Origin, Distribution and Reservoir Characteristics of Hydrothermal Dolomite in Lower Paleozoic Carbonates in New York State

Final Report

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John P. Martin
Senior Project Manager

Prepared by

New York Geological Survey

Langhorne Smith
Richard Nyahay
Brian Slater

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Abstract

In the past decade, twenty new natural gas fields have been discovered in laterally discontinuous dolomites of the Upper Ordovician Black River Group in south-central New York. The dolomites form around basement-rooted wrench faults that are detectable on seismic data. Most fields occur in and around elongate fault-bounded structural lows interpreted to be negative flower structures. Away from these faults, the formation is composed of impermeable limestone. In most cases the faults die out within the overlying Trenton Limestone and Utica Shale. Most porosity occurs in saddle dolomite coated vugs, breccias, and fractured zones. Matrix porosity is rare in the Black River cores described for this study.

The patchy distribution around basement around basement-rooted faults and geochemical and fluid inclusion analyses support a hypogene, fault related hydrothermal origin for the saddle and matrix dolomites. The breccias are interpreted to have formed in space created by transtensional faulting with a component of dissolution by hydrothermal fluids flowing up the faults. Using the appropriate integrated structural-stratigraphic-diagenetic model, more hydrothermal dolomite natural gas reservoirs are likely to be discovered in the Trenton and Black River Groups of eastern North American and in carbonates around the world.

Key words: hydrothermal dolomite, Trenton-Black River, natural gas

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Executive Summary

The Black River hydrothermal dolomite natural gas play has brought national and even international attention to New York State over the past six or seven years. Personnel at the New York State Museum have spent much of that time conducting research into the processes, products and reservoirs of hydrothermal alteration not only in the Black River, but in the underlying Cambro-Ordovician Beekmantown Group as well. This report summarizes much of that work.

This report focuses on our work on the Black River hydrothermal dolomite play and primarily consists of a paper published in AAPG Bulletin. The Black River play occurs in fractured, vuggy dolomite that forms around faults that have components of both strike-slip and extension (transtensional). The dolomite formed when high-pressure, high-temperature fluids flowed up faults while they were active, hit sealing strata in the basal part of the Trenton and flowed laterally into the underlying Black River. Geochemistry shows that the fluids were 110-170°C, had salinities around 15wt%, were depleted with respect to $\delta^{18}O$, were enriched in iron and manganese, and had radiogenic $^{87}Sr/^{86}Sr$ values relative to Late Ordovician seawater. All of these support a hydrothermal origin for the dolomite. This alteration is interpreted to have occurred during Trenton and Utica time, when the Black River was buried to a depth of <350 meters. The report discusses possible sources of heterogeneity in the reservoirs.

The appendix of the report consists of field studies for each of the Black River hydrothermal dolomite fields in New York that through 2005. For each field there is a log cross section that shows the distribution of dolomite and in many cases we have displayed interpreted horizontal well logs. These cross sections will help to understand how the dolomitization of the Black River varies from field to field.

In Phase II of this study, an outcrop analog for the Black River hydrothermal dolomite reservoirs found in a quarry in the Mohawk Valley is described and interpreted in detail and presented in a separate report.

Section 1
INTRODUCTION

The Black River hydrothermal dolomite play has been the most significant discovery for the New York Oil and Gas industry in several decades. Gas production reached a record high in 2005, in large part due to production from the Black River. According to Bloomberg (2005), the most productive well drilled onshore US in 2004 was drilled into a Black River reservoir in New York (the Reed #1 well). All this from a state that very few people would normally associate with oil and gas production. These production numbers have caused excitement in the industry and generated a lot of interest from across the country. Many new companies have come into the State and drilled wells in the play with mixed results. The problem is that for every well that produces at a high rate, there are several dry holes and several more wells with only moderate production. Some dry holes find only limestone and others find dolomite but no porosity or permeability.

To better understand this exciting but complex play we have undertaken a multi-disciplinary study of the Black River reservoirs and other Lower Paleozoic carbonate reservoirs with some potential. We have looked at seismic data, cores, logs, cuttings, thin sections and done a range of geochemical and fluid inclusion analyses. Our goals have been to better understand how the reservoirs formed and possible sources of heterogeneity.

Section 2

BACKGROUND

Oil and gas have been produced from laterally discontinuous dolomitized zones in the Upper Ordovician Trenton and Black River carbonates in eastern North America for more than a century. The first discoveries were made in the dolomites of the Lima-Indiana Trend of Ohio and Indiana (Figure 1) in 1884. Most of the dolomites are demonstrably fault-related as they align with the NNW-SSE trending Bowling Green Fault and other fault zones (Wickstrom et al., 1992). More than 500 million barrels of oil and over a TCF of gas were produced from the Lima-Indiana Trend (Wickstrom et al., 1992), making it the first giant oilfield in the world. Smaller yet still significant discoveries were subsequently made in fault-controlled dolomites at Dover Field, Ontario, and Deerfield and Northville Fields in Michigan (Hurley and Budros, 1990).

The next major discovery in Trenton-Black River laterally discontinuous dolomites was the Albion Scipio Trend in southern Michigan (Figure 1). Porous matrix dolomite, saddle dolomite-cemented breccias, saddle dolomite-lined fractures and vugs, occur in a trend of *en echelon* structural lows that is ~50 km long (30 miles) long and about 1.6 km (1 mile) wide (Hurley and Budros, 1990). The Albion-Scipio Field has produced more than 250 MMBOE since its discovery. Several smaller fields have subsequently been discovered in Michigan and Ontario.

Natural gas was discovered in laterally discontinuous dolomite in the Black River Group of south-central New York in 1986. Since then, at least twenty new fields have been discovered in dolomites of the Trenton-Black River (Figure 2). Most of the fields are between 7,000 and 10,000 feet deep. Several wells have produced at sustainable rates of > 10MMCF/D, and the best well produced in excess of 35MMCF/D for several months. As of the end of 2004, the well with the best cumulative production had produced more than 15 BCF and is still flowing at a high rate.

These dolomitized fields occur in long, narrow, fault-bounded *en echelon* structural depressions (Harding, 1974; Prouty, 1988; Hurley and Budros, 1990; Colquhoun, 1991) and along other wrench and possible normal fault systems (Wickstrom et al., 1992). The reservoir facies consists of matrix dolomite with saddle dolomite cemented vugs, breccias and fractures around the faults. The reservoirs are laterally sealed by tight, undolomitized limestone. Although some fields have a major component of cavernous porosity (Albion-Scipio is famous for its bit drops of up to ~20 meters (60 feet)), others, including those in New York, have little or no cavernous porosity.

Loucks (1999, 2003a, 2003b) recently suggested that the brecciation occurred when the Trenton and Black River collapsed into meteoric caves in the underlying Cambro-Ordovician Beekmantown carbonates.

