geological Survey
1612 Mail Service Center
Raleigh, North Carolina 27699-1612

with contributions by

Paul E. Olsen
Lamont-Doherty Earth Observatory of Columbia University
61 Rt. 9W
Palisades, New York 10964-1000

and

O. F. Patterson, III
Patterson Exploration Services, Inc.,
1907 Boone Trail Road
Sanford, North Carolina 27330-9414

26 March 2011

Suggested citation: Natural Gas Potential of the Sanford sub-basin, Deep River Basin, North Carolina, by Reid, Jeffrey C. and Taylor, Kenneth B., with contributions by Olsen, Paul E., and Patterson, III, O.F., *in* Taylor, Kenneth B. and Jeffrey C. Reid, editors, “Field Trip Guidebook – 60th Annual Meeting,” Southeastern Section, Geological Society of America, Wilmington, North Carolina, March 2011.

Note: Larger tables and figures are in the back of this field trip guidebook.

Field trip sponsors

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Acknowledgements

We want to thank the landowners for access to their property for the field trip stops. These include: Mr. Hal Stamper for permission to park our vehicles on his property while visiting Stop 5 (Sanford Fm. on NC42), Mr. Edward Myrick (Butler #3 well head stop), the Keisler Land Company, LLC (Alton Creek stop), Hanson Brick (Pekin Formation stop), and Mr. Phillip Oldham (Black Diamond Mine).

In particular we want to thank Patterson Exploration Services, Inc. for hosting the core workshop. We also want to thank the sponsors for the field trip that are listed above and Sandhills Porta-John, Inc., Martin-Marietta Materials, Bost Distributing Company, Mr. Bobby Branch, B.A. Branch Properties, Inc., and Mr. J. Daniel Butler (Jireh Properties, LLC).

We appreciate the support and encouragement of both Mr. James D. Simons, Director and State Geologist, and DENR Secretary Dee Freeman, for the natural gas resource studies of North Carolina. Dr. Ronald K. Perkins, Geology Professor Emeritus, Duke University provided early and continuing encouragement.

Introduction, Objectives and Location

The purpose of this one day field trip is to provide an overview of the natural gas potential in Triassic strata of the Sanford sub-basin, Deep River Basin, Lee, Chatham and Moore counties, North Carolina. The Deep River Basin is a 150-mile long northeast-trending half-graben with a steeply-dipping eastern border fault in central North Carolina (Figures 1, 2). The information herein is as of February 2011 and is subject to revision with new data.

The Deep River Basin is divided into three sub-basins, which are named (from north to south) the Durham sub-basin, the Sanford sub-basin and the Wadesboro sub-basin. The three sub-basins are filled with ~7,000 feet of Triassic strata, which are divided into the following three formations in descending stratigraphic order (Figures 3, 4): (1) Sanford Formation (red and gray siltstone and shale); (2) Cumnock Formation (black shale, with some beds of gray shale, sandstone and coal); and (3) Pekin Formation (gray sandstone and shale). The Cumnock Formation includes a ~800 foot thick interval of Upper Triassic (Carnian) organic-rich black shale. This shale extends across ~59,000 acres, at depths of less than 3,000 feet in the Sanford sub-basin, Lee and Chatham counties. These Triassic strata were deposited in fresh water, shallow lakes similar to African rift valley lakes in a paleo-equatorial geographic location. The Cumnock Formation is the source rock in this sub-basin.

Organic geochemistry and thermal maturation analyses indicate that the black shale in the Cumnock Formation is gas-prone, and that values of total organic carbon (TOC) exceed 1.4 percent in places. The Cumnock Formation contains systematic fractures that are observable in outcrop, on 1:24,000-scale geologic maps superimposed on LiDAR data, and possibly in drill cores. The primary fractures trend north-west, whereas the conjugate fractures trend northeast. In some places along the west side of the basin, the primary fractures are filled with diabase dikes (that locally heated the Cumnock Formation), although mapping in underground coal mines (now closed) has shown that the diabase dikes do not extend far into the basin.

We interpret the Sanford sub-basin as a total petroleum system containing a source rock (the Cumnock Formation), seal (the Sanford Formation), and having traps (structural and depositional). This is a relatively untested exploration area that has about 8,765 acres under lease since January 2010.

Thirteen of the 28 wells (including old coal holes) that were drilled in the Cumnock Formation have reported natural gas and oil shows, and two shut-in wells have measured pressures: 900 psi (Butler #3) and ~250 psi (Simpson #1). One of these shut-in wells (Butler #3) is located within 3.5 miles of a six-inch natural gas distribution line to the Sanford industrial park with large volume gas users (Figure 5). Well drilling preceded acquisition of ~75 miles of 2D seismic lines in the mid-1980's that provide three-dimensional control in the Sanford sub-basin and parts of the Durham sub-basin. Deeper parts of the Sanford sub-basin are unexplored. Preliminary seismic interpretation suggests multiple stratigraphic and/or structural targets.

The Sanford sub-basin is included in the U.S. Geological Survey's (USGS) 2011 Mesozoic basin assessment to determine the amount of technically recoverable natural gas. Potential resource geologic units were developed for coal bed methane (CBM) and shale gas. The USGS is assessing state data and expects to publish a report in 2011. Unconventional methods of drilling, using horizontal drilling and hydraulic fracturing, are required to tap into the potential resource; changes to state law, dating from 1945, would be necessary. There is no past or current production from these wells, or non-Mesozoic petroleum exploration wells drilled on the Coastal Plain.

In the Deep River Basin, many families sold the mineral rights to their property to pay for taxes during the Great Depression, and significant underground coal mining occurred during the 1930s. Information on mineral rights and deed transfers may be found using online county land records. The North Carolina oil and gas law may be viewed online at the following Web site: <http://www.ncleg.net> (see short cut to General Statutes). Additional information on natural gas and oil, and permitting in North Carolina, may be found in N.C. Geological Survey Information Circular 36, available online at: www.geology.enr.state.nc.us (see 'Publications' at that URL). The legal authority / statute reference is: G.S. 113-378 to 113-415 – “Sub-chapter V. Oil and Gas Conservation – Article 27”; 15A NCAC 05D – “Subchapter 5D – Oil and Gas Conservation” (see also URL <http://www.ncga.state.nc.us/gascripts/statutes/Statutes.asp>). Some mineral rights were extinguished (recombined) by act of the North Carolina General Assembly. Some minerals rights bought after the last extinguishments are still active.

Seismic data, drill cores and well logs from the Deep River Basin will be examined as part of this field trip. These materials and cutting may be examined by arrangement at the facilities of the North Carolina Geological Survey (NCGS) in Raleigh, North Carolina. Sample borrowing agreements under certain conditions are allowed. Interested parties should contact the NCGS' Chief Geologist for further information.

The Sanford sub-basin, Deep River Basin, is one of several Mesozoic rift basins in North Carolina. Refer to Figures 1 and 2 for the locations of the other basins. Figure 5 was prepared to provide in one location a comparison of North Carolina's Mesozoic rift basins (as of February 2011) and factors important in hydrocarbon exploration including basin size (acres), presence or absence of coals, total organic carbon, vitrinite reflectance (%Ro), source rock thickness, targets for resource evaluation, number of shut-in wells, depth to basement, erosion estimates and other information including current leasing status. One Mesozoic basin has been confirmed by drilling under the Coastal Plain cover sediment (Weems and others, 2007). The extent and depth, and presence of organic units are unknown. Its presence indicates that other buried Mesozoic basins exist under the Coastal Plain and have yet to be discovered.

Past exploration history and recent developments

There has been a lengthy resource exploitation history in the Sanford sub-basin beginning with the Revolutionary and Civil War eras. Post Civil War coal mining encountered gassy mines and a series of major explosions resulted in fatalities. There was a period of coal mining and coal resource evaluation from the mid-1940's to mid-1950's (Reinemund, 1949, 1955). Reinemund had access to the underground coal workings for his subsurface geologic coal resource mapping. In the 1980's a series of “wildcat” petroleum exploration holes were drilled for oil in the Sanford sub-basin without the benefit of seismic resulting in ‘blind drilling’. Subsequently seismic was acquired along lines connecting the wildcat wells resulting in our current database. One coal bed methane test well was drilled in 1981. The last petroleum exploration holes drilled were in 1998. A summary chronology follows:

- ☐ 1775 – Revolutionary War era, coal exploration for iron and munitions.
- ☐ 1776 – N.C. Colonial Records mentioned “Pit Coal” ...in good quantities....
- ☐ 1820's – 1850's – Coal reports ‘rediscovered’.
- ☐ 1861 – 1873 – Civil war and post war coal production.

- ▣ Coal mine explosion: December 19, 1895 (killed 46 men) – Egypt Coal Mine (High Point Enterprise, May 21, 1995 – Section D, page 1).
- ▣ Coal mine explosion: May 22, 1900 (killed 22 men) – Egypt Coal Mine – (High Point Enterprise, May 21, 1995 – Section D, page 1).
- ▣ Coal mine explosion: May 27, 1925 (killed 53 men) – three separate explosions documented – Carolina Coal Mine Co. (Coal Glen Mine) (High Point Enterprise, May 21, 1995 – Section D, page 1).
- ▣ 1920's – 1940's – Underground coal mining, exploration; gassy mines – see notable explosions above.
- ▣ 1955 – U.S. Geological Survey publishes Reinemund's milestone Professional Paper 246 on the coal resources of the Deep River Basin (Reinemund, 1955). Reinemund had access to the underground coal mines and detailed maps were produced. He concluded that about 110 million tons of available coal in the Sanford sub-basin. His surface and subsurface geological mapping beginning in the late 1940's and various coal quality studies by the U.S. Bureau of Mines was incorporated in USGS Professional Paper 246, and subsequently was incorporated in the North Carolina Geological Surveys' 2008-2010 natural gas resource assessment. Reinemund tabulated a number of shows of gas, oil and asphalt in diamond drill core and in the underground mine workings that he had access to for his study.
- ▣ ~ 1 million short tons coal produced – 1700's–1930's. Another effort in the 1980's was abandoned because of faulted nature of the coals. Approximately 3,000 tons of coal were mined during a surface mine feasibility study in the 1980's by Chatham Coal Company, Inc.
- ▣ 1980's – 1990's – Exploration drilling (all vertical holes) began in 1974. During this period, four holes were drilled (VR Groce #1, Dummitt-Palmer #1, Butler #1 and Bobby Hall #1 wells). Seismic reflection data was collected using a dynamite source in April 1986 taking advantage of the existing wells that had been drilled before (VR Groce – 1974; Dummitt-Palmer #1 – 1982; Butler #1 and #3 – 1983). All the named wells are within 500 feet of the dip section Seismic Line 113. The Elizabeth Gregson #1 well was drilled in 1987 on Seismic Line 113. The Simpson #1, drilled in 1998, is also on Seismic Line 113. The VR Groce #1 well was used as the cross over point between the dip section (Seismic Line 113), and the strike section (Seismic Line 106B). The seismic data was further tied using the Butler #1 well a the cross over point between the east-west seismic section (Seismic Line 102) and the dip section (Seismic Line 113). Butler #2, drilled in 1991, was more than 2,000 feet from Seismic Line 113, and the Butler #3 well, drilled in 1998, was more than 9,400 feet from Seismic Line 113.
- ▣ 2008 – Organic geochemical data published (Reid and Milici, 2008).
- ▣ North Carolina Geological Survey reports thick section of organic shale as a potential natural gas resource.
- ▣ 2008 – Initial industry presentation by North Carolina Geological Survey staff (Reid and Taylor, 2008).
- ▣ 2009-2010 – Flurry of industry interest including site visits. Leasing begins in the Sanford sub-basin. Currently about 9,500+ acres are currently under lease or have representation.
- ▣ 2008-2011 – North Carolina Geological Survey staff conduct 54 briefings and presentations to public, state and local government and professional groups (see Reid and Taylor, 2010; Reid, Taylor and Simons, 2010; Reid, 2009; Reid and Taylor 2009a-c; Reid and Taylor, 2008).
- ▣ 2010-2011 – North Carolina Geological Survey staff compiles all available data and interprets all seismic lines for U.S. Geological Survey's assessment and transmit it to the U.S. Geological Survey.

Potential Resource Geologic units (GU's)

There are five preliminary Potential Resource Geologic Units (GU's) proposed for the coal bed methane (CBM) and Shale Gas in the Sanford sub-basin of the Deep River Basin in North Carolina (Figure 6, Table 1). The measured areas of these units are below the 300-foot overburden level for lithostatic load pressure.

Coal Bed Methane (CBM)

Potential Resource Geologic Unit Sweet Spot – This area was determined from the georegistered coal structure contour map (Plate 7) in Reinemund (1955). This unit includes the area from where the mapped coals are 300 feet (100 meters) below the surface and ends where the coals are faulted-out by the Deep River Fault down dip. The GU Sweet Spot has an area of ~10,345 acres.

Potential Resource Geologic Unit B-1 – This area was also determined from the Plate 7 contour map. The unit includes the area from the mapped coal outcrop to where the Cumnock coals are faulted-out by the Deep River Fault down dip, consistent with the southeast edge of the Sweet Spot AU. The AU B-1 has an area of ~3,196 acres.

Potential Resource Geologic Unit B-2 – This area was identified by Reinemund (1955) as coals which extend beyond the Deep River Fault. The shape of this AU was modified from Reinemund based on additional evidence. This unit is bounded by coal outcrops to the southwest and northeast. The southeast boundary is limited by the absence of coal in the VR Gross #1 well (LE OT-01-74) and the interpretation of seismic lines which show the domination of siliciclastics to the basin fault margin. The GU B-2 has an area of ~15,193 acres.

The total area of the CBM Potential Resource Geologic Units is ~28,734 acres (Figure 6, Table 1).

Shale Gas

Potential Resource Geologic Unit Shale Gas – This area includes Cumnock shale which is more than 300 feet (100 meters) below the surface. There are two shale geologic units – Area 5 and Area 3.

Area 5 extends southwest and does not include mapped Cumnock shale which based on shallow shale cores and faulting indicated that the shale is less than 300 feet from the surface. Black shale occurs at depth of 386 to 409 feet (TD 529 feet) in well MO-C-04-81. The south-eastern border of the GU is based on two lines of evidence -- the presence of Cumnock in the Bobby Hall #1 well (LE-OT—02-83) and the absence of Cumnock in the logs from the Elizabeth K. Gregson #1 well (LE-OT-01-87) as well as the interpretation of seismic lines which show the Cumnock reflector ending between these same two wells. GU Area 5 extends over ~58,933 acres.

Area 3 extends to the northeast and again includes the Cumnock Fm. at a depth greater than 300 feet (100 meters) below the surface. Drill hole CH-C-02-81 shows black shale is too shallow at 140-160 feet depth (TD 270 feet). The measured dip in Reinemund (1955) is 25 degrees to the southeast and the Area 3 geologic unit ends at the basin fault margin. GU Area 3 has an area of ~17,211 acres.

The total area of the Shale Gas Potential Resource Geologic Units is ~76,144 areas (Figure 6, Table 1).

Coal bed methane

Coal bed methane (CBM) is one set of geologic units. Included in the coal is oil-bearing 'blackband' or shale oil that is stratigraphically associated with the coals. Reinemund (1955) compiled the thickness and original reserves of coal by "area" and by coal bed. Combined these are about 111,959 million short tons.

Reinemund (1955, p. 104-111) provides extensive information and data on the coal composition, physical properties and utility. Reinemund (p. 104) states that "...The coals of the Deep River Field are bituminous, except where metamorphosed by intrusive and provides data (Reinemund's Table 10) showing the range of compositions and heating values among the bituminous coals. This would place the bulk of the coal in the oil window with a Ro% of 0.8 – 1.0. These values are useful for the gas resource evaluation by assigning the coal rank as a proxy for vitrinite reflectance (%Ro). Limited amounts of coal desorbition data are available from the Dummitt-Palmer #1 coal bed methane test well (Hoffman and Buetel, 1991).

Anthracitic coals are localized within 50 feet of diabase sills or diabase sill-like intrusives (Reinemund, p. 104). The largest accumulations are near Carbonton. Coke occurs in zones four to five feet wide adjacent to the diabase intrusives. Anthracite coals are restricted to a narrow band around intrusive diabase dikes and overall tonnage is comparatively low (see Reinemund's Figure 4.5). Thus their contribution to the assessment is quite low despite their higher equivalent %Ro.

Access to underground coal workings were mapped by Reinemund. These maps show that diabase dikes intrudes between blocks of basin rock. In addition, Reinemund's maps show that the diabase sheet that outcrops along the southwest margin of the basin, does not extend into the basin or even into the underground coal workings. This has been a potential concern heard from natural gas exploration companies worried about drilling into a diabase sheet in the interior of the Sanford sub-basin.

Drilling and exploration history

Modern exploration of the Deep River Basin began with the coal resource investigations including surface geologic mapping by Reinemund (1949, 1955). Reinemund had access to underground coal mines and his maps remain useful today. Diamond core drilling was done as part of his coal resource investigations and a wealth of coal quality and quantity data were accumulated. These drill cores are located in the North Carolina Geological Survey's repository in Raleigh, North Carolina. Core descriptions are included in the appendix of Reinemund's U.S. Geological Survey's Professional Paper 246 (Reinemund, 1955). The organic sections of the cores have been sampled by various parties, including the North Carolina Geological Survey (NCGS), over the years for TOC, Rock-Eval, %Ro and recently mineralogy by XRD. These data began the organic geochemical database the NCGS now uses and to which the NCGS has added data in recent years.

The typical geophysical log suite for the petroleum exploration holes are: gamma, SP, caliper, density, induction, density and neutron. There are, however, variations of the geophysical tools run in each hole. No geophysical logging was done on diamond drill cores used by Reinemund for the coal assessment program.

Reinemund noted evidence of petroleum and natural gas as part of his subsurface coal resource investigations. Coal bed methane has been part of the coal mining history of the area (see 'Shows' below).

Petroleum exploration began in the mid-1980's and consisted of a series of vertical exploration wells that sought oil. During this era no seismic data was available; consequently holes were drilled "blind" having limited knowledge of required depth or basin structure.

Two dimensional (2D) seismic lines were acquired in 1985 after the initial drilling in the Sanford- and Durham sub-basins. Seismic lines were run as dip- and strike sections – generally connecting the locations of previously drilled wells. The original seismic data tapes were recovered but they proved unreadable. Consequently we initially interpreted the seismic using the available paper plots. Figure 7 is the eastern part of Seismic line 113 – a dip section across part of the Sanford sub-basin from the northwest to the southeast. An alluvial fan complex (green form lines) has prograded northwest from the southeastern highlands and the Jonesboro fault system (red form lines at right side of image) that bounds the rift. The Bobby Hall #1 well was drilled to a total depth of 4,500 feet. It encountered 370 feet of Cumnock Formation from a depth of 3,930 feet to 4,300 feet. Subsequently we converted the seismic and drill logs to digital formats for use in industry standard petroleum exploration software (SMT's Kingdom Suite).

LiDAR maps

North Carolina has statewide LiDAR (Light Detection and Ranging) coverage. Hillshade LiDAR shows structural and lithologic features in great detail in the Sanford sub-basin. Examples include intrusive diabase dikes, faults, fracture patterns, and trend lines of sedimentary strata. Greater understanding of the Sanford sub-basin can be visualized when digitally georegistered geologic maps are superimposed on a LiDAR base. The orthogonal joint system is particularly evident (Figures 8, 9) and can be seen at the outcrop scale as well (see also Figure 31 in Field Trip Stop 4).

Natural gas and oil shows, shut-in wells and initial flow rates

There is a lengthy history of coal mine explosions (High Point Enterprise, May 21, 1995 – Section D, page 1). Mr. J. Daniel Butler, son of Mr. Howard Butler (deceased) was interviewed by telephone on May 7, 2010 regarding his recollections and information from newspaper clippings of natural gas and oil shows in his father's coal mine. The summary was that the coal mines were gassy and no oil was found. Examples of the gassy nature of these mines follows:

- Coal mine explosion: December 19, 1895 (killed 46 men) – Egypt Coal Mine
- Coal mine explosion: May 22, 1900 (killed 22 men) – Egypt Coal Mine
- Coal mine explosion: May 27, 1925 (killed 53 men) – three separate explosions documented – Carolina Coal Mine Co. (Coal Glen Mine).

Thirteen of twenty-eight drill holes (oil and gas tests, and coal cores) including the gassy coal mines have direct evidence of hydrocarbons.

Two wells are shut-in with measured gas pressure in March 2009. They are the: 1) Butler #3 well (measured pressure of 900 psi), and 2) the Simpson #1 well (measured pressure of ~250 psi). Both wells were failed nitrogen frac jobs. The Butler #1 well also encountered significant gas pressures but the well has been plugged and abandoned. The Dummitt-Palmer #1, a shallow coal bed methane test well, encountered gas but the pressure is not available in well records.

The initial flow rates for these wells (where known from the daily drilling reports) are in the following list. The gas flow was flared (burned) from all four wells (Butler #1, Butler #3, Simpson #1 and Dummitt-Palmer #1). Figures 10a,b show the flaring of gas from the Simpson #1 well.

Number	Event	Source
1	Gassy coal mines – see discussion directly above – recurring natural gas explosions occurred in these mines. Multiple fatal methane-charged explosions (some coal dust may have been a contributing factor). Mines long closed and workings now inaccessible.	High Point Enterprise, May 21, 1995 – Section D, page 1. Also recent telephone interview with son of deceased mine owner and manager (Butler family).
2	Butler #1 well – well flared; no initial flow rate or initial pressure data can be found; gas burned. Multiple shows of gas, asphaltic, oil, oil and gas, gas, gas and oil, gas, oil, coal and condensate rated as poor to good in depth range of 456 feet to 3,805 feet.	A video of this well shows a forceful gas flow through 5.5-inch (?) pipe and subsequent ignition of gas stream by operator. See USGS Open-File Report 2008-1108 (Reid and Milici) for original data.
3	Butler # 3 well – current measured pressure of 900 psi (March 2009). Initial flow rate – unknown.	See daily drilling reports. See also petrophysical report on this and the Simpson #1 well for documentation of pressures during nearly year-long test. See Isotech lab report for molecular chemistry, BTU, and stable isotope composition of the gas.
4	Simpson #1 – current measured pressure of 250 psi. Initial flow rate of 3,000 mcf/d, ultimately settling at 231 mcf/d. Well flared (see Figure 10).	See daily drilling reports (NCGS). See also Holmes (1998) and the Butler #3 well for documentation of pressures during nearly year-long test.
5	Dummitt-Palmer #1 well – drilled as a coal bed methane (CBM) well in the shallow part of the basin near the western margin. Produced very high BTU gas. Estimated production potential of 40,000 cubic feet of gas per day. Shut-in pressure was reported to be 250-400 psi (2011, Personal communication to J.C. Reid by O.F. Patterson, III).	See North Carolina Geological Survey, Open-file report 91-1 for details.
6	'Blackband' - 'oily' section in the Cumnock Formation. Retorted Cumnock samples yield between 3.9 – 12.4 gallons of oil per ton of rock (Vilibrant, 1927). Reinemund (1955) recomputed Vilibrant's 1924 analyses to show that three separate beds of black shale in the upper part of the Cumnock Fm. (having thicknesses of 7, 32 and 38 feet) yield shale oil in the amount, respectively, of 8.4, 9.8, and 12.7 gallons of per ton of shale and 1,760, 1,347, and 2,940 cu. feet of gas per ton. The blackband beds associated with the Cumnock coal bed (totaling 29 inches in thickness) yield 3.6 gallons per ton (and 734 cu. feet of gas); and the blackband beds associated with the Gulf coal bed (totaling 50 inches in thickness) yield 6.9 gallons per ton (3,260 cu. feet).	See documentation summarized below and original data in Reinemund, USGS Professional Paper 246, Table 14 and explanatory notes.
7	V.R. Groce #1 well (LE-OT-1-74) – multiple shows of gas, asphalt, gas and oil, and oil rated as poor to good over the depth interval of 1380-3120 feet	See documentation summarized in Reid and Milici (USGS Open-File Report 2008-1108).
8	Bobby Hall #1 well (LE-OT-2-83) – multiple shows of gas,	See documentation summarized in Reid

	and oil all rated a poor over depth interval from 835 to 4,588 feet.	and Milici (USGS Open-File Report 2008-1108).
9	Drill hole DH-1 – multiple shows of oil-bearing black shale and/or ‘blackband’ over depth interval from 355-645 feet. Quality of show not rated by Reinemund.	Reinemund, USGS Professional Paper 246, p. 127 – well log
10	Drill hole BMDH 2 – oil on fractures at a depth of 1,060 feet	Reinemund, USGS Professional Paper 246, p. 138 – well log
11	Drill hole BDH 9 – two occurrences of oil in the Sanford Formation: 1) oil saturated (tar-like) in coarse part of sand (463-465 feet); 2) oil saturated and oozing light oil in discrete intervals between 583 – 586.25 feet).	Reinemund, USGS Professional Paper 246, p. 148 – well log
12	BMDH DR-1 – multiple shows beginning in the Cumnock Formation at about 1,857 feet and continuing to an approximate depth of 2,192 feet in the Cumnock Formation. Details follow: 1) 1,850 – 1,857 – Sandstone impregnated with tarry patches. Oil oozing from rock 1,861 – 1,862 feet when freshly cut. 2) 1,894 – 1,910 – Claystone. Some oil seepage along fractures 3) 1,923 – 1,927 – Grayish black shale. Odor of oil on fresh breaks; some oil stain. 4) 1,947 – 1,955 – Claystone, dark-gray. Internally fractured with oil seepage along fractures. 5) 1,980 – 1,987 – Vugs at 1,985 feet coated with quartz crystals and filled with oil. 6) 2,017 – 2,022 – Shale, medium-gray. Oil seepage along fractures at top. 7) 2,044 – 2,048 – Shale, medium-gray. Badly sheared with oil seepage along fractures. 8) 2,066–2,076 – Shale, dark-gray. A few open fractures coated with bituminous material and filled with oil; internally sheared. 9) 2,100 – 2,134 – Shale, grayish-black. Scattered open fractures and vugs with oil seepage. 10) 2,160 – 2,175 – Shale, grayish-black. Oily and fossiliferous; poor core recovery. 11) 2,186 –2,187 –Siltstone, dark gray. Very hard, calcareous, oil-stained. 12) 2,192 – 2,193 – Siltstone, grayish-black. With irregular patches of brown calcite crystals; oil stained.	Reinemund, USGS Professional Paper 246, p. 150-154– well log
13	Gas in mud logs and degraded oil in Sanford Formation.	Well logs

Depth to basement

The Sanford sub-basin is a northeasterly trending half-graben basin. It has two deeper parts of the basin – the northeastern most reaching a depth of slightly more than 7,000 feet (Figure 11). An alluvial fan progrades from the southeast from a southern highland toward the northeast and the lake facies and axial basin flow. A second, deep part of the Sanford sub-basin is in the southwestern portion of the basin; it appears to have comparable depths as the northern part of the basin.

Isopach thickness of the Cumnock Formation

The preliminary isopach map of the Cumnock Formation is shown in Figure 12. Seismic lines and drill holes provide reference. The scale bar indicates Cumnock Formation thickness in meters. Coordinates are in meters (State Plane Meters, NAD83); thickness is in meters (shown by color). The thickest Cumnock Formation is not spatially located over the deepest part of the Sanford sub-basin, but is offset to the northwest.

Organic Geochemistry

Type of organic materials in the Cumnock Formation and total organic carbon

- ▣ Sediments are predominantly gas prone with some oil shows; robust database ~400 analyses.
- ▣ TOC data exceeds the conservative 1.4% threshold necessary for hydrocarbon expulsion (Figures 13, 14).
- ▣ Organic matter derived from terrestrial Type III woody (coaly) and from Type II material; Type I (algal material) likely present.
- ▣ Thermal alteration data (TAI) and vitrinite reflectance data (%Ro) indicate levels of thermal maturity suitable to generate hydrocarbons.

The organic material was derived primarily from terrestrial Type II and from Type III matter (Figure 13, 14). Likely there is an algal component (Type I) as we observe some algae mounds in core. Algae as an organic source material is very good because it is a superior organic source material.

Thermal maturity

Figure 15 shows that hydrocarbons were generated in the Sanford sub-basin. Many of the data points lie in the oil window and underwent a high level of conversion to gas. The overmature data points are associated with diabase dikes. A few samples were “overcooked” by diabase dikes (extreme right in dry gas window). A time-temperature model for the Sanford sub-basin has not been constructed. Milici and Wilkes (2003) noted that “...depending on the depth of burial and heat flow for each to the basins, hydrocarbon generation and migration into local traps appears to have been initiated concurrently with extension and sedimentation in the Triassic and continued into Early Jurassic, when the basin extension ceased following continental breakup, separation, and the initial opening of the Atlantic Ocean.”

Erosion estimates

We estimated maximum erosion is shown based on the %Ro data using the method of Dow, 1977 for determining the amount of eroded strata of the linear plots of the \log_{10} of vitrinite vs. depth (Figure

16). Estimation of erosion depth is part of our interpretation of a total petroleum system being present. The regression line through borehole data is extrapolated back of 0.2% Ro, the reflectance of early diagenetic woody plant matter to find the amount of missing section. It is assumed that there was no change in thermal conductivity or geothermal gradient in the eroded section.

We estimate a maximum of 3,000 feet has been removed. Variations from the regression line are interpreted as vertical movement of fault blocks. “Overcooked” data points are from a CBM well near the up-dip and basin edge. The Bobby Hall #1 well (only two data points) has a slope similar to the other points but is vertically offset by ~1,500 feet.

Mineralogy and ‘fracability’

The “brittleness” of the Cumnock Formation as a means to help access the Cumnock’s ‘fracibility’ is shown in Figure 17. Minerals known at this time by XRD are: clays (chlorite, kaolinite, illite and mixed layer illite/smectite), carbonates (calcite, iron-bearing dolomite, siderite), major minerals (quartz, k-spar, plagioclase) and trace minerals (pyrite, gypsum, anhydrite, carphosiderite, analcime, apatite and hematite).

Porosity

Porosity and permeability data from the Cumnock Formation unavailable in our database. The handful of available data indicate permeability of about 0.08 to 0.9 md. Holmes (1999) estimated porosity of 2.4 – 3.4% in three intervals of the Simpson #1 well, and estimated porosity of 11.8 to 12.6 from two intervals from the Butler #3 well. Cumnock Formation reconnaissance SEM images from the CH-C-1-45 (BDMDH-1 well – depth 1,454,5 feet), and the Dummitt-Palmer #1 well (LE-OT-1-82 – depth 842 feet) show substantial pores (Figures 18, 19). Their interconnectivity (e.g. permeability) has not been measured.

Gas type and possibilities for biogenic gas

Complete molecular composition, BTU, and stable isotopic data (Δ Nitrogen, Δ Carbon, and Δ Deuterium) in the shut-in well gases and pressures were obtained in March 2009 from the sub-basin’s two shut-in wells (Butler #3 and Simpson #1) through the auspices of Dr. Robert Burruss of the U.S. Geological Survey. Analyses were performed by Isotech Laboratories. These data are summarized in Tables 3 and 4. The Butler #3 well and the Simpson #1 wells were drilled in 1998. The wells have been shut-in since then. Both wells had substantial initial gas flow, considerable initial gas pressures, and both maintain much of their original gas pressure today.

Historically wells in Triassic strata in North Carolina are very dry and locating a sufficient water supply has been a problem. A down-hole video tape of the borehole of the nearby Butler #1 well showed it to be bone dry to a depth in excess of 3,000 feet from the surface. In a statistical well yield study of groundwater resources of the Piedmont and Blue Ridge provinces of North Carolina, Daniel (1989) showed that the Triassic strata had among the lowest well yield – thirteenth of fourteen units Daniel studied.

The Simpson #1 well reportedly produced some water – enough for the operator to have installed a small pump jack to attempt dewatering of the well. The pump jack has been removed. The source of the water from the Simpson #1 well is unknown (returned frac fluid(?) or formation fluids(?) or

groundwater(?) or some combination of these (?). The water's stable isotope signature is somewhat lighter than that of the Butler #3 well's gas.

We plotted our limited ΔD methane vs. $\Delta^{13}C$ methane on a cross plot of ΔD methane (deuterium isotopes for methane, ‰) vs. $\Delta^{13}C$ methane (carbon isotopes for methane, ‰) showing fields for bacterial gas, associated gas, postmature dry gas etc., from Ellis et al., 2003. Reprinted with permission from the Oil & Gas Journal (from Janell Edman, RMAG, August 2007) (see Figure 20). The methane component data point for the Simpson #1 well lies barely in the mixed gas field and may suggest the presence of some biogenic gas.

Nitrogen content of the gas

Nitrogen was measured in natural gas from the Simpson #1, Butler #3 and Dummitt-Palmer #1 wells. Based on the depleted (-3 per mill) N^{14} stable isotope data from the Simpson #1 and Butler #3 wells, the nitrogen source is thought to be from the denitrification of the ammonium sulfate contained in the "blackband" – a unit rich in ammonia sulfate and phosphate and contains from 3.8 to 12.4 gallons of oil per ton (Reinemund, 1955). The 'blackband', first described by Reinemund (1955), consists of beds of ferruginous, thick-bedded shale near the coal seams. The most extensive blackband bed is between the main bench and lower benches of the Cumnock coal bed. This bed is generally 18 inches thick. Reinemund interpreted the blackband as accumulations of carbon and iron-rich muds in the coal forming swamp at time of restricted accumulation of plant material.

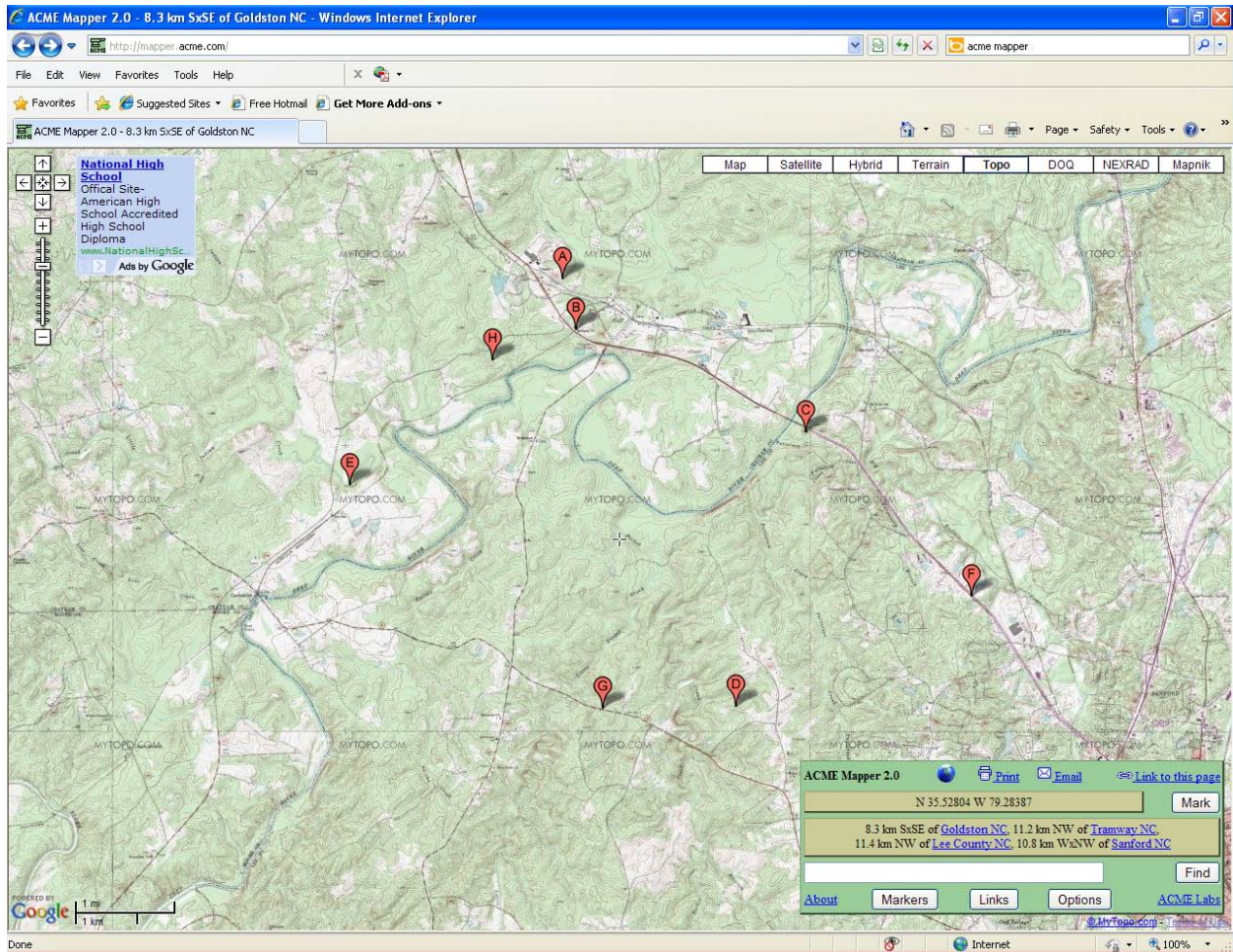
High ammonia (NH^3) concentrations were known to be associated with organic-matter-rich intervals ('blackband') above and below the coal beds in the Cumnock Formation. Krohn and others (1988) made ion chromatograph measurements that showed the highest concentration of mineral-bound ammonium was in illite-rich layers 200 feet stratigraphically above the blackband horizon and that the nitrogen may be bound inorganically throughout the stratigraphic interval of the Cumnock Formation rather than being concentrated in the blackband interval. However, the average ammonium content in these intervals is rather low, generally less than 0.1 weight percent. They note that the highest concentrations of ammonium occur in an interval roughly 200- to 328 feet above the blackband in the Dummitt-Palmer #1 (LE-OT-1-82) and North American Exploration, Inc. well NCCM-1 (CH-C-01-81) drill cores. They were not able to determine a direct cause for the distribution but noted that illite would provide a mineralogical site favorable for substitution. The depleted $\Delta^{15}N$ (this well and the Simpson #1 well – see Table 4) indicates that neither current atmospheric nitrogen (or frac nitrogen) is the source of the nitrogen.