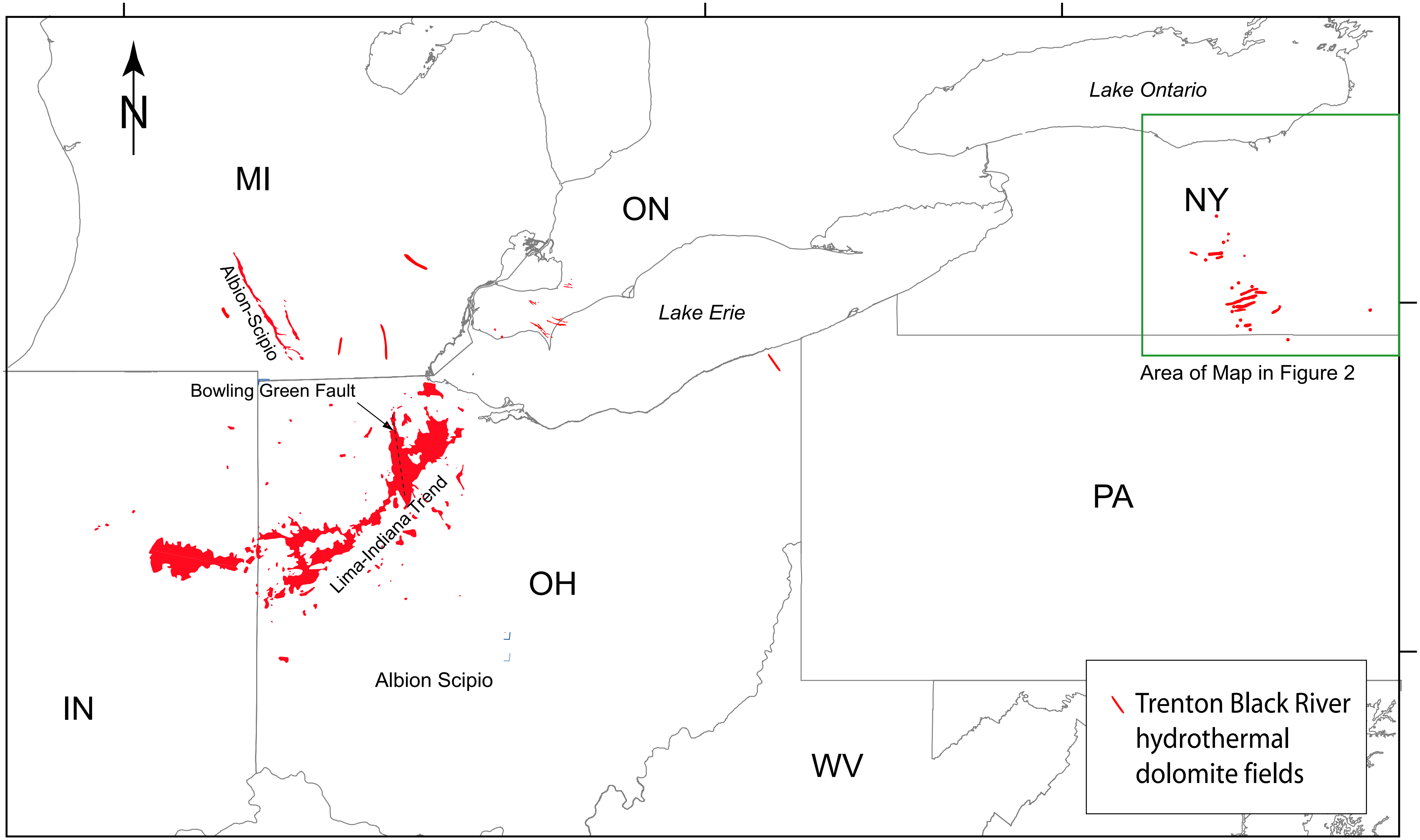


Figure 1. Map of Trenton and Black River hydrothermal dolomite fields in eastern North America.

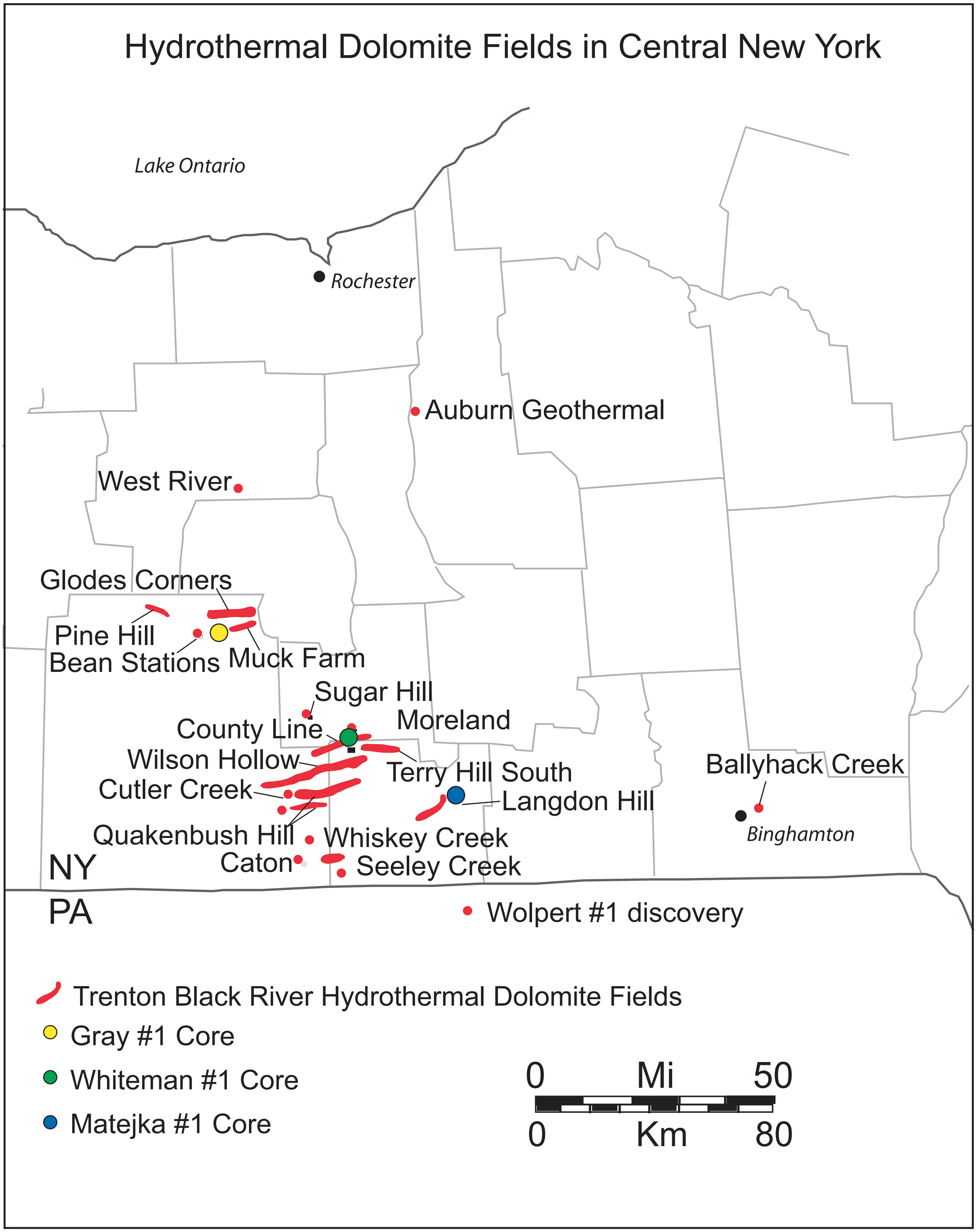


Figure 2. Map of producing dolomite fields in Black River Group of New York with locations of three cores discussed in the paper.