Similar conclusions for the locations of nitrogen associated with illite clay from the North German Basin were reached by Plessen and others (2006), and the German part of the Central European Basin (Littke and Krooss, 2009).

The 'blackband' and higher stratigraphic intervals could be packed off thus eliminating or substantially reducing potential nitrogen production. On the other hand, if nitrogen were to be produced, it could potentially be reinjected to drive additional methane recovery.

Field trip route

Figure 21 shows the locations of the core workshop and fieldtrip stop locations on a composite topographic map base. Sanford is located just under the Acme Mapper logo (lower right). Stops A, B, C and F are located along US 421 that runs from Sanford to the northwest, crosses the Deep River, and continues to Goldston, North Carolina. The northwest trend of the sedimentary strata is shown by the topographic map. The orthogonal offsets of the Deep River reflect northwesterly and northeasterly trending orthogonal fractures in the Sanford sub-basin. The Sanford sub-basin occupies a topographic low.



Balloon	Stop number and name
F	Stop 1 - Core workshop – Patterson Exploration Services
A	Stop 2 – Boren Clay Products Pit – Pekin Fm., Chatham Co.
C	Stop 3 – Lunch and Butler #3 wellhead and well discussion
H	Stop 4 – Alton Creek – outcrop of Cumnock Fm., Chatham Co.
B	Stop 4A – Bethany Church, Outcrop of the Cumnock Fm., Chatham Co. (Alternate stop)
E	Stop 4B – Black Diamond Mine, Outcrop of the Cumnock Fm., Chatham Co. (Alternate stop)
G	Stop 5 – Sanford Fm., NC Highway 42, Lee Co.
D	Stop 5A – Simpson #1 well and discussion (Alternate stop), Lee Co.

Figure 21. Field trip route showing stops. Base from Acme Mapper.

Field trip stops

STOP 1. Core workshop

The core workshop affords participants the opportunity to examine a very thick continuous cored section of the Cumnock Formation and related cores from the Sanford sub-basin. Maps and seismic sections will be available at this core workshop to provide context.

The North Carolina Geological Survey uses the following core notation (e.g., LE-OT-1-82 – the Dummitt-Palmer #1 well). The two letter designation “LE” denotes the county (Lee County in this example). The next two letter are the type of well – in this case the “OT” denotes ‘oil test’. The first number, in this case “1” denotes the first well drilled in that county for that year. The second number, in this case, “82” denotes the year (1982 in this example) that the hole was drilled.

Drill holes USBM 2 (CH-C-01-45) and BDH 9 (LE-C-4-45) are diamond drill cores drilled in 1945 and reported by Reinemund (1955) in the appendix of U.S. Geological Survey Professional Paper 246. Core logs that will be available for these two holes are from Reinemund (1955) and a new interpretive core log prepared by Paul Olsen (CH-C-01-45).

Cores that are available for this workshop are:

1. USBM 2 (CH-C-01-45)

a. Features to be observed:

- i. Refer to Paul E. Olsen’s core logs (see below) and SEM images. XRD data will also be available.

2. Dummitt-Palmer #1 (LE-OT-1-82) – Coal bed methane (see Hoffman, Charles W., and Buetel, 1991)

a. Features to be observed:

- i. Refer to the core log and SEM images.

3. BDH-9 (LE-C-4-45)

a. Features to be observed:

- i. Degraded oil in coarser part of the Sanford Formation – possible evidence of “tight gas”.

4. Coal cores from underground in the Cumnock Mine (previously known as the Egypt Mine) donated by Mr. J. Daniel Butler, February 12, 2010.

a. Features to be observed:

- i. These are the most complete coal core holes in North Carolina. The full thickness of the coal (~42 inches) is preserved in these rare cores. In comparison, the coals in the U.S. Bureau of Mines cores were extensively sampled to determine coal quality and very little remains.

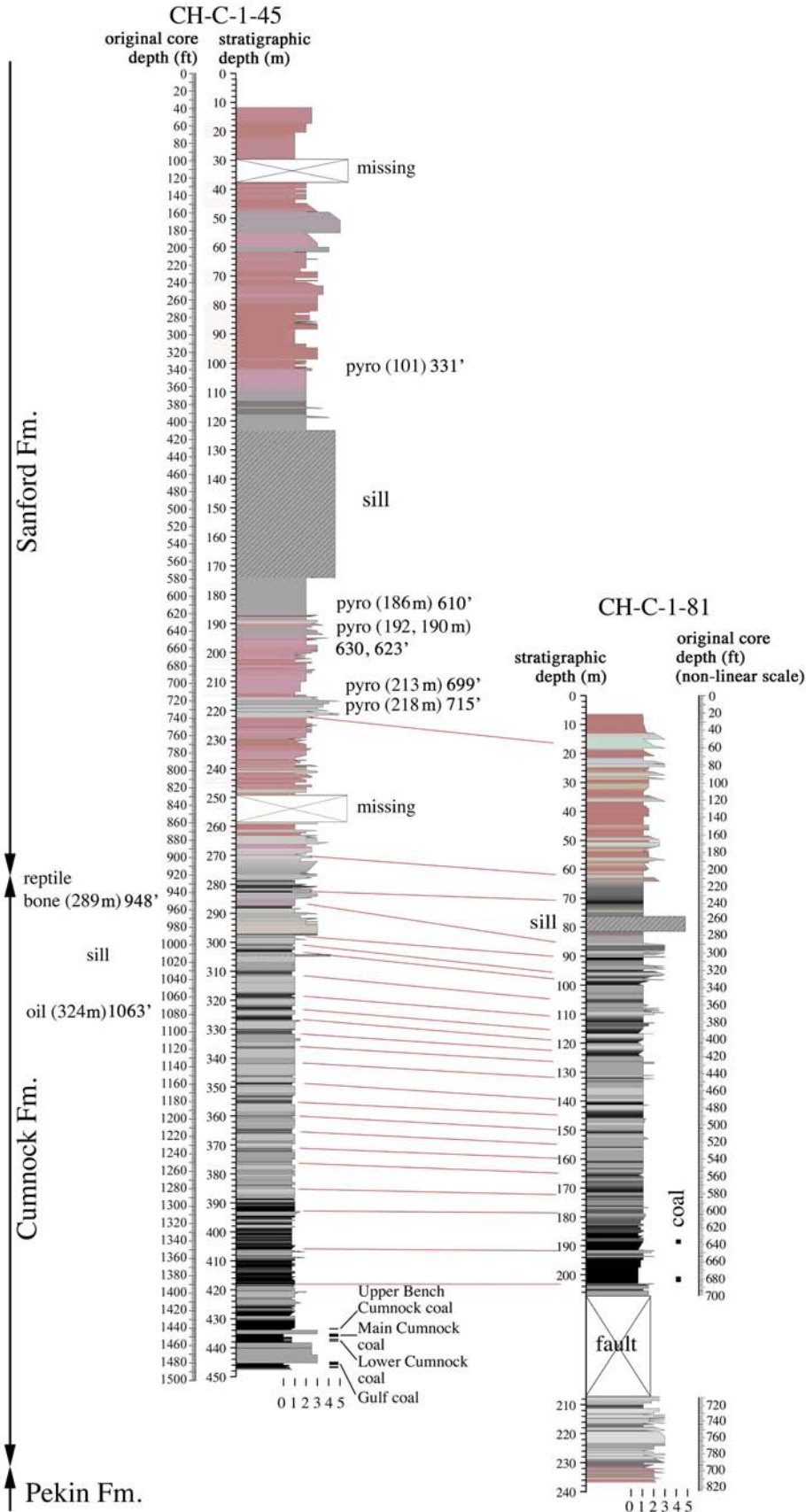
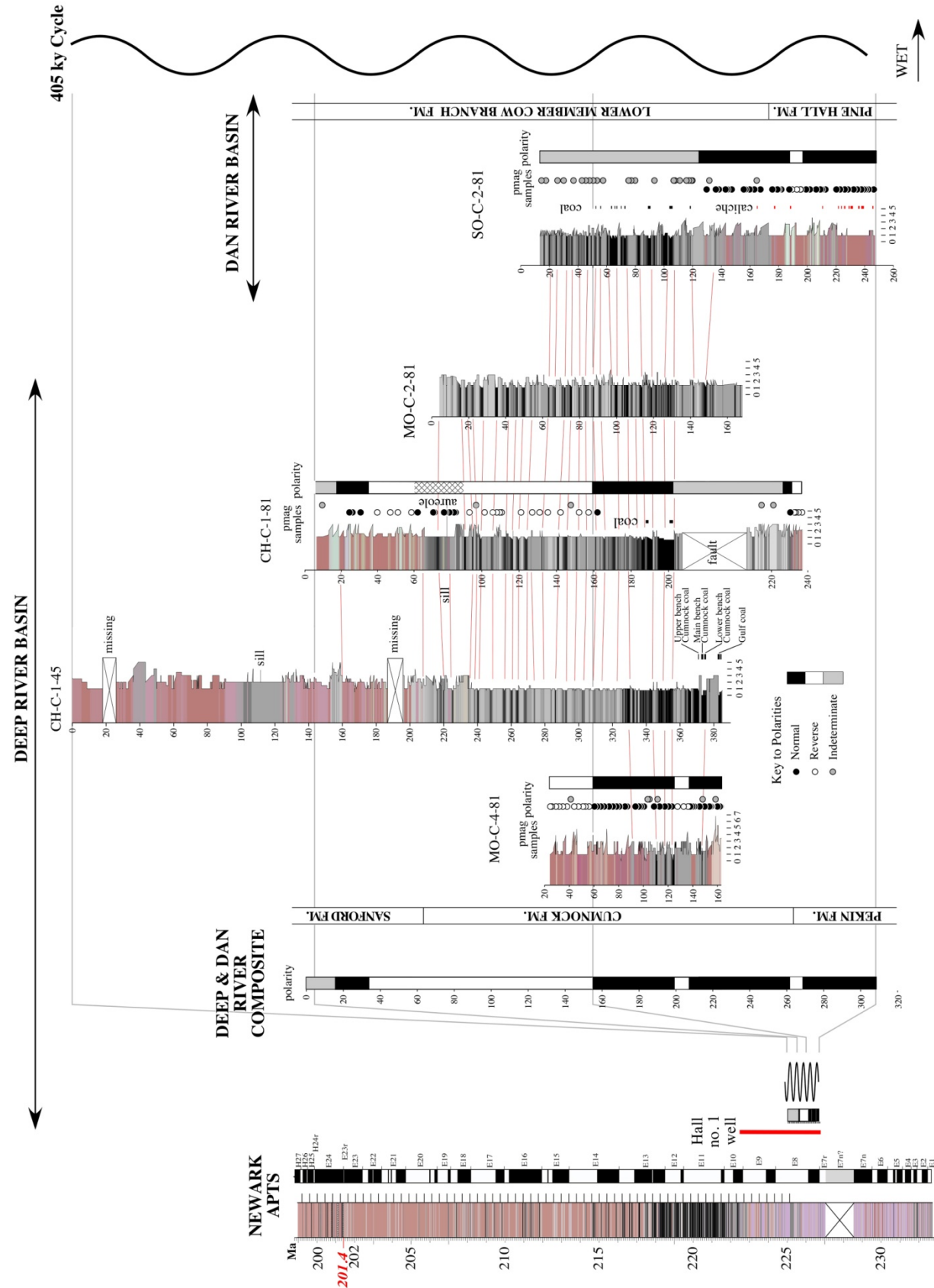


Figure 22. Drill hole CH-C-1-45 correlated with core CH-C-1-81 (both cores from Chatham County, North Carolina) (Prepared by Paul E. Olsen). Vertical scale depth from the surface (meters and feet for CH-C-1-81). Color scheme tracks rock color (exaggerated). Grain size indicated by numerical scales at base of sections (0, claystone; 1, mudstone; 2, siltstone; 3, fine sandstone; 4, medium sandstone; 5, coarse sandstone; 6, pebbly sandstone; 7, fine conglomerate). Abbreviation "pyro" stands for pyrobitumin staining. Note that original core depths are in feet and have been converted to meters.



WET

Figure 23. This figure (previous page) shows the correlation of drill hole CH-C-1-45 with cores from the Sanford sub-basin of the Deep River Basin and the Dan River Basin. Correlation prepared by Paul E. Olsen. Vertical scale depth from the surface (meters). Magnetic polarities and climatic cycles of the Newark basin Astronomically calibrated geomagnetic Polarity Time Scale (Newark-PTS; Kent and Olsen, 1999; Olsen et al., 2011). Magnetic polarity from Whiteside et al. (2011). Thin reverse polarity zones not recovered in Newark-PTS because of much lower sampling rate in Newark cores. Color and grain size as in Figure 20. Depths in meters reflects removal of sills in CH-C-1-45 and CH-C-1-81. Note extraordinary lateral correlation of sedimentary cycles (correlated by red lines) not only between the cores in the Sanford subbasin of the Deep River basin, but also with the lower member of the Cow Branch Formation of the Dan River basin, a correlation proposed by Olsen et al. (1982) based on fossil fish assemblages.

Dummitt-Palmer #1 (LE-OT-1-82 – Lee County, North Carolina). This was a coal bed methane (CBM) test well located, at the western feather edge of the sub-basin, was drilled in 1982. About one-half of the Cumnock Formation was lost because of an intrusive diabase sheet – not present in the downdip coal workings (Reinemund, 1955). This well was drilled to a total depth of 953 feet in December 1981 and January 1982. The project was designed to test the methane content of the coal beds within the Cumnock Formation of the Sanford sub-basin. Two coal zones and one black shale zone were sampled and yielded gas recoveries of 12.1 cc/g, 9.6 cc/g, and 2.4 cc/g with BTU values of 986.85, 976.45, and 908.95 as determined by the former U.S. Bureau of Mines. Stimulation *via* acid-foam frac had limited success and completion as a producing well was deemed unfeasible despite indications that about 40,000 cubic feet of good quality gas could be produced per day. This well had a pressure of about 250-400 psi.

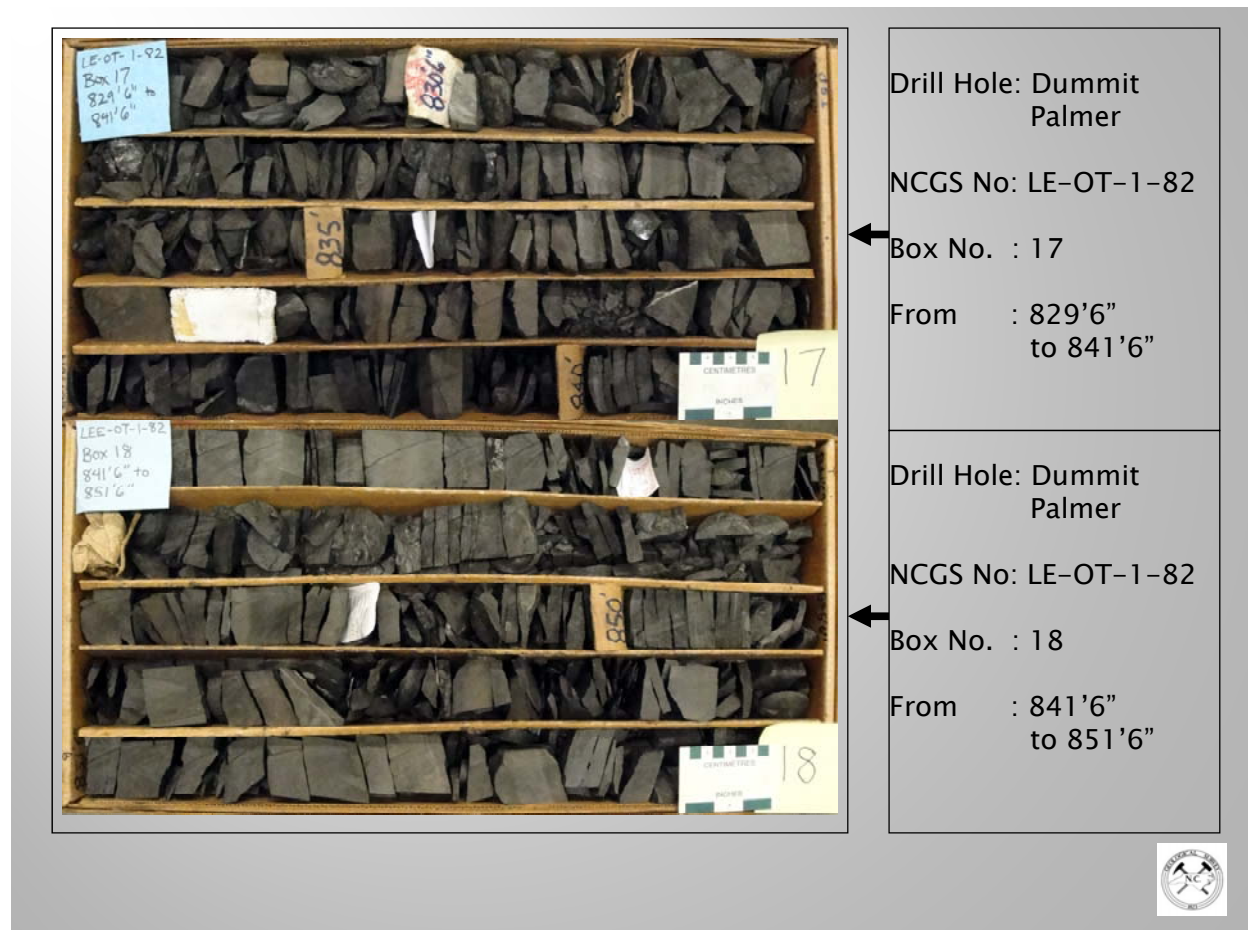


Figure 24. This is a typical interval from the Dummitt-Palmer #1 coal bed methane drill hole (LE-OT-1-82). The SEM image (Figure 19) was from an interval in the lower core box. The two core boxes contain the cored interval from 829' 6" to 851' 6".