Later, deep-burial fluids were interpreted to be responsible for the dolomitization and mineralization (Loucks 1999, 2003a, 2003b).

Most workers agree that the patchy dolomite formed from fluids flowing up basement-rooted faults and associated fractures (Harding, 1974; Prouty, 1988; Gregg and Sibley, 1984; Taylor and Sibley, 1988; Hurley and Budros, 1990; Colquhoun, 1991; Wickstrom et al., 1992; Coniglio et al., 1994; Davies, 2001; Smith et al., 2003) and has nothing to do with meteoric karst. Prouty (1988) and Hurley and Budros (1990) suggested that the elongate Albion-Scipio Field in southern Michigan formed over a left-lateral strike-slip fault system and that hot fluids flowed up the faults and fractures and dolomitized the adjacent limestone. The structural sags were interpreted to have formed by transtensional faulting and the development of negative flower structures (Harding, 1974; Hurley and Budros, 1990). Wickstrom et al. (1992) suggested a similar origin for dolomite around the NW-SE trending Bowling Green Fault Zone in Northwestern Ohio, and Colquhoun (1991) made similar interpretations about the Hillman Field in southern Ontario.

The recently discovered natural gas fields in New York are similar to the Trenton-Black River Fields in Ohio, Michigan and Ontario. Saddle dolomite-lined vugs, fractures and breccias, and matrix dolomitization occur around subtle basement-rooted faults that are visible on seismic data. Away from the faults, the Black River is unaltered limestone.

Section 3
PROJECT OVERVIEW

PROJECT OBJECTIVES

The main objectives of the project were to better understand how the Black River hydrothermal dolomite reservoirs formed, how they might be best explored and developed, possible sources of heterogeneity and determination of the occurrence of hydrothermal dolomite across the State. The ultimate goal is to help the public better understand these complex reservoirs.

TASKS

The following were the tasks outlined in the proposal. All of these have been accomplished. The results are included in the following report.

Task 1.- Core description. Three cores were described for this study from the Matejka #1, the Whiteman #1 and the Gray #1 wells. The cores were described in detail and photographed. These descriptions are displayed and discussed in this report.

Task 2. - Thin section description. Thin sections from cores and cuttings were described, interpreted and photographed. Thin sections were used to develop the paragenetic sequence for the Trenton and Black River dolomites.

Task 3 - Geochemistry and Fluid Inclusion Analysis. Samples from the NY cores as well as cores in Ohio and Kentucky were analyzed for stable isotopes, strontium isotopes, trace elements and fluid inclusions in order to better understand the characteristics of the dolomitizing fluid.

Task 4 - Link Core and Cuttings Description to Logs. Cores were slipped up against wireline logs to better understand the log response to various geological features. Dolomitized intervals were noted to occur where the density shifted to the right of the neutron log (when the density was plotted on a 1.95-2.95g/cc scale and the neutron was plotted on a 30 to -10% scale). This relationship was used to correlate the dolomites across the State.

Task 5 - Log Correlations. The Trenton, Black River and dolomitized intervals within them were correlated across the State. Field studies were done primarily using logs and are included in the appendix.

Task 6 - Seismic Interpretation/Structural Model. Seismic lines over hydrothermal dolomite reservoirs were obtained from exploration companies. These were interpreted and the results are included in the report.

The dolomitized reservoirs are found in structural sags interpreted to have formed over transtensional segments of strike-slip faults.

RECOMMENDATIONS

1. Look for similar dolomitized features across the State. Our work shows that stratigraphically discordant dolomite likely to be of a hydrothermal origin occurs in the Black River in most parts of the State where the Formation occurs. Gas has been produced from the Auburn Geothermal well in Onondaga County for more than 20 years (total production 200-300MMCF). Oil and gas shows were reported in a well in northern Seneca County. Gas and water have been produced from many wells outside the main producing area.

2. Horizontal drilling. Based on the work presented in this report, it appears that these reservoirs are best drilled with horizontal wells. Within a seismic feature that looks good one can find limestone, tight dolomite or porous dolomite. Horizontal wells cut through this heterogeneity. If wells are going to produce they usually have some porous dolomite in the top 50 feet of the Black River. Horizontals should be oriented to cut through Black River on the downthrown side of faults in the upper 50 feet of the Black River.

3. Offset tight dolomite wells with horizontals – One good strategy might be to find wells that have found some dolomite but have not produced any gas (or water) and offset them with horizontal wells.

4. Future work should concentrate on learning why some wells produce water even when they are located updip or at the same depth as wells that produce gas. At this point we do not have an answer for this (although it could be linked to faults that are connected to the underlying Beekmantown, Galway or Potsdam or a lack of charge from the overlying Trenton and Utica. Other work could be focused on learning more about possible matrix porosity in the Black River in southernmost NY.

Section 4
GEOLOGIC SETTING

The Grenville Basement, which underlies New York State and much of the Eastern United States, has been subjected to numerous tectonic events that produced numerous fault and fracture trends. The Grenville Orogeny occurred approximately 1.1 billion years ago (Moore, 1986) and during this event, thrust faults and associated tear faults formed. After the Grenville Orogeny, North America was part of a supercontinent that underwent a long-lasting episode of rifting in the Late Precambrian (612-550 ma: van Staal, 2005). There were numerous failed rift zones such as the Rome Trough, Reelfoot Rift and many other features (Burke and Dewey, 1973; Thomas, 1991), some of which extend into New York. Along with the extensional faults there were associated strike-slip transfer faults (Thomas, 1991). The faults that formed during these earlier events were likely reactivated during subsequent tectonic events.

After the Late Precambrian rifting of the supercontinent, New York was situated on a passive margin. The Middle Cambrian Potsdam Sandstone (0-100 feet thick) rests unconformably on the rifted basement and is overlain by the Cambro-Ordovican Beekmantown Group carbonates and siliciclastics (Figure 3). In New York, the lower portion of the Beekmantown is composed of the Cambrian Little Falls Dolomite, which has common vugs, breccias and fractures partially filled with saddle dolomite, “Herkimer Diamond” quartz crystals and anthraxolite, a carbonate mineral with solid hydrocarbon in the matrix. The upper part of the Beekmantown consists of the Tribes Hill Formation, which is dolomitized near faults and mostly limestone away from faults where it outcrops in the Mohawk Valley of New York (Landing et al., 1996; Smith et al., 2004b). The Beekmantown and its equivalents across North America (Knox, Ellenburger, Arbuckle, St. George and Romaine) commonly host Mississippi Valley Type Lead-Zinc sulfide deposits and dolomitized oil and gas reservoirs. The global Lower Ordovician Knox Unconformity overlies the Beekmantown.