Drill hole BDH-9 (LE-C-4-45 – Lee County, North Carolina). Degraded oil in coarser part of the Sanford Formation – possible evidence of “tight gas”.

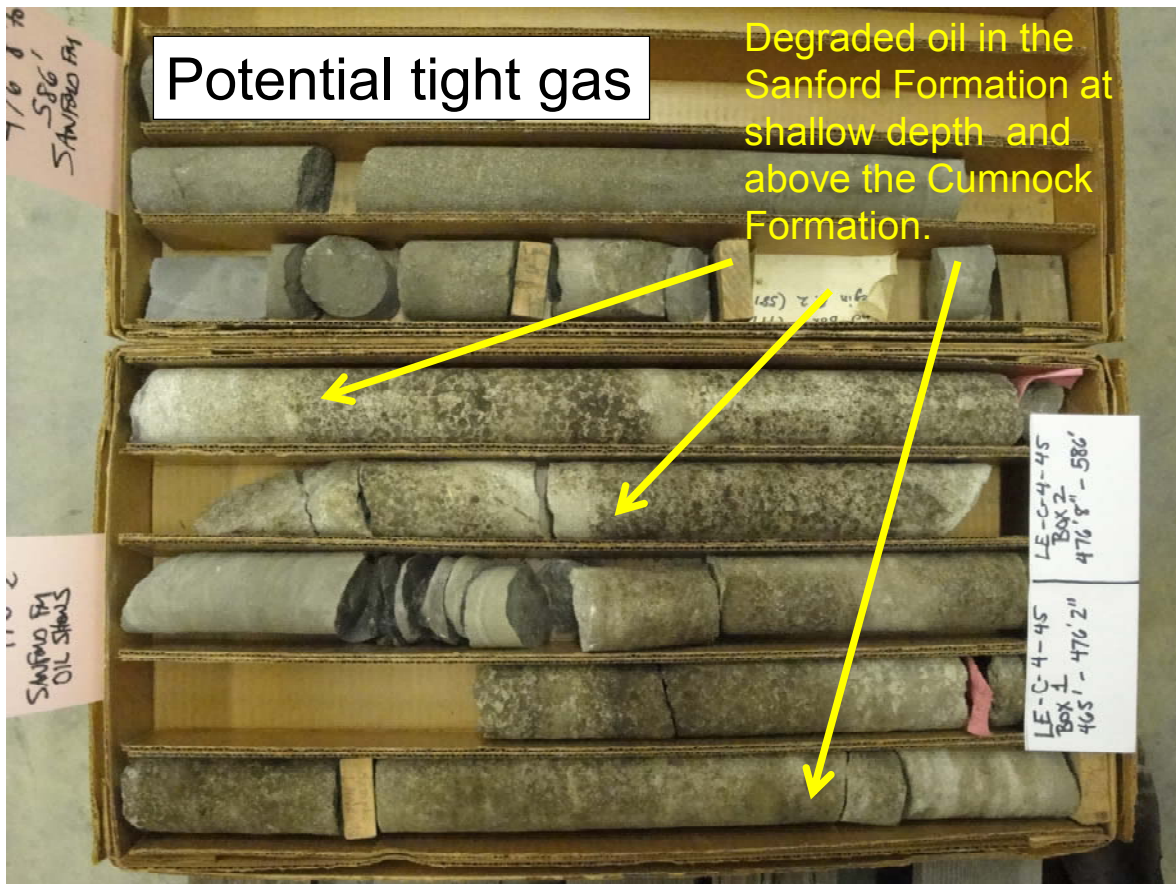


Figure 25. Degraded oil in the Sanford Formation about 300 feet stratigraphically above the Cumnock Formation. The total depth of this hole (BDH-9) is 1,425 feet. Cumnock was logged from 723 feet to TD – this also shows the Cumnock to be at least 700-feet-thick here. These oil shows plus gas kicks in the well logs suggest the possibility of tight gas. There is a fair amount of porosity in these sands to hold the oil. Tight gas is not included in the geologic units (GU’s).



Figure 26 - Unnamed Cumnock Formation underground coal cores. These coal cores are from the Cumnock Mine, formerly known as the Egypt Mine (Chatham County, NC). These coal cores, probably from the 'Main Cumnock Coal', are the most complete coal core holes in North Carolina and may have been preserved from the U.S. Bureau of Mines coal evaluation program. These cores may be from the USBM 'BDH' coal core holes described originally by Berry (1946). The full thickness of the coal (~42 inches) is preserved in these rare cores. The coals in the U.S. Bureau of Mines (USBM) cores in the North Carolina Geological Survey core repository were extensively sampled by the USBM to determine coal quality and very little remains or the original coal intervals.

Stop 2 – Pekin Formation

Location: 35.566005°N, -79.2942555°W Hanson Brick (formerly Boren Clay Products pit) Gulf, Chatham County, North Carolina.

Synopsis: This is the lowest stratigraphic unit known in the Sanford sub-basin. It is exposed along the western sub-basin margin in outcrops and abandoned clay pits. The Pekin is known in the subsurface from several hydrocarbon exploration holes including the Butler #1 and V.R. Groce wells that penetrated basement. This locality is about 2,000 feet stratigraphically below the Cumnock Fm. and an estimated 1,200- to 1,400 feet above basement rocks.

Features to view:

- *Fracture pattern in outcrop corresponds with LiDAR images,*
- *Faults and slickensides, bedding and channels, joints, fractures, intrusive diabase dikes with baked zones, and*
- *Diverse plant and animal fossils, burrows.*

In the mid-to-late 1960's, two of the most significant assemblages of Upper Triassic fauna and flora to date were discovered in North Carolina (Baird and Patterson, 1967; Hope and Patterson, 1969; Patterson, 1969; Hope and Patterson, 1970; Delevoryas and Hope, 1971). These significant localities lie between 400 and 1100 feet stratigraphically above the base of the Pekin Formation and both within 600 feet of this stop.

In the now abandoned Pomona Pipe Company pit to the north, approximately 400 feet stratigraphically above the base of the Pekin formation, a bone bed containing teeth and bones of large and small heterodont, osteoderms of the armored pseudosuchian *Longosuchus* (previously unknown east of Texas), teeth resembling those of *Teratosaurus* and the similar Cumnock genus *Zatomus* – both rauisuchian pseudosuchians, along with several individuals of a dicynodont mammal-like reptile (the first found in the Newark Supergroup) have been identified as the kannemeyeriid *Placerias* previously known only from the lower Chinle Formation of Arizona. A series of vertebrate tracks has also been described, the oldest from the Triassic of Eastern North America (Olsen and Huber, 1996).

In the old Boren Clay pit plant fossils consisting of ferns, cycadophytes, and conifers were found in a light tan to light gray siltstone about 1,100 feet stratigraphically above the base of the Pekin Formation. The most common plant fossils impressions are the sphenophyte *Neocalamites virginiensis* (Fontaine) Berry, ferns *Lonchopteris virginiensis* (Fontaine), *Cladophlebis microphylla* (Fontaine), *Phlebopteris smithii* (Daugherty) Arnold, *Pekinopteris auriculata* Hope and Patterson, and the cycadophytes *Otozamites powelli* (Fontaine) Berry, *Otozamites hespera* (Fontaine) Berry, and *Leptocycas gracilis* Delevoryas and Hope. *Pterophyllum*, *Pseudoctenis*, and *Williamsonia* are also abundant.

Numerous faults and joints (Figures 27, 28) along with many sedimentary features and fossils may be observed in the old pit.



Figure 27. Pekin Formation (fractured) as seen in Boren Clay Products pit (now Hanson Brick). Bedding and channels are apparent at this point. The Pekin Formation is the lowest stratigraphic unit in the Sanford sub-basin. These conjugate fractures trend west- to northwest and east- to northeast. These near vertical fractures may serve as “plumbing” for migration of hydrocarbons through Cumnock self-sourcing, or from a deeper (unknown) source rock. The Boren pit is well known for the diverse assemblage of diverse plant fossils. These plant fossils include ferns and their relatives (pteridophytes), horsetails, and gymnosperms, including conifers, cycads, and cycadeoides (Olsen and Gore, 1989; Hope and Patterson, 1969; and Patterson, 1969).



Figure 28a (left), b (center), c (right). Pekin Formation. Bedding trends ~N65E and follow remnants of past clay mining. One fault exposed (Figure 28a) in the pit trends N65E/45W; slickensides on the fault plane trend N55E/55W. The fractures pattern at this locality generally runs N0E to N15E with an orthogonal set oriented at about N92E (Figures 28b-c). The joints have a near vertical dip. One other fracture set trends about N35-36W (Figure 28c) with a steep dip. A very thin diabase dike trends N355W and has a small baked zone. A similar baked zone in the Dummitt-Palmer #1 CBM well yielded considerable quantities of natural gas. The view in Figure 28a is toward the northeast. On Figures 28b-c north is toward the bottom of the photograph. Pocket knife and boots for scale in Figures 28b-c. Line showing trace of fractures is purposefully offset from the feature so that it can be seen.

Stop 3– Butler #3 wellhead

Location: 35.543617°N, -79.250778°W

Synopsis: One of two shut-in natural gas wells in North Carolina.

Features to view: The primary feature to observe at this locality is Butler #3 well head and the re-vegetated drill pad.



Figure 29. Butler #3 wellhead. The Butler #3 well was drilled vertically in 1998 reaching a total depth of 2,655 feet. The well penetrated the Cumnock Formation and was subsequently logged geophysically. There was an attempt to hydrologically frac the well using nitrogen foam but it appears to have failed. Initial flow rate is unknown. There were multiple completion zones in this well.

In March 2009 the well pressure was measured at 900 psi and the well’s gas was sampled for molecular chemistry, BTU content and stable isotope composition by Jeffrey C. Reid (NCGS) and Robert C. Burruss (USGS). See Figure 28 for well construction detail schematic, and Table 3 for the well’s gas composition. No flow test has been done on this well so far as is known. Since the pressure testing was completed, the well has been shut in until we measured its pressure and sampled the gas in March 2009. It is unknown the extent of tubular products that may still be in this well. The nitrogen in the well is believed to come from the denitrification of the thin stratigraphic “blackband” rock in this well and from illite-bearing sections about this unit.

Holmes (1998) in a petrophysical log study of this well suggested it had the parameters on a 160- acre drainage spacing.

	Interval 1,700-2,300 ft.	Interval 2,300-2,658 ft.	Both
Thickness, ft.	6	5.9	11.9
Porosity, %	12.6	11.8	12.1
Water saturation, %	32.9	45.8	39.2
In-place, gas, MMCF	230	175	405

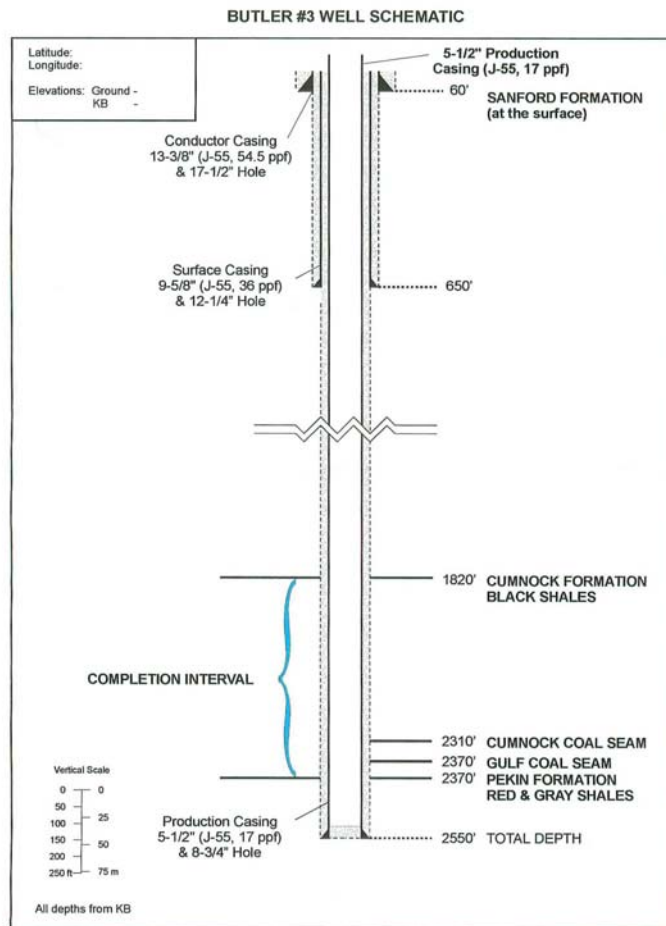


Figure 30. Butler #3 well schematic diagram showing completion interval. See Table 3 for well gas molecular and stable isotope chemistry and depth (feet) of well perforations. High ammonia (NH_3) concentrations were known to be associated with organic-matter-rich intervals ('blackband') above and below the coal beds in the Cumnock Formation. Krohn and others (1988) made ion chromatograph measurements that showed the highest concentration of mineral-bound ammonium was in illite-rich layers 200 feet stratigraphically above the blackband horizon and that the nitrogen may be bound inorganically throughout the stratigraphic interval of the Cumnock Formation rather than being concentrated in the blackband interval. However, the average ammonium content in these intervals is rather low, generally less than 0.1 weight percent. They note that the highest concentrations of ammonium occur in an interval roughly 200- to 328 feet above the blackband in the Dummitt-Palmer #1 (LE-OT-1-82) and North American Exploration, Inc. well NCCM-1 (CH-C-01-81) drill cores. They were not able to determine a direct cause for the distribution but noted that illite would provide a mineralogical site favorable for substitution. The depleted $\Delta^{15}\text{N}$ (this well and the Simpson #1 well – see Table 4) indicates that neither current atmospheric nitrogen (or frac nitrogen) is the source of the nitrogen. Note: Plan depth slightly less than measured depth.

Similar conclusions for the locations of nitrogen associated with illite clay from the North German Basin were reached by Plessen and others (2006), and the German part of the Central European Basin (Littke and Krooss, 2009).

There is no video of the testing of this well; however, a video recovered of the Butler #1 well, shows that the gas flow was very strong and that the gas burned.

Table 3. Butler #3 well - gas chemistry and BTU values and well perforations.

Component	Chemical mol. %	Delta 13C per mil	Delta D per mil	Delta 15N per mil
Carbon Monoxide	nd			
Hydrogen Sulfide	nd			
Helium	0.218			
Hydrogen	0.0250			
Argon	nd			
Oxygen	nd			
Nitrogen	45.60			-3.32
Carbon Dioxide	nd			
Methane	48.78	-45.11	-178.5	
Ethane	3.86	-36.81	-175.8	
Ethylene	nd			
Propane	1.15	-31.61	-121.3	
Iso-butane	0.0930	-31.96		
N-butane	0.186	-31.25		
Iso-pentane	0.0264			
N-pentane	0.0436			
Hexanes +	0.0366			
Total BTU/cu. Ft. dry @ 60deg F & 14.7psia, calculated 605				
Specific gravity, calculated 0.778				

Well perforations (depth in feet)

- 1,976
- 2,066
- 2,264
- 2,360
- 2,439
- 2,444
- 2,450
- 2,456
- 2,462
- 2,501
- 2,510
- 2,519
- 2,527
- 2,535
- 2,543
- 2,551
- 2,558

Stop 4 – Cumnock Formation at Alton Creek, Chatham County, North Carolina.

Location: 35.557465°N, -79.298638°W

Synopsis: Outcrops in creek show orientation of high angle joints.

Features to view: The primary feature to observe at this locality is the fracture orientation in the exposed Cumnock Formation – the source rock.

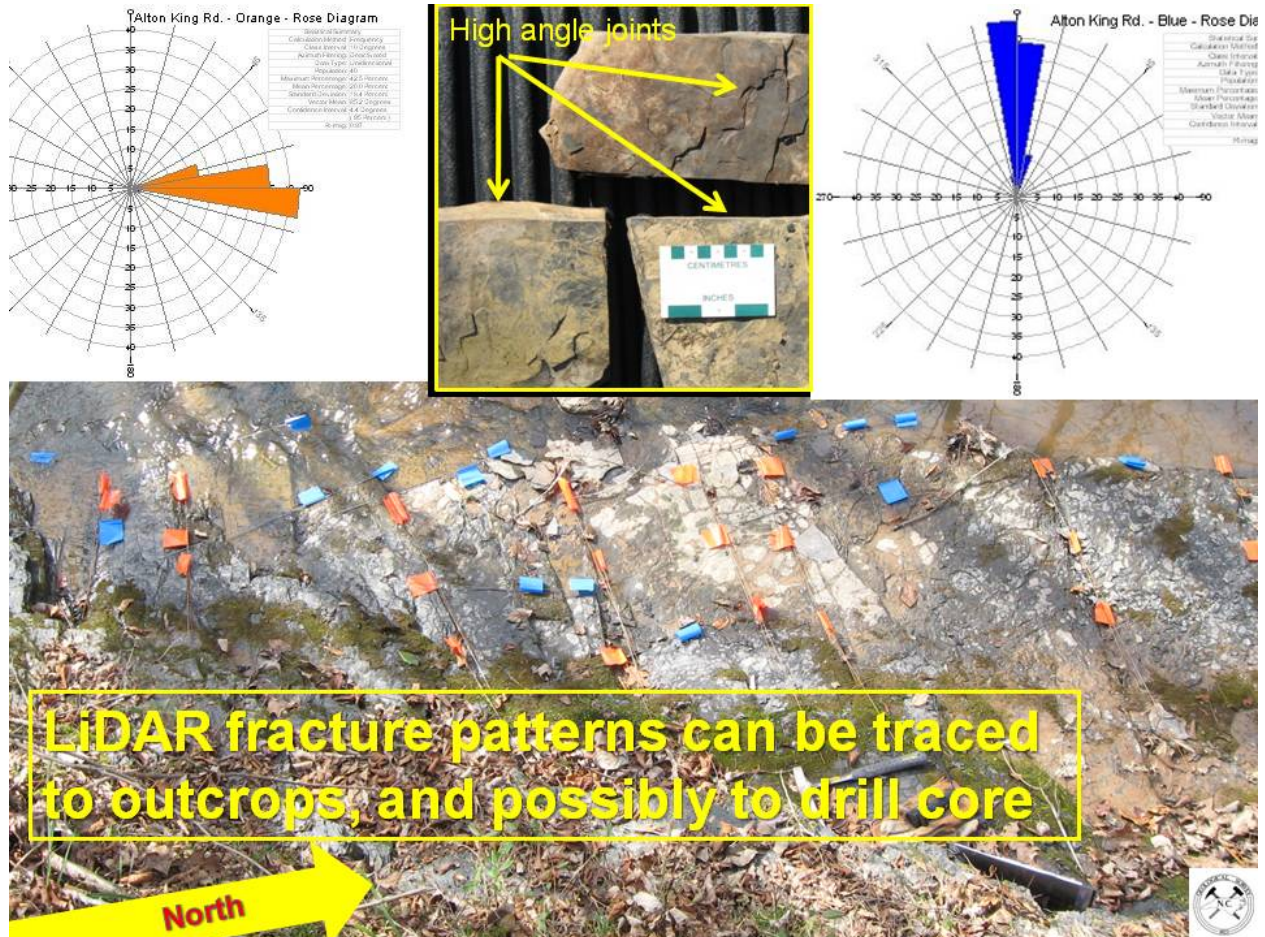


Figure 31. Alton Creek, Chatham County, North Carolina. Orthogonal fractures observed at the sub-basin scale in LiDAR occur at the outcrop scale. Fractures are steeply dipping and have smooth sharp edges (inset top center). At this locality the fractures trend easterly (orange flagging and left rose diagram), and northerly (blue flagging and right rose diagram). Slight variations of fracture orientations coincident with LiDAR trends have been observed at different locations in the Sanford sub-basin. Knowledge of fracture orientation and spacing may prove helpful to directional- and horizontal petroleum exploration drill holes.

Two samples from this outcrop were analyzed for TOC (1.58% and 1.30%); the corresponding %Ro values are 1.86% and 3.34% -- apparently from vitrinite. The high maturity is because of heating from nearby intrusive dikes and a diabase sill that precludes identification precisely of the organic matter (OM) type. However, the finely disseminated grains that grade to amorphous size particles suggest that most OM was humic and primarily gas prone at a lower maturity. Plant spores, which are good indicators throughout the oil window are absent. The visual kerogen analysis indicates 90% gas prone, 5% oil prone, and a TAI ranging from 3.5-4.0 consistent with %Ro.

Stop 4A (Alternate) – Cumnock Formation at Bethany Church, Gulf, Lee County, NC

Location: 35.558663°N, -79.291963°W

Synopsis: Outcrop of coal-bearing Cumnock Formation.

Features to view: Coal and the transition from the Cumnock Formation to the underlying Pekin Formation along the railroad track.

The description of this stop is adapted with permission of Paul Olsen (2011) from Olsen and Gore (1969). As of December 2010 the outcrop's condition is poor and it is mostly covered by a new highway bridge foundation for the eastbound lanes of US Highway 421. Outcrop cleaning, scraping and digging beginning at the first outcrop south of the new bridge footings and along the east bank of the railroad cut yields black shale and coaly material. To access this site park at the Bethany Church then walk downhill from the back side of the parking lot and to the east to the railroad track. Turn south along the railroad track and walk to the second (newer) bridge footing.

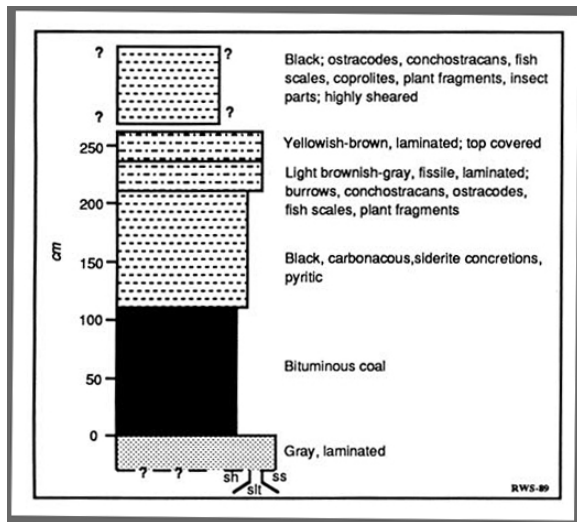


Figure 32a. Measured section from near Bethany Church, used with permission from Olsen and Gore (1969).



Figure 32b. Bethany Church outcrop is in poor condition in December 2010 showing locations of both bridge footings for US421. The newer eastbound bridge over US421 is in the foreground and the concrete apron has covered important parts of the original outcrop. Photograph taken in December 2010.



Figure 32c. This is an exposure of the Pekin Fm. looking south toward the US421 bridge located very close to Bethany Church. Photograph taken in December 2010.

Proceed down embankment to railroad tracks. Look for small outcrops of the Cumnock Formation coal and black shale near the bridge. The shale and shaly coal are extremely fossiliferous, containing a non-marine Invertebrate fauna consisting of conchostracans (*Cyzicus* sp.) and several species of smooth-shelled ostracodes in the genus *Darwinula*. Shiny, black, rhombic fish scales, coprolites, reptile bones and teeth, and plant fragments are also present (see list below). The Cumnock coals, unlike the coals of the Richmond basin, are consistently interbedded with shales containing a rich lacustrine fauna. The Cumnock coals themselves apparently contain a large proportion of conifer material rather than cycadeoid material common in the Richmond basin coals.

Walk to the left (northeast) along the railroad tracks for about 100 m and enter the brushy clearing on the right (southeast) side of the tracks. Outcrops of red to brown sandstone, siltstone, and mudstone of the Pekin Formation are present here (Figure 30c). These rocks are similar to those seen in the Boren pit (now Hanson Brick). According to a paced section presented by Bain and Harvey (1977), approximately 77 m of the Pekin are exposed here. These rocks are massive to poorly bedded with abundant bioturbation, and local cross-stratification and they are generally non-calcareous. Gray reduction spots are present locally, particularly around root marks and scattered plant remains. There are thin, olive gray silty to shaley interbeds locally, but thick gray horizons with plant fragments or coarse, organic carbon-rich sandstones are not exposed here. *Scoyenia* burrows with the typical external striations and internal backfilled structure are common but smaller here with most ranging from 3 to 7 mm in diameter. Carbonate nodules (caliche?) 1-2 cm in diameter are abundant in some layers. This is a pronounced difference from the Boren pit exposures.

Fossils from the Cumnock Formation

PLANTS

- Sphenophytes
 - Equisetales (horsetails)
 - Neocalamites* sp.

ANIMALS

- Arthropods
 - Crustacea
 - Diplostraca (clam shrimp and water fleas)
 - Cyzicus* sp.
 - ?*Paleolimnadia* sp.
 - Ostracoda
 - Darwinula* sp.
 - undetermined forms

- Insecta
 - Coleoptera (beetles)
 - undetermined fragments
- Pisces (fish)
 - Actinopterygii (bony fishes)
 - Palaeonisciformes
 - Synorichthys* sp
 - Cionichthys* sp.
 - Sarcopterygii (lobe finned fish)
 - Coelacanthini
 - cf. *Parwnegus (Diplurus)* sp.
- Reptilia
 - Archosauria
 - Phytosauridae (crocodile like archosaurs)
 - Rutiodon* sp.

Proceed downhill to the south in the direction of dip, roughly toward the highway, until reaching a small (nearly dry) stream. Follow the stream downhill to outcrops of bituminous coal and black shale. The coal and black shale belong to the Cumnock Formation and are part of the same unit exposed along the railroad tracks. The beds are in fault contact with the Pekin red beds, but the fault zone is covered here. The Cumnock Coal exposed here is known to lie about 60-80 meters above the base of the Cumnock Formation, but in this area it is only a few meters from the Pekin red beds.

Stop 4B – (Alternate) – Black Diamond Mine - Lee County, North Carolina

Location 35°32'9.69"N, -79°19'56.64"W; Goldston 7.5-minute quadrangle

Synopsis: Outcrop along Indian Creek of a coal bed that was mined from an incline in the hill behind.

Features to see: Thin coal (with blackband) and normal fault with drag. This is among the thickest exposures of Cumnock Formation.



Figure 33. Alternate Stop 4B, Cumnock Formation, Black Diamond Mine. Thin coals and coaly organic shale alternate (near notebook) and coalesce to a coal about 14 inches along with 'blackband' unit about two inches thick near rightmost hammer.



Figure 34. Alternate Stop 4B, Cumnock Formation, Black Diamond Mine. Normal fault (approximate location of large tree center of image) vertically offsets coaly strata (right) about 12-15 feet stratigraphically. There is a significant amount of drag folding on the hanging wall side that includes coaly organic shale.

Stop 5 – Sanford Formation, Lee County, North Carolina

Location: 35.50373°N -79.28715°W.

Synopsis: Outcrop showing series of diverse sedimentary features in the Sanford Formation.

Features to view: Sanford Formation (apparent seal), diverse sedimentary features

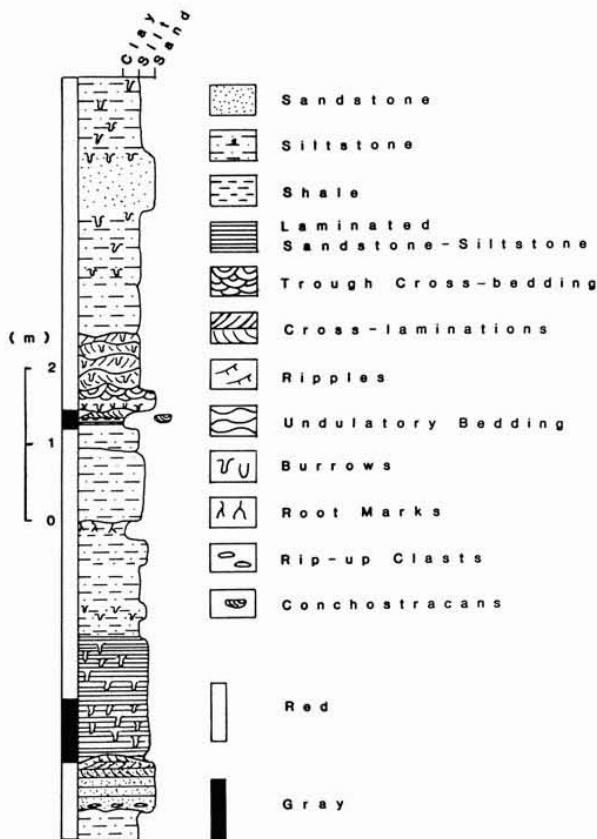


Figure 35. Adapted from Olsen, Schlische, and Gore, 1989, with permission. This road cut exposes 9.5 m of red to brown sandstone, siltstone, mudstone and shale of the lower Sanford Formation, the upper of three formations in the Sanford sub-basin (Gore, 1986a). Bedding in this outcrop (Figure 36) tends to be more tabular than in obvious fluvial deposits in the Pekin and Sanford formations, but most of the beds change thickness laterally. The more resistant ledge forming units are red to brown, non-calcareous, cross-stratified sandstone and massive siltstone (Figure 33). The less resistant beds are massive to poorly-laminated mudstone and shale. Two fining-upward sequences are present, consisting of an abrupt contact (scour surface) overlain by cross-stratified sandstone, grading up into bioturbated siltstone and mudstone (Gore, 1986a).

A convex-upward sandstone lens with rip-up clasts and climbing-ripple cross lamination in the upper part occurs along the left (western) end of the road cut. The morphology, texture, and sedimentary structures of this unit suggest that it may be a crevasse-splay deposit. Approximately 5.5 m above the base of the section is a thin (21 cm) gray bed. The gray bed occurs at the top of a 1.4 m-thick fining-upward sequence (Gore, 1985).

The gray bed may be subdivided into three parts: (1) a lower unit, 5 cm thick, of light gray, massive to poorly-laminated, non-calcareous, plant-fragment-bearing siltstone, fining upward into (2) a middle unit, 8 cm thick, of

light gray, fissile, non-calcareous clay shale containing closely-packed conchostracans on some bedding planes overlain by (3) an upper unit, 8 cm thick, of laminated, wavy-laminated, and cross-laminated, non-calcareous siltstone with asymmetrical ripple marks (Gore, 1986a). The mineralogy of the gray bed consists of quartz, illite, chlorite, plagioclase, siderite, and possibly ankerite (x- ray diffraction data from Andy Thomas, Texaco). The uppermost beds of the outcrop consist of tabular fine sandstone and inter-bedded mudstone beds with unidirectional cross beds at the base and abundant possible oscillatory ripples higher up. *Scoyenia* and roots are very abundant and have obscured the ripple cross lamination characteristics of the tabular thin-bedded sandstones.

There is debate about the depositional environments represented by this outcrop with two opposing hypotheses: 1) all of the deposits are related to a fluvial environment with the inter-bedded lacustrine strata being the deposits of shallow ponds and small lakes on a low relief flood plain; 2) the sequence represents alternating basin-wide shallow lake deposits and fluvial low-stand deposits.

Gore (1985, 1986a- c) argues that the presence of cross stratification and fining-up ward sequences indicates primarily fluvial deposition for the sand-stones. The thinness of the lacustrine bed and its position at the top of an apparent fluvial fining-upward sequence suggests that it was deposited in a shallow floodplain lake (Gore, 1985) partially filled by crevasse splays. The presence of oscillatory sand-stones associated with the conchostracan-bearing siltstones is not in conflict with this interpretation. Olsen argues that the conchostracan-bearing silt-stone represents substantial lake conditions, and that the associated tabular sand-stones are wave-formed beds and associated distributary channels and bars. The associated fluvial beds were deposited during low-stands of the lake and dissection of the lake margin deposits by streams.

According to Olsen, alternations between fluvial and lacustrine deposition would thus be controlled by basinwide changes in lake level, not lateral migration of channels and floodplains. The sequence appears intermediate in facies between the marginal facies of the Cumnock Formation as exposed near Carthage (Olsen, 1986) and the fully fluvial upper Sanford Formation. **Note:** Olsen and Gore continued this discussion on their field trip noting that resolution of the arguments rests on determining the regional distribution of beds which is difficult due to poor exposure.



Figure 36. This figure shows the distribution of the geologic units at Stop 5 – Sanford Fm., located on NC 42.

Stop 5A (Alternate) – Simpson #1 well, Lee County, North Carolina

Location: 35.5039691°N, -79.263184°W

Synopsis: The second of two shut-in natural gas wells in North Carolina.

Features to view: Well head and revegetated well pad.



Figure 37. The gas in the Simpson #1 well was sampled in March 2009. The wellhead consists of a small 'Christmas tree'. The well pad has naturally revegetated with pines and other vegetation. The well is located very near an unnamed splay of the Deep River Fault that could provide a conduit for surface water to enter the rocks. During well development a small pump jack was reported to have been used to handle water from the well. The Butler #1 well drilled to a depth of 4,540 feet and nearly one mile north encountered an entirely dry borehole as evidence from a borehole video.



Figure 38. Simpson #1 well being flared in the spring, 1998. In March 2009 the measured pressure was 250 psi. The well had an initial flow rate of 3,000 mcf/d. Subsequently the flow rate settled at 231 mcf/d. See well construction diagram and molecular, BTU and stable isotopic gas analysis (Table 4). The water produced may have been a combination of returning frac water, and surface water. If surface water is involved there is the potential of biogenic gas (see stable isotopic data for carbon and oxygen – see Figure 19 discussion).