The overlying Black River Group is primarily composed of muddy and fine-grained shallow marine carbonates. The Black River is overlain by the Trenton Group, which is composed of deeper water argillaceous limestones and calcareous shales and high-energy shallow marine grainstones and packstones (Brett and Baird, 2002). The Trenton and Black River thin toward eastern New York, where they are absent in some places, and thicken into the south-central part of the state where most of the recent production occurs (Rickard, 1973). The Trenton is overlain by the deeper-water Utica Shale, which is a black shale that blankets much of the eastern North America. This contact is diachronous as the Trenton Limestone grades laterally into the Utica Shale to the south and east. The Utica Shale grades up into the Ordovician Lorraine Siltstone and Queenston Sandstone, which are siliciclastics that prograded from the Taconic Mountains across most of New York in the Late Ordovician.

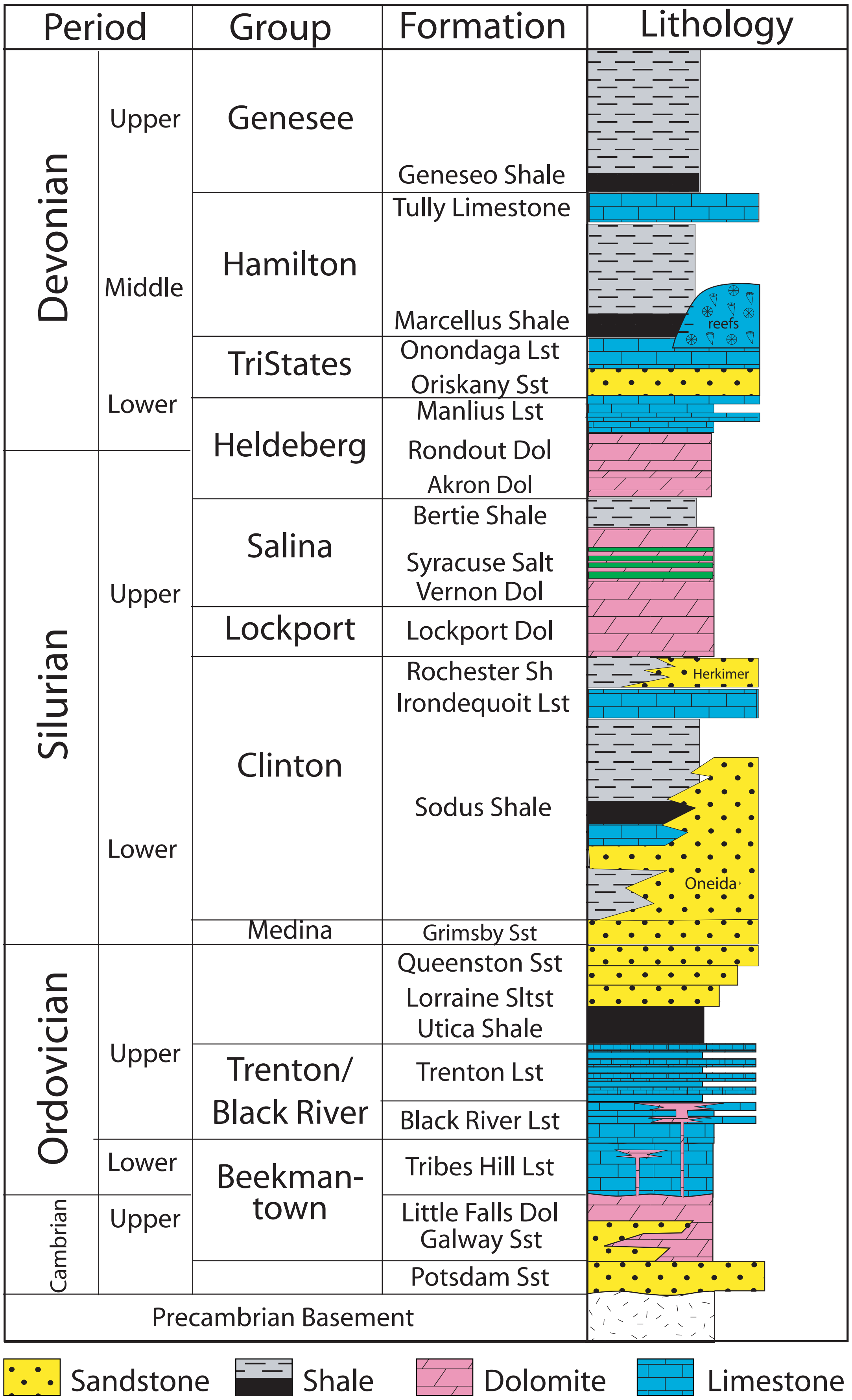


Figure 3. Generalized stratigraphic column for central New York. The Black River Group is earliest Late Ordovician in age.

The Taconic Orogeny began in the Late Ordovician when an island arc collided with proto-North America to the present day east of New York. This collision continued throughout the Late Ordovician and into the Early Silurian (Ettensohn and Brett, 2002). Both the Black River and Trenton Groups contain bentonite (volcanic ash) beds, some of which can be correlated for great distances (Kolata et al., 1996). Further evidence for tectonic activity at this time includes development of a foreland basin to the east, Late Ordovician extensional faulting in the foreland area of the Mohawk Valley (Bradley and Kidd, 1991), spatial and temporal variations in differential subsidence in the Trenton Group and the occurrence of seismites in the outcrops of Trenton and Utica-aged rocks in New York, Kentucky and Ohio (Pope et al., 1997; McLaughlin et al., 2002; Ettenshohn et al., 2002).

Section 5
METHODS

Logs were analyzed and maps were constructed using *Petra* software and then imported into *Adobe Illustrator* where they were manipulated for presentation. Cores were described using slabs and thin sections. Sampling for geochemistry was done in the laboratory at the New York State Museum. Samples of matrix dolomite, saddle dolomite, calcite and quartz were collected separately for each set of analyses. In some cases, samples were split four ways so that we could get fluid inclusion, stable isotope, trace element and strontium isotope date for the same samples.

Fluid inclusions were analyzed by Fluid Inclusion Technologies, Inc using commonly accepted techniques and equipment. Polished slabs of rock material were prepared and studied optically with a petrographic microscope. Samples were placed into a gas-flow temperature stage (manufactured by Fluid Inc.) and individual inclusions in aqueous inclusion populations were viewed optically during heating and cooling ($-196^{o}C$ to $+200^{o}C$ or higher). Phase equilibria within the trapped fluids reflect their composition and bulk density, which, in turn, is a function of trapping temperature, pressure and fluid composition for each inclusion.

Stable isotopes values were measured by Peter Swart at the University of Miami. Samples were reacted for 10 minutes using the common acid bath method at 90°C and the CO2 produced analyzed using a Finnigan MAT-251. Standard isobaric corrections were applied. Data for both carbon and oxygen isotopes are reported relative to the Vienna Pee Dee Belemnite standard (V-PDB) using the conventional notation. Trace elements and strontium isotopes were analyzed by Mihai Ducea at the University of Arizona. Approximately 100 mg of each sample were dissolved in 2.5M nitric acid. About 10% of that was used for trace element analyses; the remainder was taken up in 3.5M nitric acid and passed through Sr Spec chromatographic columns for rapid Sr elution. The separated Sr cut was then re-dissolved in 1% nitric acid. Trace elements were analyzed in a mild nitric acid using a Perkin Elmer Elan DRC-II instrument. Strontium isotopes were analyzed on a VG Sector 54 instrument. During the period of our analysis, the measured $^{87}Sr/^{86}Sr$ ratios were 0.71025±1 for standard NBS 987.

Section 6
DATA

MAPS AND CROSS-SECTIONS

Figure 2 shows the distribution of Trenton-Black River producing hydrothermal dolomite fields and discoveries in New York. Many of these fields are in the process of being drilled and extended and this map is likely to look quite different when all drilling is completed.

The distribution of dolomite in the Trenton and Black River Groups helps to understand its origin. The Trenton Group carbonates are primarily limestone and argillaceous limestone throughout most of New York and are only rarely dolomitized. This is in contrast to Ohio, Michigan and Ontario where the Trenton is commonly dolomitized and produces more hydrocarbons than the underlying Black River. Furthermore, there is no "cap" dolomite in New York (*sensu* Wickstrom et al., 1992), which is a tight regional dolomite in the uppermost Trenton between 10 and 50 feet thick that blankets much of northwestern Ohio and southwestern Michigan.

Most of the dolomitization in New York occurs in the Black River Group and is laterally discontinuous. Where there are enough wells to map out dolomite bodies, the dolomite occurs in sub-linear trends that are up to 25 km long and 1 km wide (Figure 2). Undolomitized wells occur within short distances of wells with significant quantities (tens of feet) of dolomite in the same stratigraphic interval (Figure 4). All productive wells have at least some porous dolomite in the upper half of the Black River Group and almost all wells have dolomite in the top 20 feet. Figure 4 shows the distribution of wells with at least 2 feet of dolomite in the upper half of the Black River along with wells that are entirely composed of limestone in that interval. Dolomite thickness within the Black River ranges from a few feet to several hundred feet. Analysis of cuttings thin sections from dolomitized wells outside the producing area confirms the presence of both matrix and saddle dolomite (Nyahay and Smith, 2003). As of 2003, 345 wells with logs have been drilled to the Black River. Of these, 175 wells have encountered at least some dolomite in the upper half of the Black River and 48 wells have produced at least some gas. It should be noted that since 1996, almost all wells that were drilled to the Black River were drilled into structures looking for dolomite while prior to that date they were mainly drilled with other targets in mind and were less likely to encounter dolomite.

Figure 5 is a cross section of wells in and near the Glodes Corners Road Field (the discovery field for the New York trend). The field is about 10 km long and 0.7 km wide and has produced about 8 BCF. Within the Black River, the cross-section includes several dolomitized producing wells, two tight dolomite wells and a tight limestone well. Dolomite is picked using the PEF curve or where that is absent, in zones where the density log reads greater than 2.75 g/cc or where the density log (on a limestone scale) reads about 5% less porosity than the neutron log. When the Black River is productive, it is almost always dolomitized in

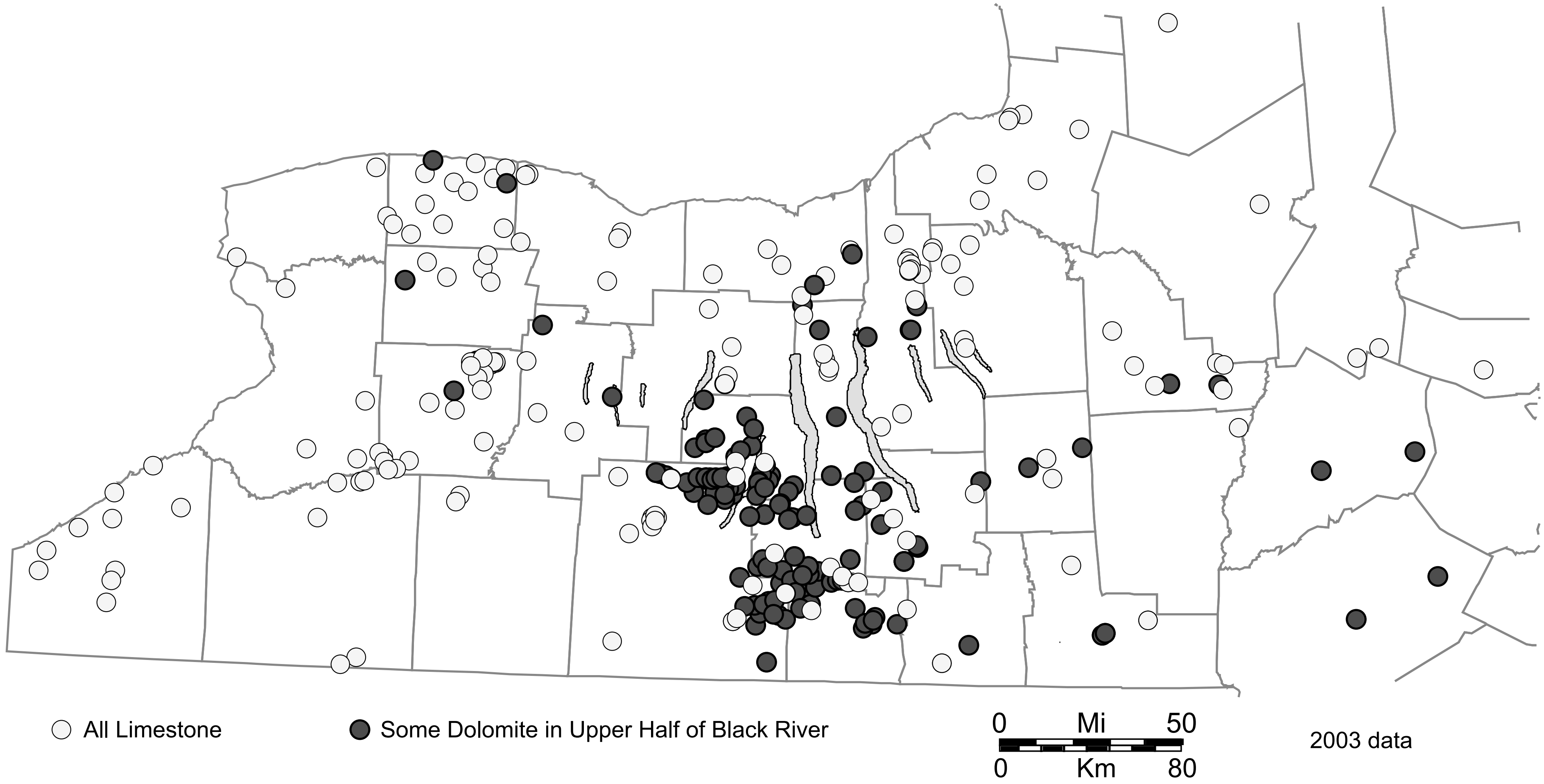


Figure 4. Map of central and western New York with locations of wells with at lest two feet of dolomite in the upper half of the Black River and wells that are all limestone in this interval.