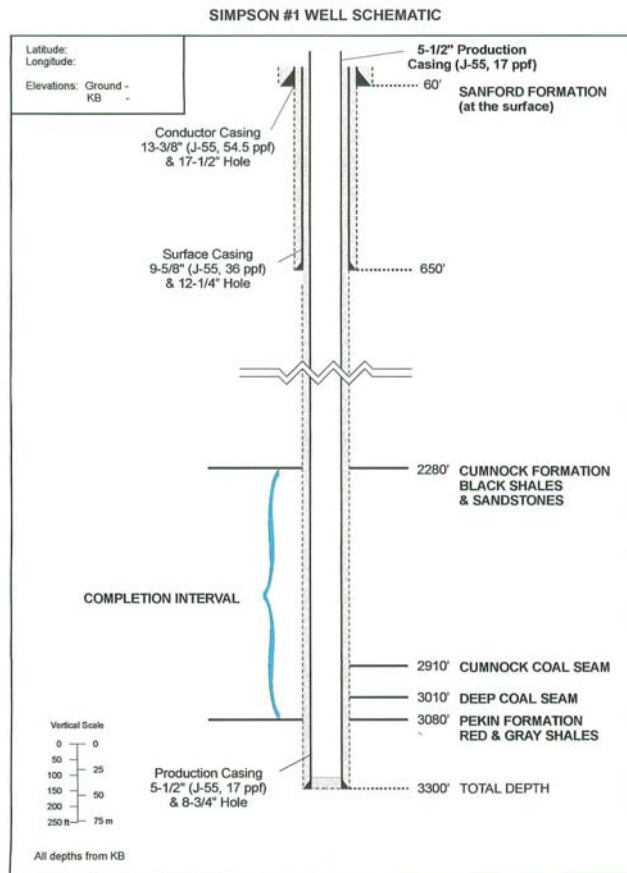


Figure 39. The Simpson #1 well was drilled vertically in 1988 reaching a total depth of 2,250 feet. The well penetrated the Cumnock Formation and was subsequently logged geophysically. In March 2009 the well pressure was measured at 250 psi and the well’s gas was sampled for molecular chemistry, BTU content and stable isotope composition by Jeffrey C. Reid (NCGS) and Robert C. Burruss (USGS). See Table 4 for the well’s gas composition. No flow test has been done on this well so far as is known. Since the pressure testing was completed, the well has been shut in until we measured its pressure and sampled the gas in March 2009. It is unknown the extent of tubular products that may still be in this well. The nitrogen in the well is believed to come from the denitrification of the thin stratigraphic “blackband” rock in this well and/or illite in the Cumnock Formation above the ‘blackband’ – see discussion at Stop 3 – the Butler #3 well (above) .

Holmes (1998) in a petrophysical log study of this well suggested it had the following parameters on a 160-acre drainage spacing:

	Interval 2,250 ft.	Interval 2,500-3,000 ft.	Interval 3,000 - 3,302	Total
Thickness, ft.	50	71.8	29	150.8
Porosity, %	3.2	3.4	2.4	3.2
Water saturation, %	46.3	43.4	45.5	44.7
In-place, gas, MMCF	400	650	185	1,225

Table 4. Simpson #1 gas chemistry and BTU values and well perforations.

Component	Chemical mol. %	Delta 13C per mil	Delta D per mil	Delta 15N per mil
Carbon Monoxide	nd			
Hydrogen Sulfide	nd			
Helium	0.223			
Hydrogen	0.0047			
Argon	0.0074			
Oxygen	0.0177			
Nitrogen	45.49			-3.32
Carbon Dioxide	nd			
Methane	51.65	-51.41	-174.8	
Ethane	1.89	-34.60	-151.4	
Ethylene	nd			
Propane	0.501	-29.66	-120.6	
Iso-butane	0.0847	-27.90		
N-butane	0.0814	-28.85		
Iso-pentane	0.0216			
N-pentane	0.0142			
Hexanes +	0.0130			
Total BTU/cu. Ft. dry @ 60deg F & 14.7psia, calculated 577				
Specific gravity, calculated 0.759				

Well perforations (depth in feet)

- 2,049
- 2,052
- 2,159
- 2,297
- 2,383
- 2,672
- 2,672
- 2,772
- 2,777
- 2,783
- 2,788
- 2,792
- 2,797
- 2,804
- 2,963

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TABLES

Table 1 – This table summarizes the acres of each of the proposed resource geologic units (GU's) for coal bed methane and shale gas, and provides total acres for the GU's.

	GU's	GU acres	Total acres
Coal bed methane (CBM)	3		
• Sweet spot		~10,345	
• B-1		~3,196	
• B-2		~15,193	~28,734
Shale gas	2		
• Area 5		~58,933	
• Area 3		~17,211	~76,144
Total geologic units	5		

Table 2. Cumnock bituminous coal composition (from Reinemund, 1955).

	<i>Main bench</i>	<i>Lower benches</i>	<i>Gulf coal</i>
Fixed carbon	52.6 to 59.6 percent	38.3 to 59.0 percent	38.6 to 58.1 percent
Ash content	5.8 to 15.9 percent	13.1 to 35.7 percent	8.4 to 38.0 percent
Sulfur	1.1 to 4.3 percent	1.7 to 4.1 percent	1.4 to 4.1 percent
Heating value	12,190 to 14,030 BTU	8,890 to 13,700 BTU	9,510 to 13,200 BTU



Figure 1. Map showing the distribution of Mesozoic basins in the eastern United States (from Robinson and Froelich, 1985). Lee and Chatham counties are located inside the red box.

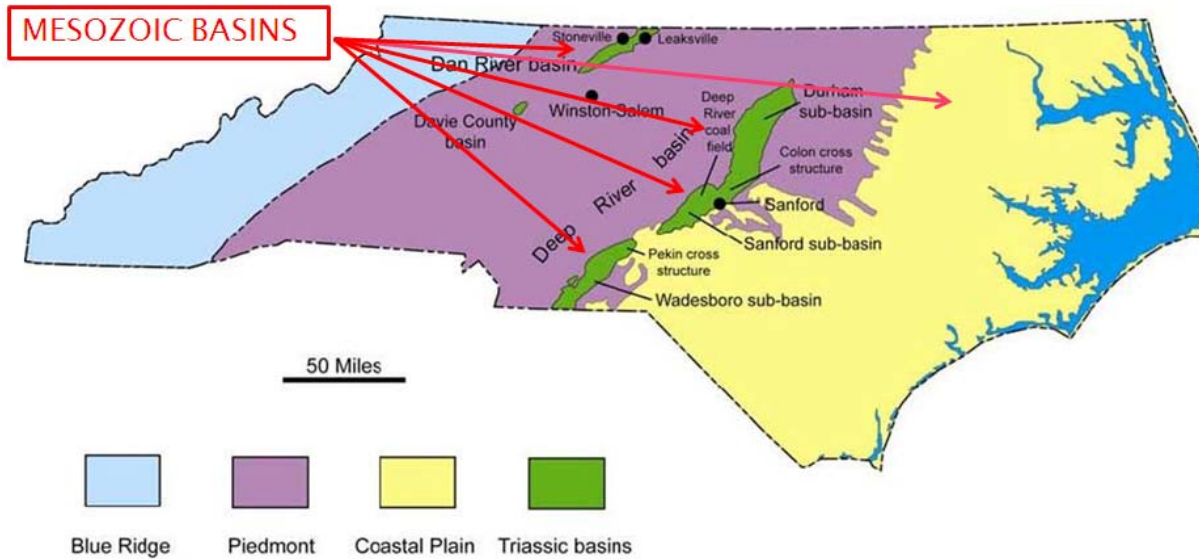


Figure 2. Map showing the distribution of Mesozoic basins in North Carolina (from Reid and Milici, 2008). The long arrow points to the approximate location in Bertie County, NC, where the USGS Hope Plantation Core (BE-110) encountered Upper Triassic strata at a drilled depth from 1,026.0 – 1,094.5 feet (see URL <http://pubs.usgs.gov/of/2007/1251/> - Weems and others, 2007).

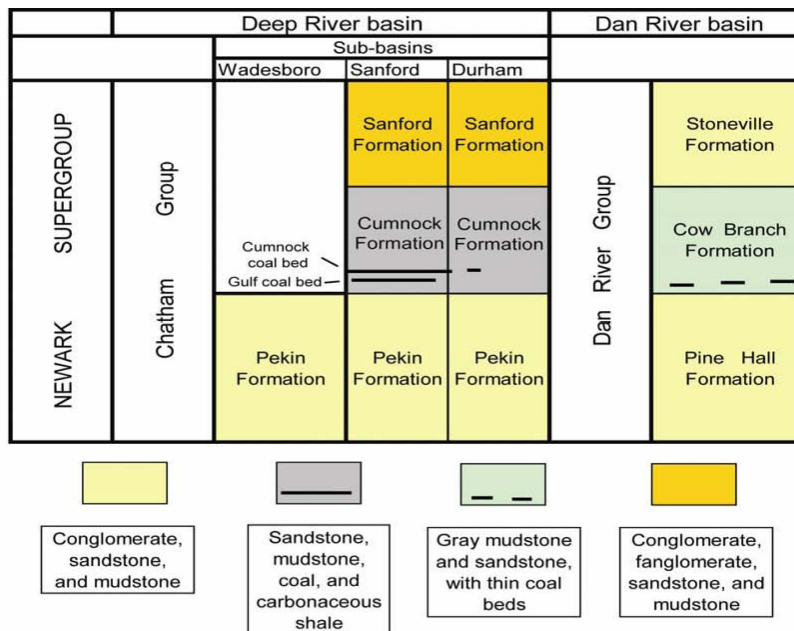


Figure 3. Generalized stratigraphy of the Deep River and Dan River basins showing the stratigraphic position of the Triassic Cumnock Formation in the Deep River basin and the stratigraphically equivalent Cow Branch Formation in the Dan River basin (from Reid and Milici, 2008). Recent field work by North Carolina Geological Survey staff confirms the presence of Cumnock-like strata in portions of the Wadesboro sub-basin, Deep River Basin. A comparison of rift basins in North Carolina is provided as Figure 5.

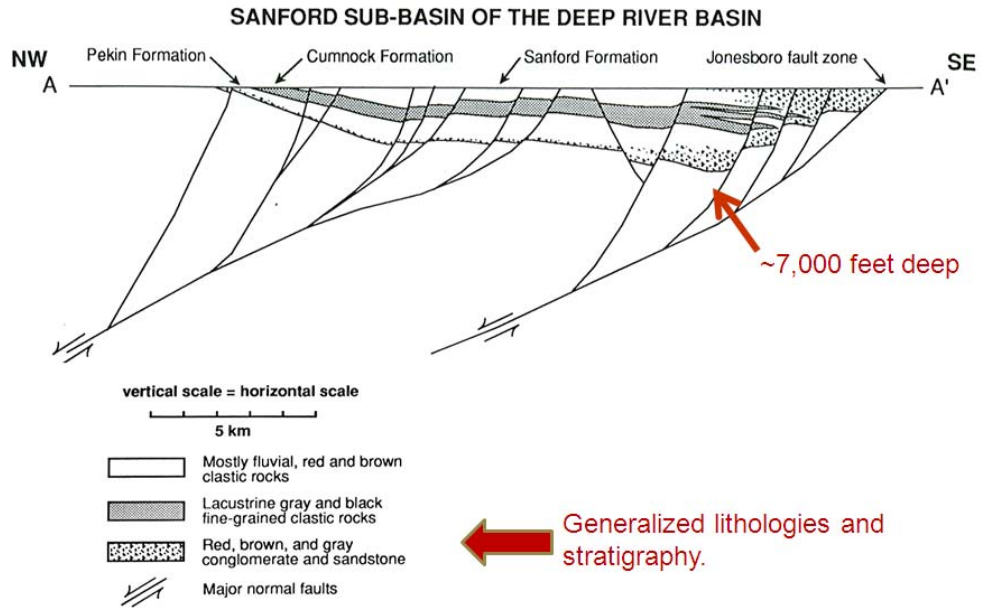


Figure 4. Stratigraphic cross sections through the Sanford sub-basin of the Deep River Basin and Dan River Basin (adapted from Olson *et al.*, 1991). This view roughly corresponds to Seismic Line 113 and shows the half-graben nature of the Sanford sub-basin and generalized stratigraphy, and faulting. Alluvial fans prograded at times from the southeast from the Jonesboro fault zone toward the sub-basin's center.

Figure 5. Exploration overview - North Carolina on-shore Triassic lacustrine rift basins
As of March 15, 2011

Basin name => sub-basin name => Size (surface acres)	Deep River			Dan River	Davie	Ellerbe	Bertie County Buried coastal plain basin
	Sanford sub-basin prospective)	Durham sub-basin	Wadesboro sub-basin				
Coal present	146,530 (~59,000 prospective)	405,236	205,809+	64,817	~3,932	6,283	Unknown
TOC (core or cuttings)	Yes (thin) 33.62 - 0.01 (range); avg. 1.94 (n=344)	Unknown n/a	Unknown n/a	Yes (thin) 8.31 - 0.81 (range); avg. 3.42 (n=8); NCGS study in progress	No n/a	No n/a	Unknown Unknown
%Ro (core and cuttings)	0.8 - 1.0	n/a	n/a	1.23 - 3.02; avg. 2.07	n/a	n/a	Unknown
%Ro (surface samples)	n/a	n/a	n/a	NCGS study in progress	n/a	n/a	Unknown
Source rock thickness (feet)	up to 800	Unknown	Unknown	300 - ~3,000	0	0	Unknown
Targets	Shale gas and CBM	Shale gas, possible CBM	Shale gas, possible CBM	Shale gas	None	None	Unknown
Shut-in wells	2	0	0	0	0	0	0
Geophysical logs available	Yes	Yes	No	Yes	None	None	Yes
Depth to basement (feet)	~7,100	~5,500-6,200	Unknown but likely similar to Sanford and Durham sub-basins	At least 4,700 feet by drilling; probably deeper	Probably very shallow	200 feet maximum depth	Unknown
Shows (gas, oil, asphalt)	Numerous	None reported	None reported	Some, poorly known	None known	None known	Unknown
Well pressures (psi)	900,250	n/a	n/a	n/a	n/a	n/a	n/a
Leasing (acres)	8,765	None	None	None	None	None	None
Erosion estimates	~3,000	Probably similar to Sanford sub-basin	Probably similar to Sanford sub-basin	Not determined	Unknown	Unknown	Basin buried; past thermal history unknown
Tight gas	Maybe	Unknown	Unknown	Unknown	Not likely	Not likely	Unknown
Previous drilling (gas and oil)	Yes	No - water well	No	Yes	No	No	No
Previous drilling (coal)	Yes	No	No	Yes?	No	No	No
Seismic available	Yes	Yes	No	No	No	No	No
Core available	Yes	No	No	Yes	n/a	No	Yes
Cuttings available	Yes	Yes	No	No	n/a	No	No
Paleo lake water depth	Shallow - subject to currents action	Probably shallow - subject to current action, one shallow water well	Likely shallow - subject to current action	Shallow - subject to current action, and deep - below current action	No lake facies present	No lake facies present	Unknown - lake facies yet to be identified. Basin known by only one shallow water well.
Counties	Lee, Chatham, Moore	Durham, Chatham, Orange, Wake, Granville	Union, Anson, Richmond, Montgomery	Stokes, Rockingham (continues into VA)	Davie, Yadkin	Richmond	Bertie, and perhaps others?
Comments		NC Geological Survey studies in progress	NC Geological Survey studies in progress	NC Geological Survey studies in progress	Likely once part of the Dan River Basin	Likely once part of the Wadesboro sub-basin	Known from 1 shallow water well
Key citations	Reid, 20xx; Reid and Mlici, 2008; Reid and Taylor, 2008- 2010 -- multiple reports -- refer to citations in this guidebook			Thayer and Robbins, 1992; Whiteside, 2006; Stone, 1910; Kirstein in Thayer and others, 1970; Robbins, 1982	Thayer, 1970	Dineen, 1982	Weems and others, 2007

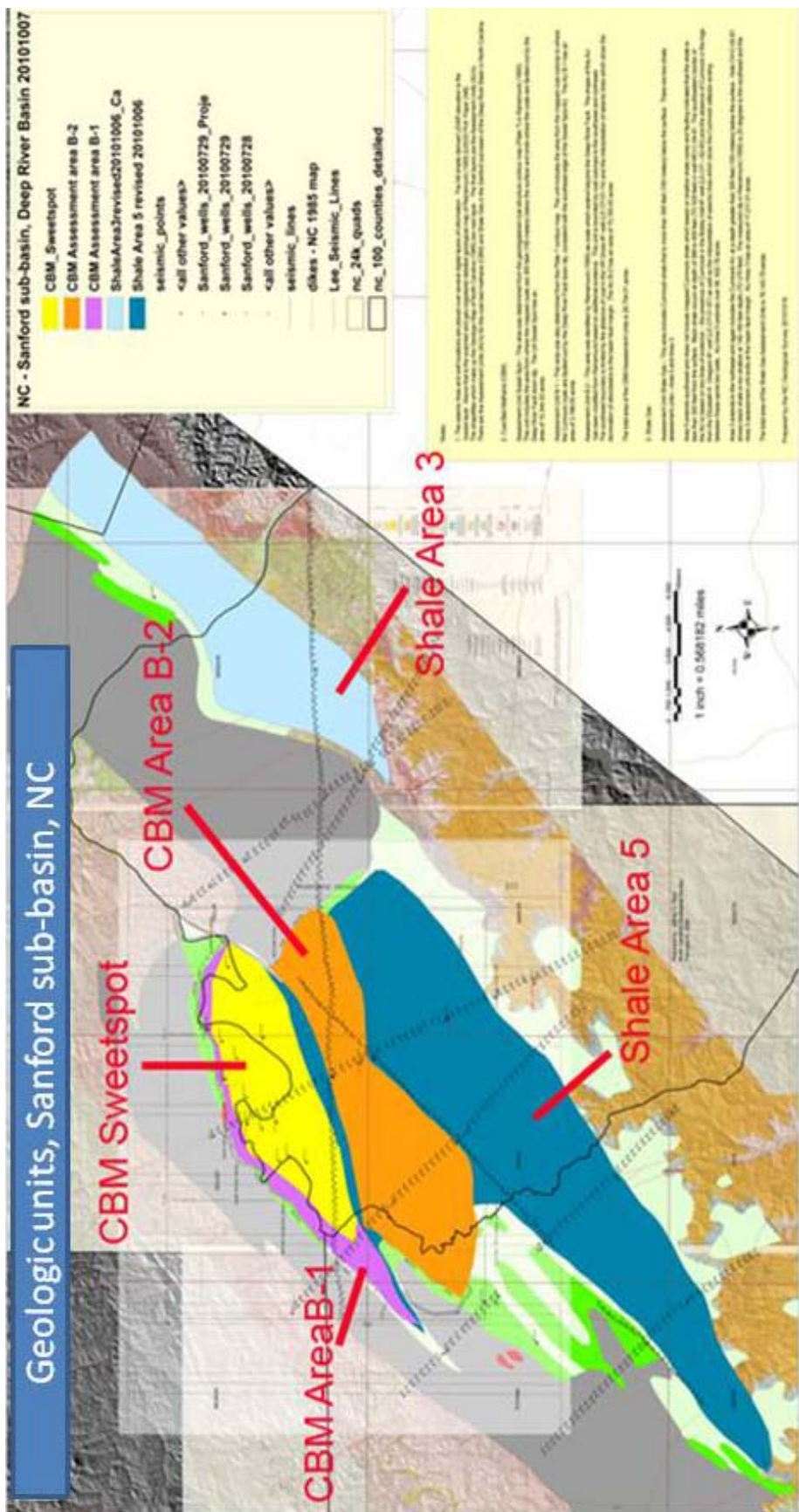


Figure 6. The distribution of the preliminary Geologic Units (AU's) is shown here. The Lee County boundary is shown as a black line.

NW

SE

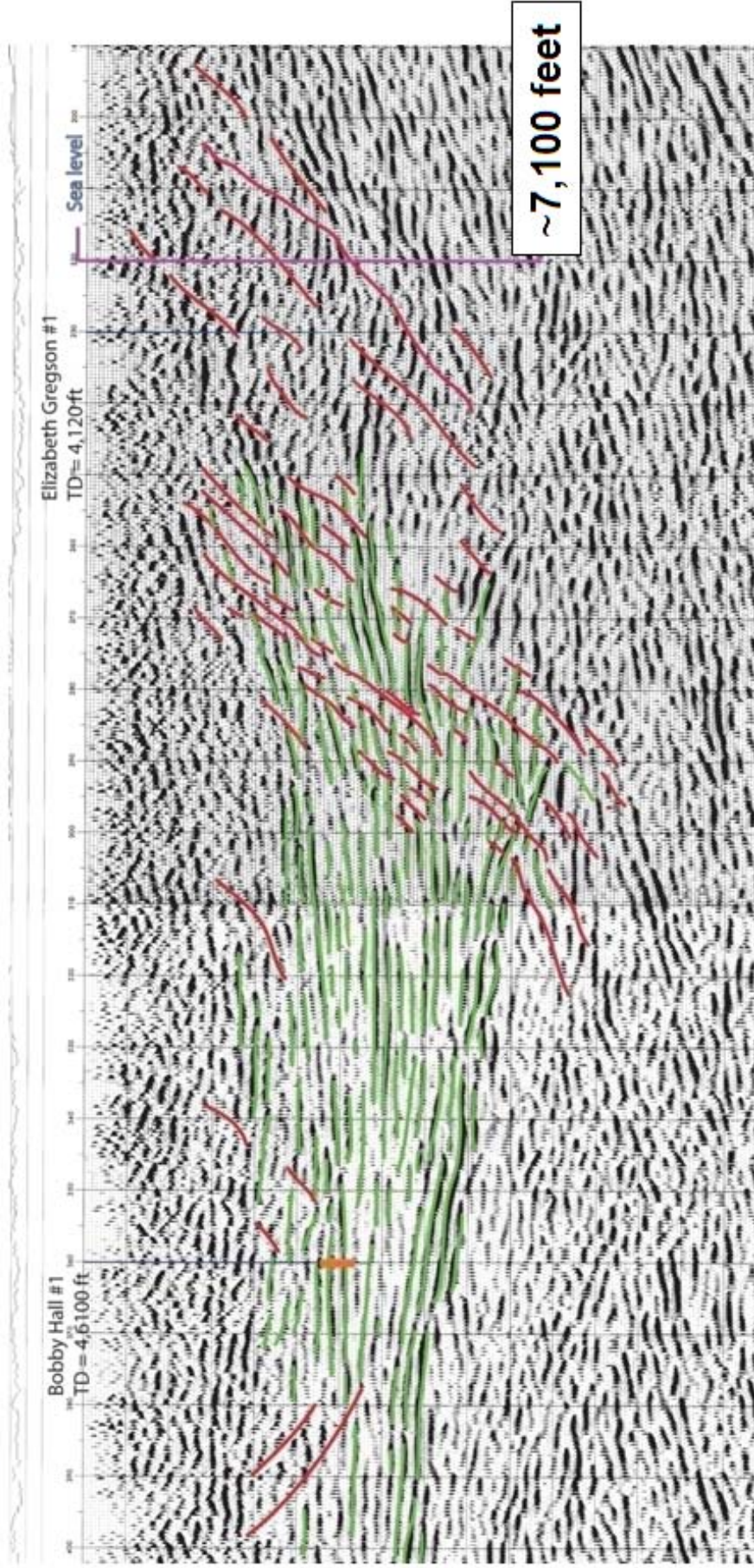


Figure 7. Seismic line 113 - Dip section across part of the Sanford sub-basin from the northwest to the southeast. An alluvial fan complex (green form lines) prograded northwest from the southeastern highlands and the Jonesboro fault system (red form lines at right side of image) that bounds the rift. The Bobby Hall #1 well was drilled by Sepco in 1983 to a total depth of 4,622 feet according to the mud log. It encountered the Cumnock Formation from a depth of ~3,940 feet to 4,306 feet.

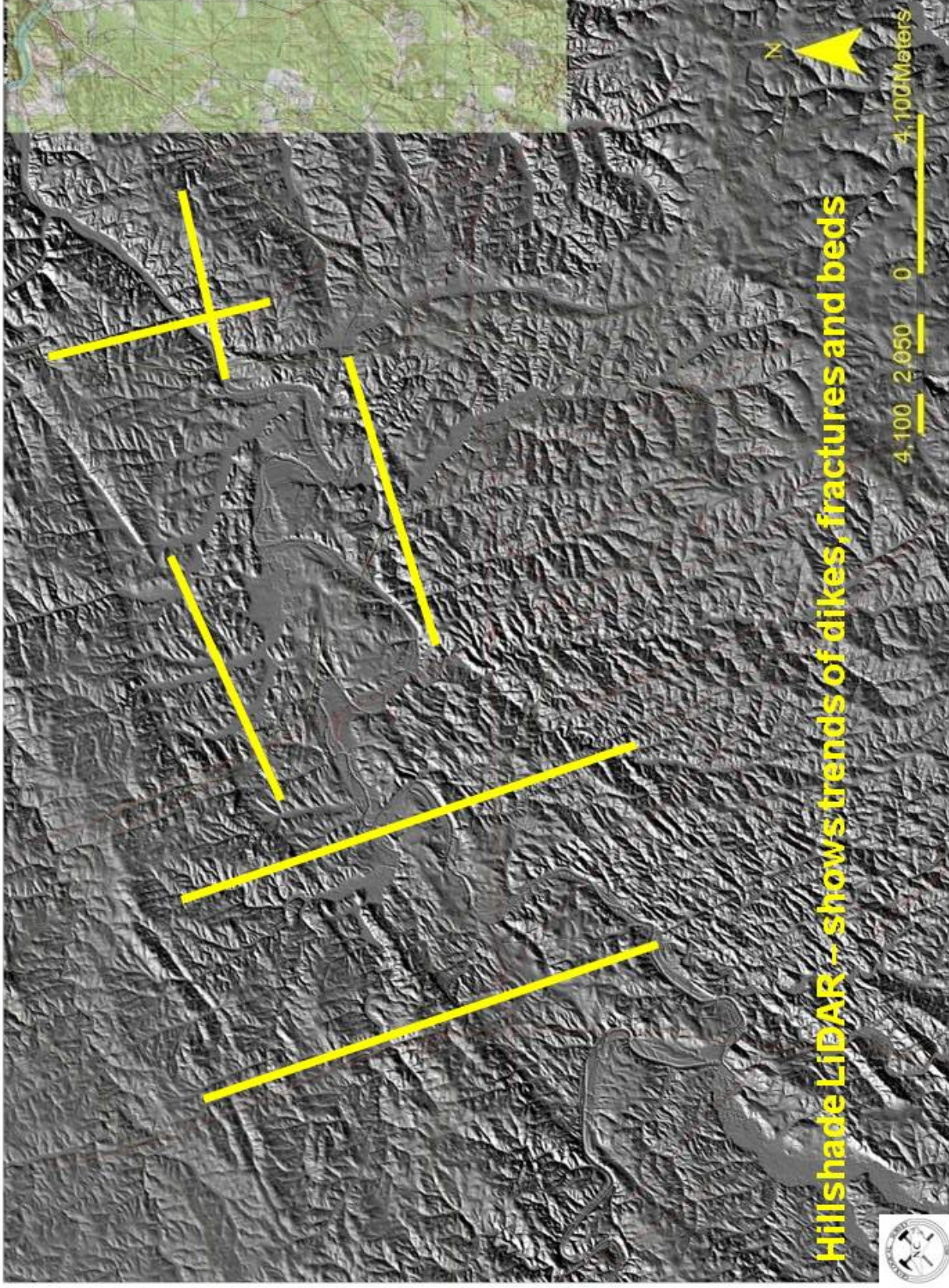


Figure 8. Hillshade LiDAR shows trends of diabase dikes, fractures and trend of sedimentary strata. The Deep River forms a sinuous border between Lee and Chatham counties, NC. The Sanford sub-basin occupies low relief terrane in the center of the image. Diabase dikes trend along northwest-striking fractures. The orthogonal fracture pattern observed in this image can be found at the outcrop scale and will be of interest to natural gas exploration and production.

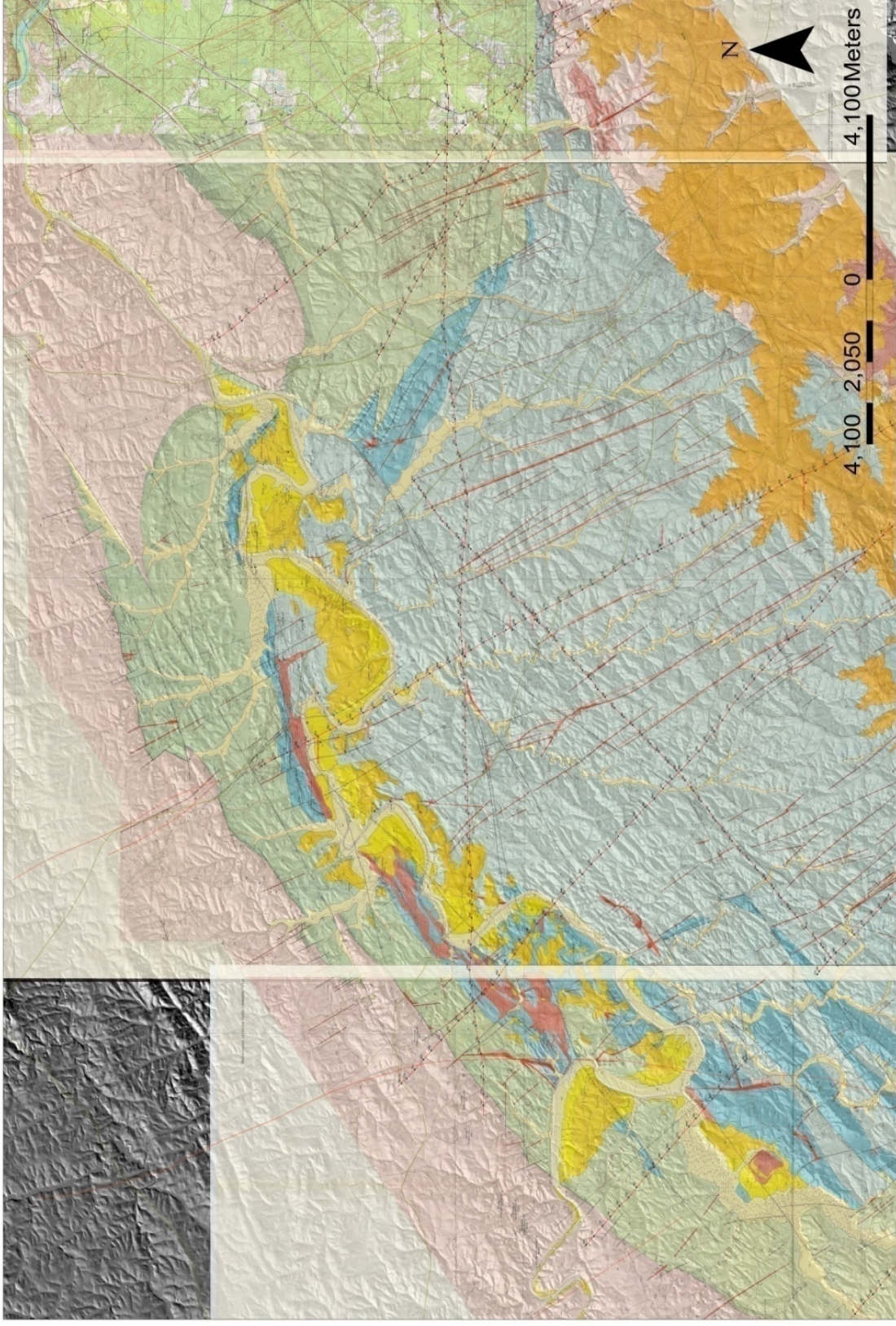


Figure 9. Geology of the Sanford sub-basin, Deep River basin draped on a LiDAR base with seismic lines. The area covers the field trip route. The three sub-basins of the Deep River Basin are filled with ~7,000 feet of Triassic strata, which are divided into the following three formations in descending stratigraphic order (see Figures 3 and 4). The colors are: (1) metamorphic basement rock (pink), (2) Sanford Formation (red and gray siltstone and shale) (light blue); (2) Cumnock Formation (black shale, with some beds of gray shale, sandstone and coal) (darker blue); and (3) Pekin Formation (gray sandstone and shale) (light green). Diabase dikes of Jurassic age are colored red. Higher level, unconsolidated Tertiary sands are orange. Geologic maps adapted from Reinemund (1955) and draped on a LiDAR base. The Cumnock Formation includes a ~800-foot-thick interval of Upper Triassic (Carnian) organic-rich black shale. Younger sediments are light orange and yellow.



Figure 10a,b. Simpson #1 well being flared.

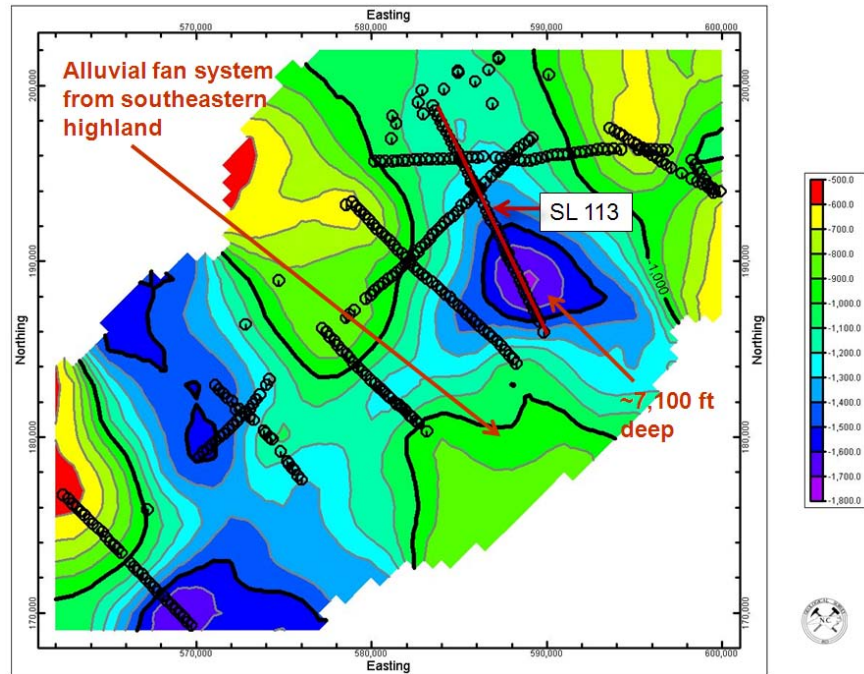


Figure 11. Preliminary depth to basement map, Sanford sub-basin. Seismic Line 113 (SL113) is a dip line through the Sanford sub-basin. Basin depth is in meters.

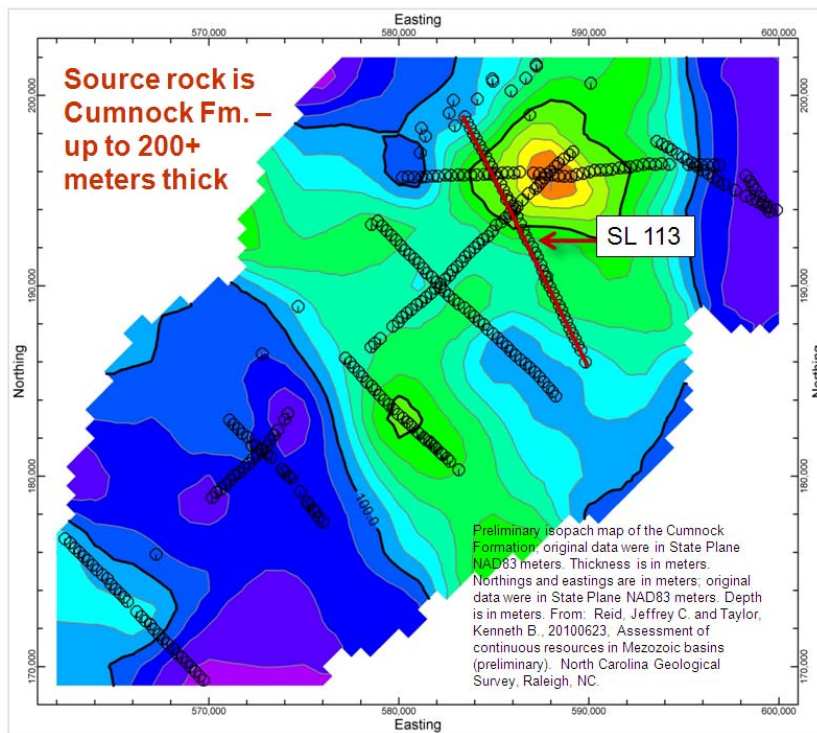


Figure 12. Preliminary isopach map of the Cumnock Formation, Sanford sub-basin. Seismic Line 113 (SL113) is a dip line through the Sanford sub-basin. Basin depth is in meters.