Glodes Corners Road Field

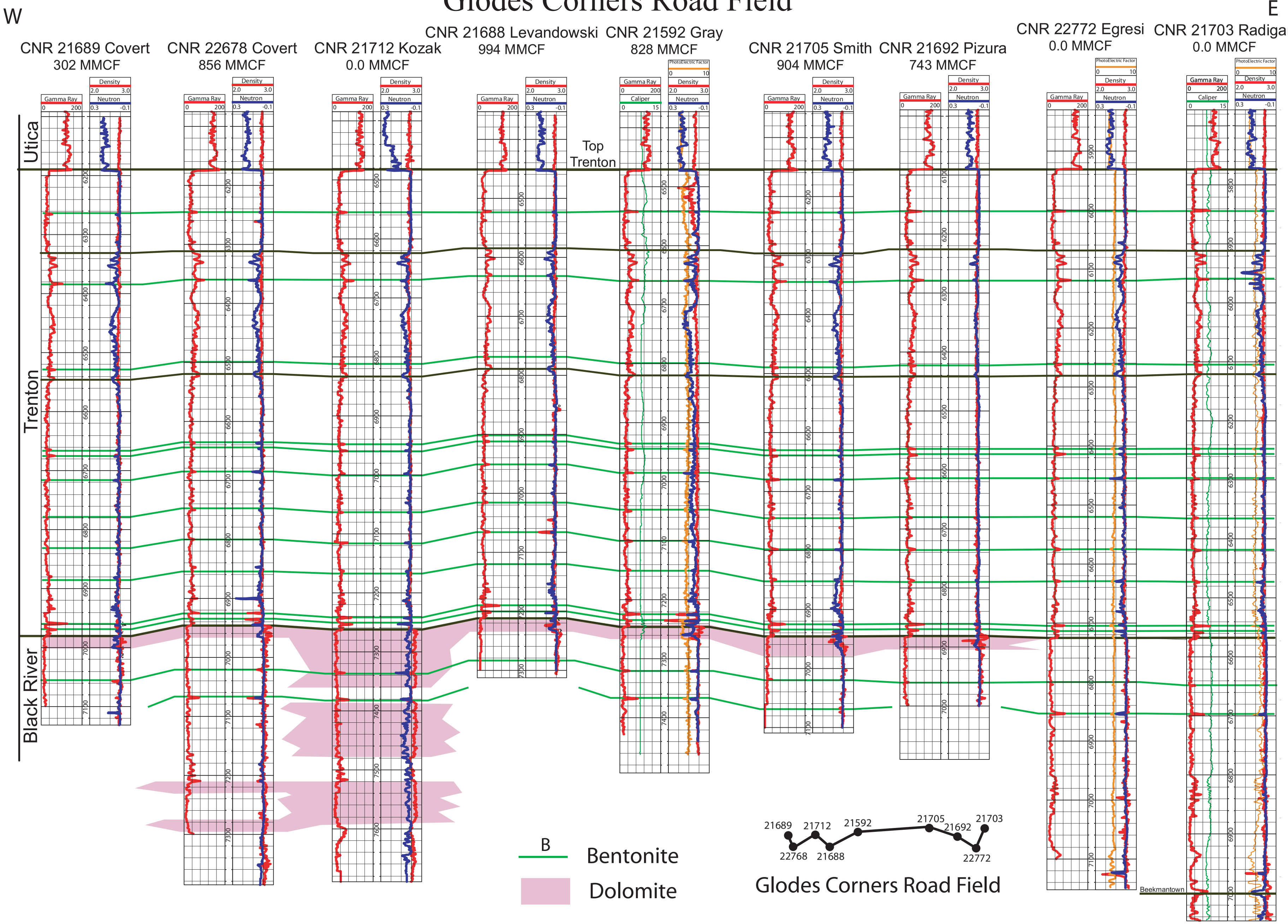


Figure 5. Cross section of Trenton and Black River Groups at Glodes Corners Road Field, New York. Dolomite is highlighted in pink. The rest of the Trenton and Black River Groups are composed of limestone. Well labels include the operator (Columbia Natural Resources or CNR), the shortened API number, lease name and cumulative production as of 2003.

the uppermost 50 feet under the argillaceous limestones at the base of the Trenton (Figure 5). The thickening and thinning and laterally discontinuous nature of the dolomite suggests that the source of the dolomitizing fluids was highly localized.

Figure 6 is a cross section of some of the better wells in a few of the major producing fields. The cross section trends from Glodes Corners Road in the Northwest to Seeley Creek Field in the southeast. In many cases, once gas was discovered, operators would stop drilling and hook the wells up, so some logs do not go all the way through the Black River. Note the variable dolomitization from just a few feet in Glodes Corners Road and Muck Farms Fields to near pervasive dolomitization in the Lant #1 (Terry Hill South Field) and Parker #1 (Wilson Hollow Field) to the more interbedded dolomitization in several other wells. This variability in dolomitization demonstrates again that the dolomitization was not regional but highly localized. The porosity distribution also varies from well to well, but the zone that is most consistently porous is in the top 50 feet (15 meters) of the Black River.

SEISMIC DATA

Black River hydrothermal dolomite fields are discovered using seismic data. The dolomitized zones occur primarily in and around *en echelon* fault-bounded structural lows (Prouty, 1983; Hurley and Budros, 1990; Davies, 2004). These features are commonly called “grabens” or “sags.” Figure 7 is a time structure contour map of the top of the Trenton from a producing hydrothermal dolomite oil field in Ontario that shows *en echelon* sags. Oil was produced from fractured, vuggy dolomite located within the structural lows and most of the Trenton and Black River strata outside the sags are impermeable limestone (Horvath et al, 2004). The *en echelon* sags are interpreted to be negative flower structures formed as a result of transtensional (strike-slip and extensional) faulting (*c.f.* Hurley and Budros, 1990).