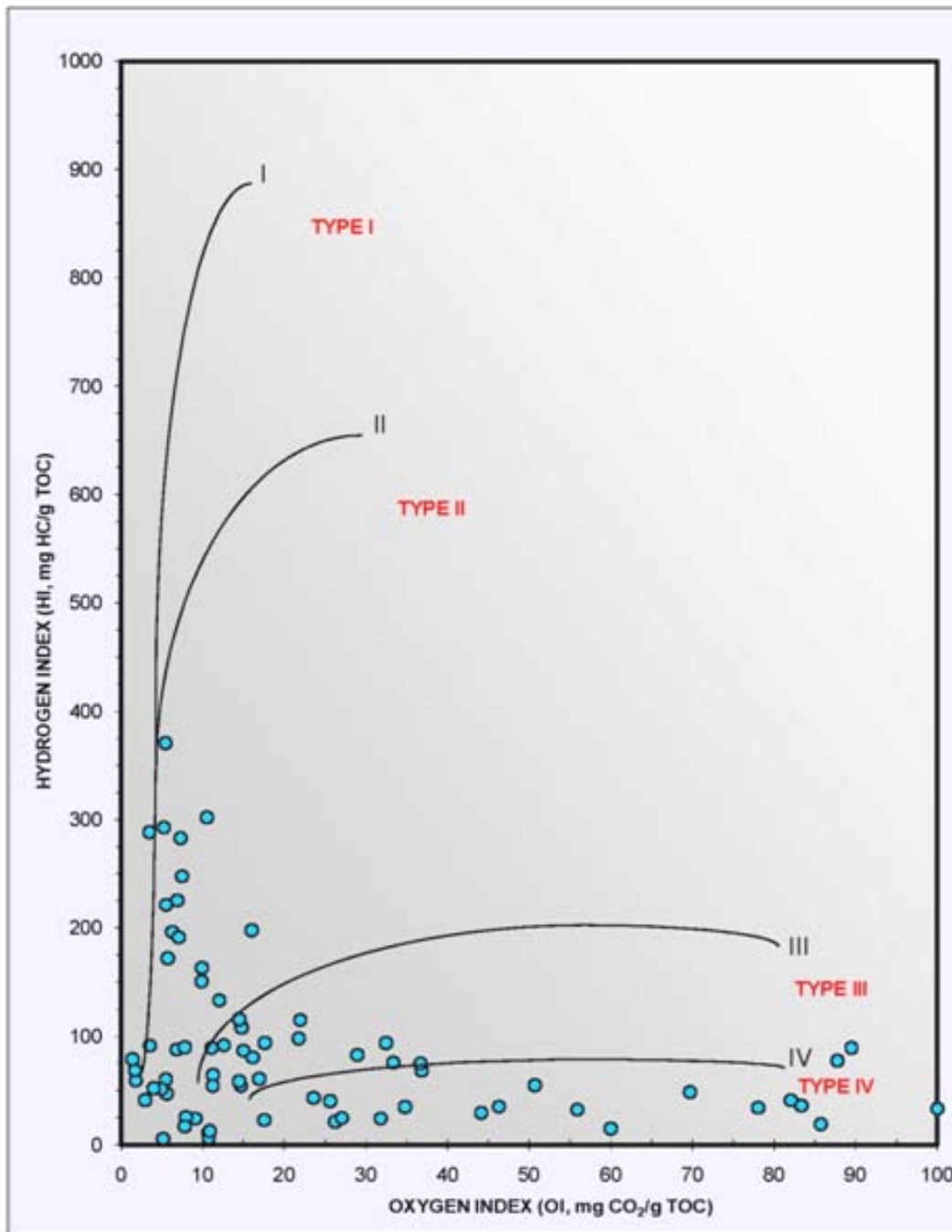
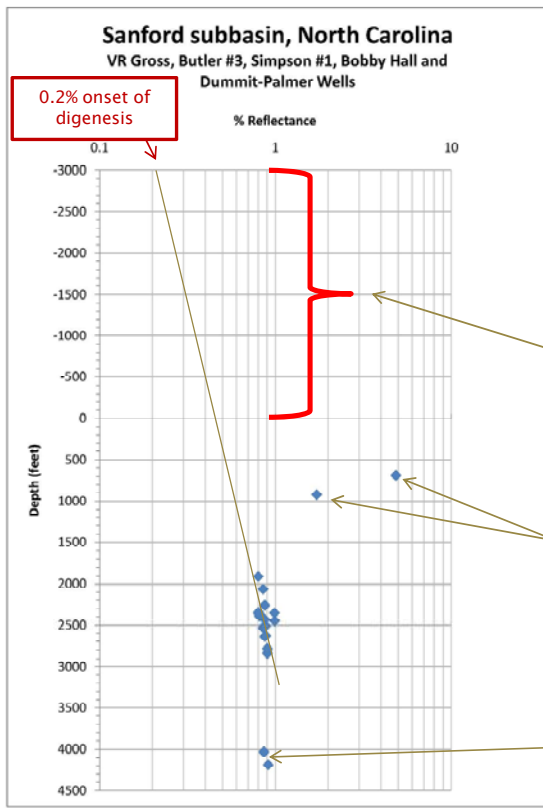


Figure 14. Hydrogen and oxygen indices from Rock-Eval pyrolysis in relation to kerogen type. The organic material in the Cumnock Formation contains Type II and Type III organic matter. Type I organic matter is likely present also.



**%Ro – All data,
 Sanford sub-basin**

Estimated maximum erosion is ~3,000 ft

Observed variations are:

- V.R. Groce #1: -1,800 ft
- Butler #3: -1,000 ft
- Simpson #1: -3,000 ft (maximum observed)

Dummitt-Palmer #1 (CBM) – “near dikes”
 and “overcooked” (updip, basin edge)

Bobby Hall #1

After Dow, 1977 (method)



Figure 16. Erosion depth estimates from multiple wells, Sanford sub-basin, Deep River Basin, North Carolina. Estimated maximum erosion is shown based on the %Ro data using the method of Dow, 1977 for determining the amount of eroded strata of the linear plots of the \log_{10} of vitrinite vs. depth. The regression line through borehole data is extrapolated back of 0.2% Ro, the reflectance of early diagenetic woody plant matter to find the amount of missing section. It is assumed that there was no change in thermal conductivity or geothermal gradient in the eroded section. Offsets in the data points from the regression line reflect local block faulting (e.g., Bobby Hall #1 well). The two Dummitt-Palmer #1 (CBM) points that lie off the regression line are samples that were ‘overcooked’ by diabase dikes resulting in anomalous %Ro values.

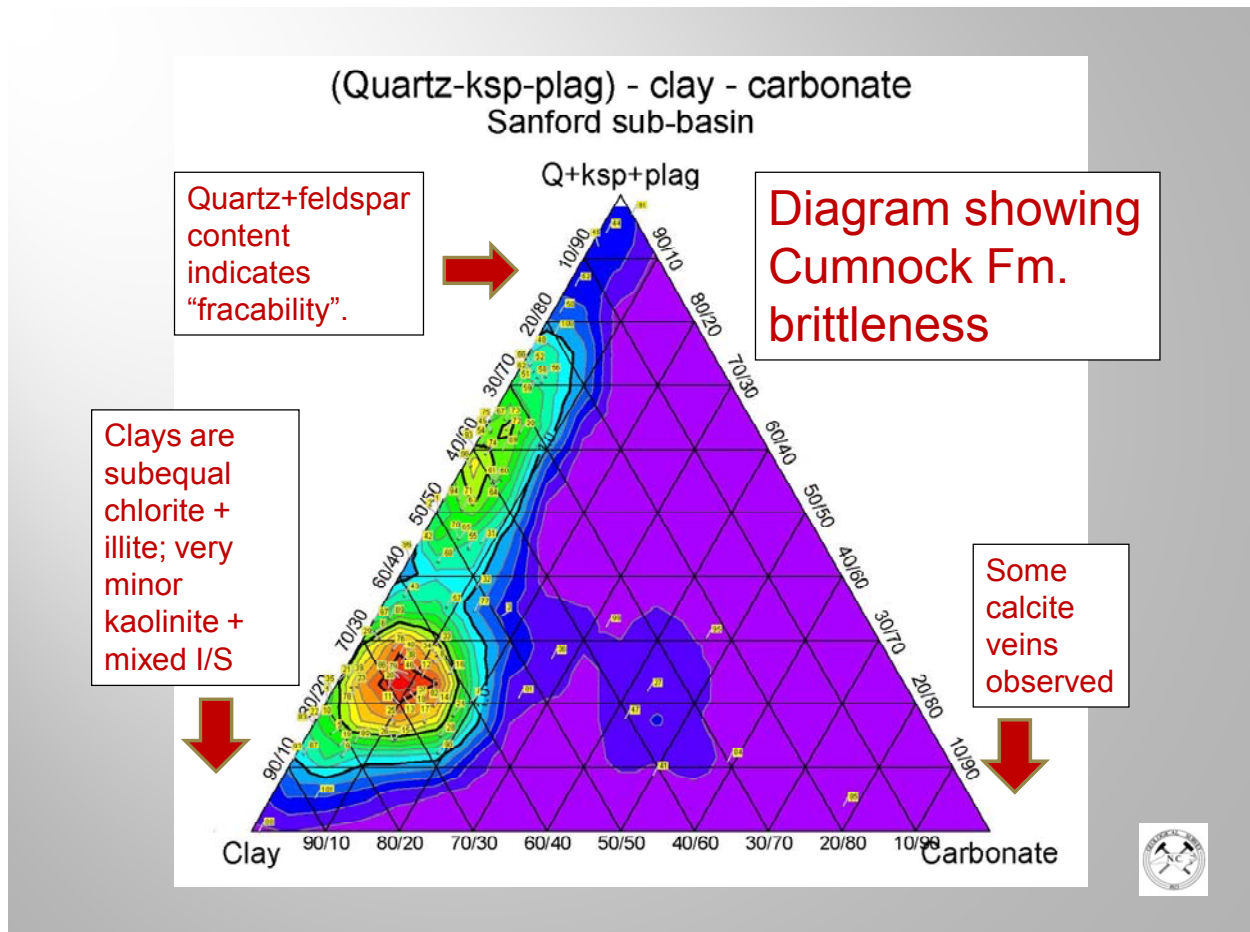


Figure 17. Diagram showing ‘brittleness’ of the Cumnock Fm. to help access ‘fracability’. Minerals known at this time by XRD are: clays (chlorite, kaolinite, illite and mixed layer illite/smectite), carbonates (calcite, iron-bearing dolomite, siderite), major minerals (quartz, k-spar, plagioclase) and trace minerals (pyrite, gypsum, anhydrite, carphosiderite, analcime, apatite and hematite).

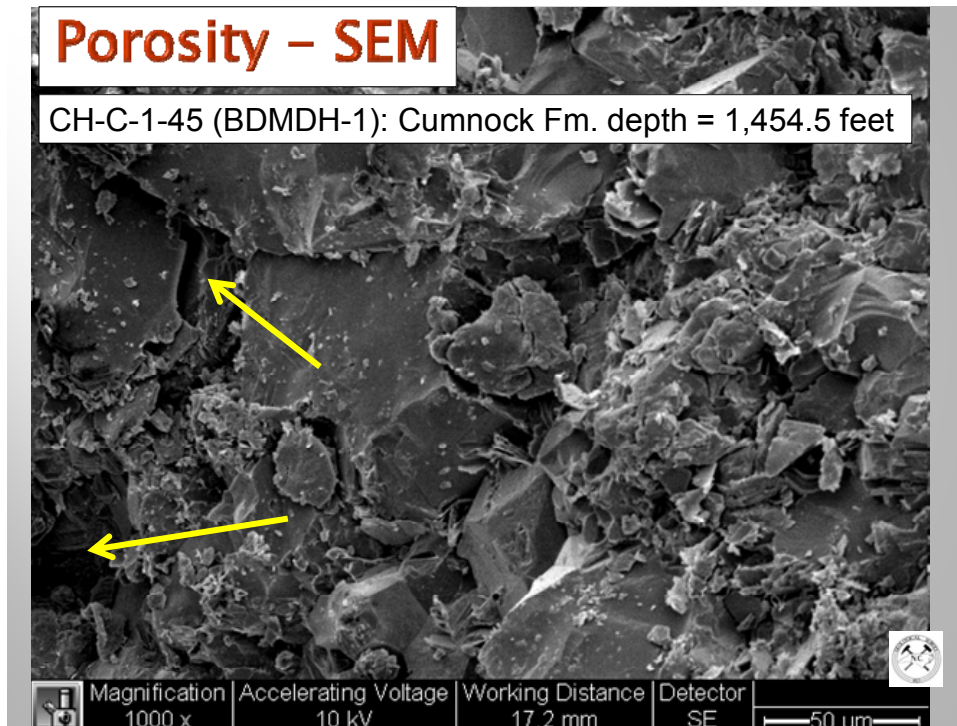


Figure 18. SEM image of the Cumnock Fm., magnification 1,000x. The yellow arrows point to porosity.

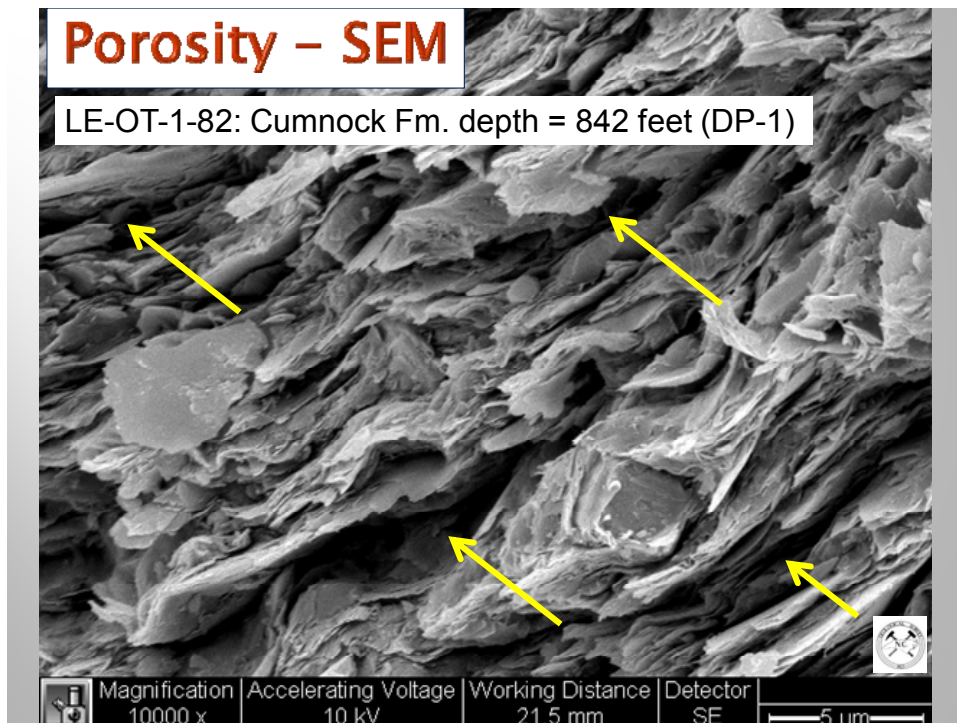


Figure 19. SEM image of the Cumnock Fm., magnification 10,000x. The yellow arrows point to porosity.

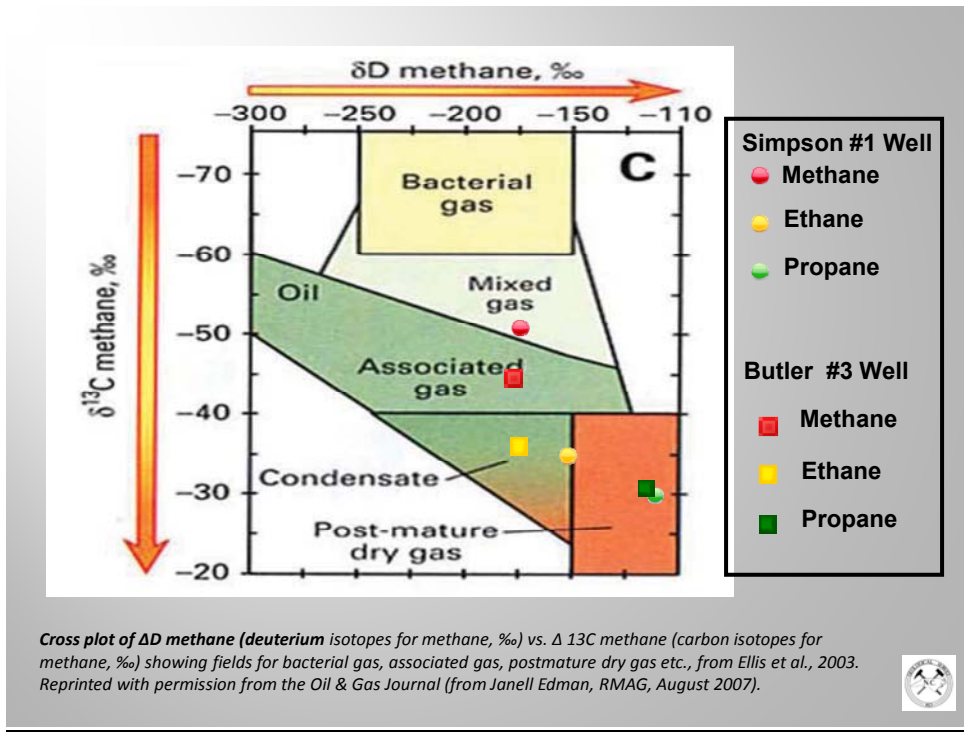


Figure 20. Cross plot of ΔD methane (deuterium isotopes for methane, ‰) vs. $\Delta^{13}C$ methane (carbon isotopes for methane, ‰) showing fields for bacterial gas, associated gas, postmature dry gas etc., from Ellis et al., 2003. Reprinted with permission from the Oil & Gas Journal (from Janell Edman, RMAG, August 2007).