Figure 8 shows the seismic signature of two different productive Black River hydrothermal dolomite fields in New York, Muck Farms Field (Figures 8A, B and C) and Wilson Hollow Field (Figures 8D, E and F). The dolomite occurs in the Black River, typically within the structural lows. The fault picks in the basement (Figures 8B and 8E) are equivocal, but reflectors are demonstrably offset and faulted. Typical of some negative flower structures, reflectors immediately overlying the basement are not as obviously vertically offset by the faults while those higher in the section have clear vertical displacement (see cross sections in Dooley and McClay, 1997 for examples of how these might form). Note that the productive dolomitized structures look very different in the two cases. This is typical of wrench-faulted zones, which significantly change in character along strike. Most of the vertical offset of the seismic traces occurs within the Black River with little offset in the overlying Trenton or underlying Beekmantown. Most of the faults with associated dolomitization die out in the Trenton or overlying Utica Shale. Note that on the Muck Farm line where the Beekmantown reflector can be picked (Figure 8B), there is no collapse into the

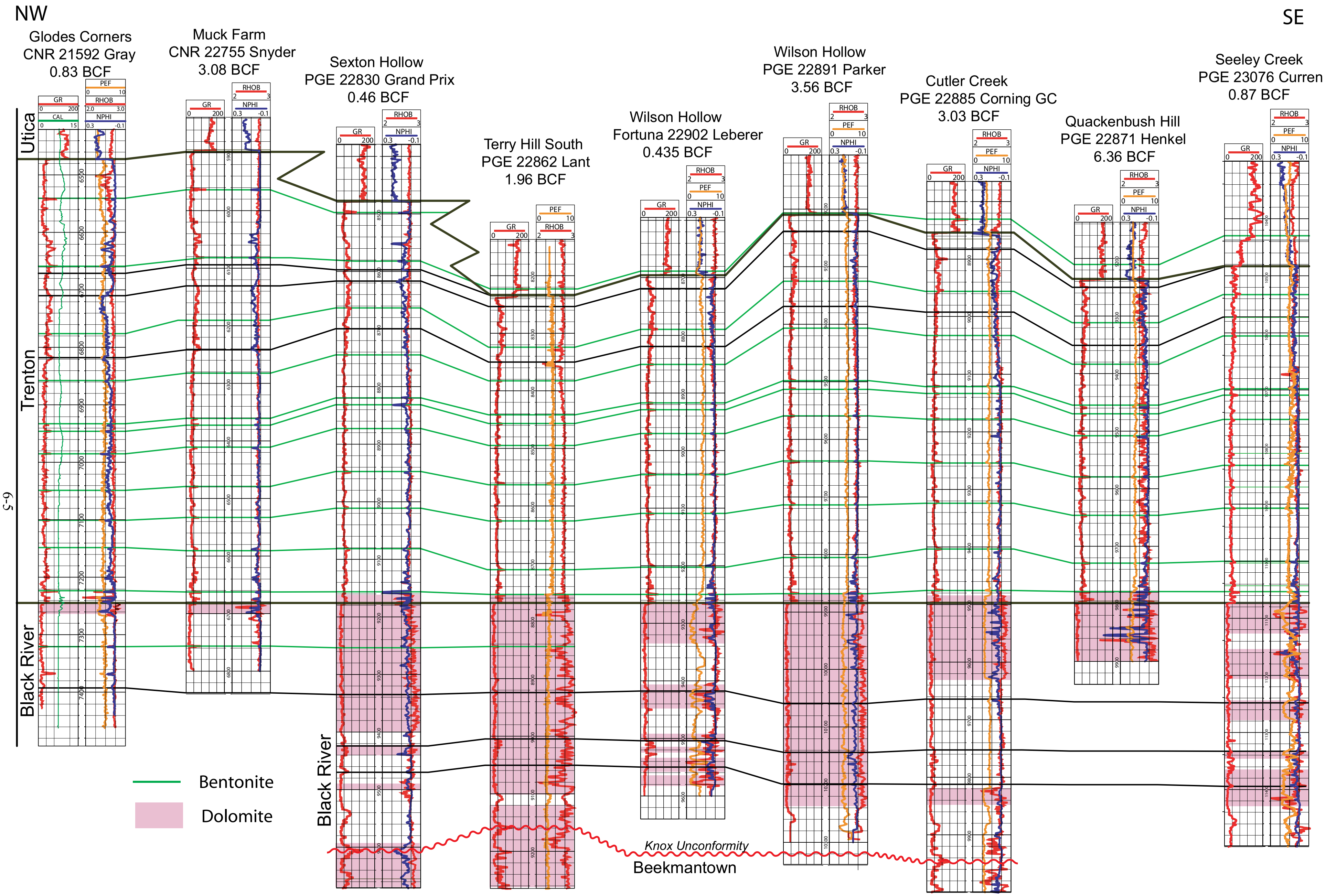


Figure 6. Cross section of Trenton and Black River Groups from NW to SE through eight of the producing fields in the trend. Note variable dolomitization and porosity development. Well labels include Field name, operator, shortened API number, lease name and production as of December 2004. The wells have produced for varying amounts of time and all continue to produce.

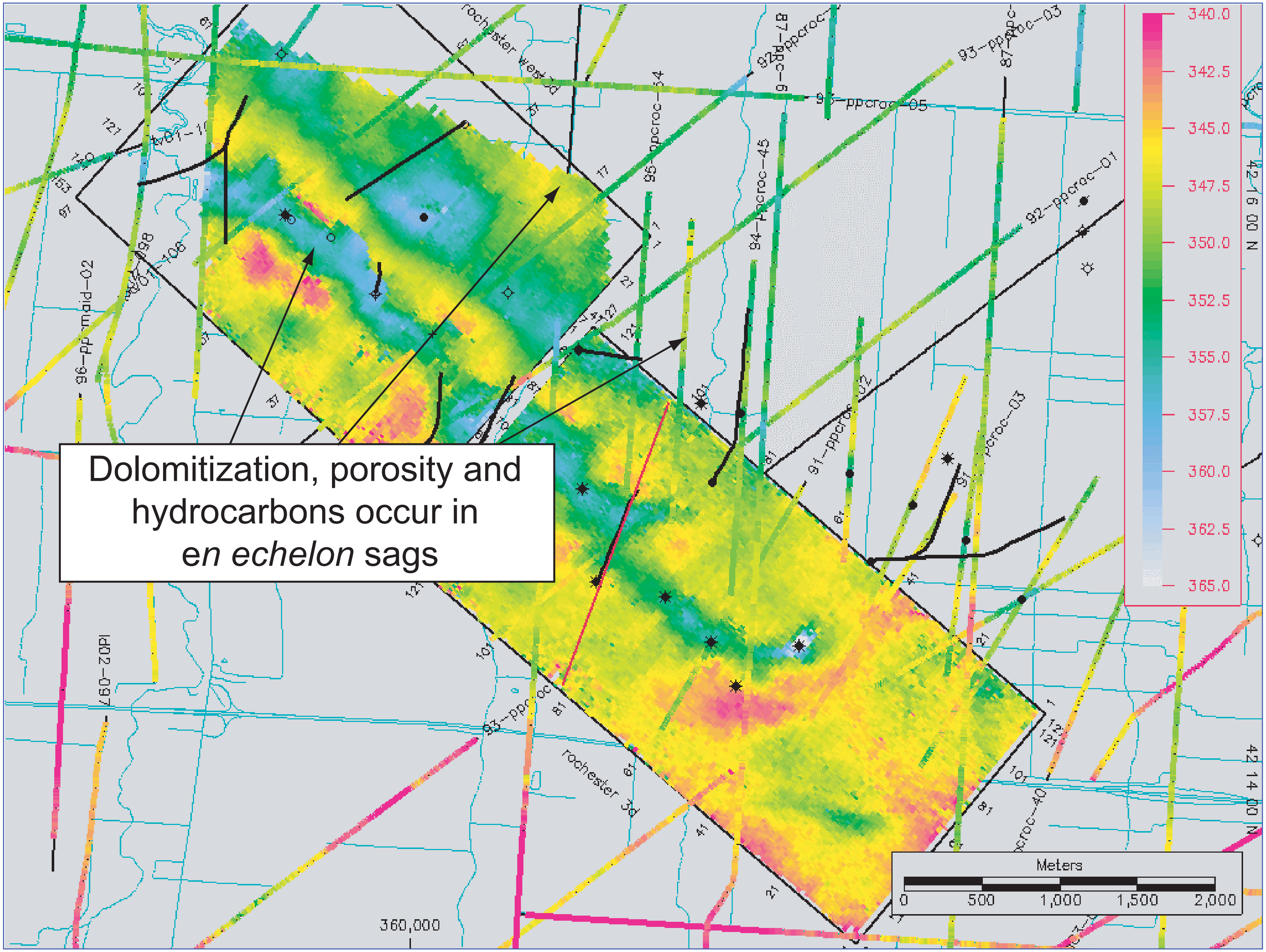


Figure 7. Time-structure map of the top of the Trenton Group, Rochester Field, Ontario based on 3D seismic data (courtesy Talisman Energy). Note *en echelon* sags where dolomitization, porosity and oil occur. Color bar scale is in meters below sea level. See Figure 1 for location of Rochester Field.

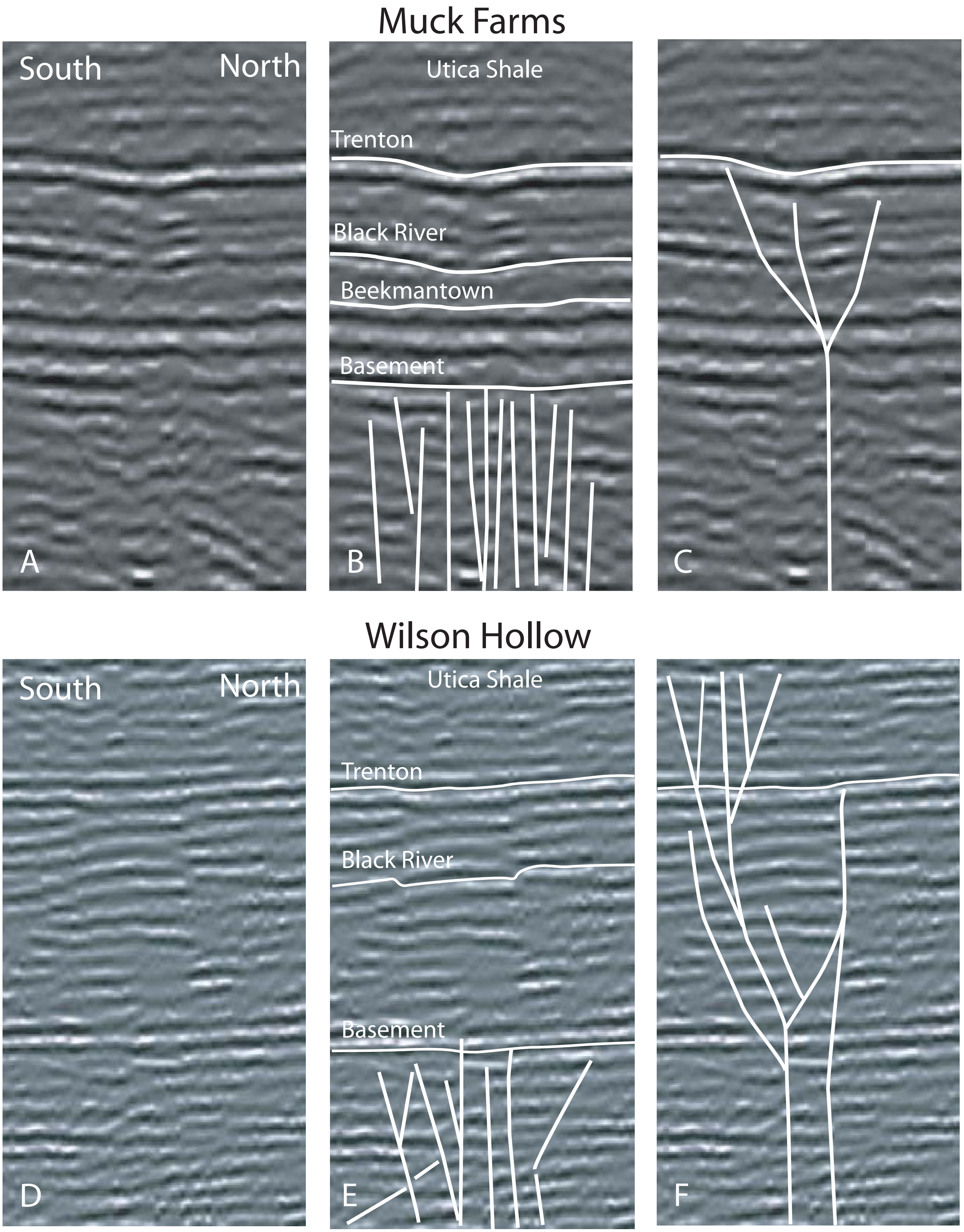


Figure 8. Seismic lines from Muck Farm and Wilson Hollow Fields, New York. A) Uninterpreted line over Muck Farm Field. B) Formation picks and possible faults in basement. Note sag at top of Trenton and lack of sag in Beekmantown. C) Interpreted flower structure with faults bounding structural sag. D) Uninterpreted line over Wilson Hollow Field. E) Formation and possible basement fault picks. Note that the sag is accommodated in Trenton and lower Utica. F) Possible basement-rooted flower structure with faults bounding sag in Trenton and Black River.

Beekmantown. Also note on the Wilson Hollow line that much of the structural sag affecting the lower Trenton and Black River is filled in by earliest Utica time (Figure 8E).

CORES

There are three publicly available cores from the Black River hydrothermal dolomite play in New York. Each of them has features that are important to understanding the sedimentology, stratigraphy and diagenesis of this play. The locations of the cores are presented in Figure 2.

ROCK TYPES AND STRATIGRAPHY

The Black River Group carbonates were deposited on a shallow low-relief tropical carbonate ramp. Rock types include mudstone (sometimes with fenestrae and clay drapes), fine-to coarse-grained skeletal wackestone, and very fine-to-fine peloidal packstone and grainstone (See Cornell, 2000 for more detailed facies analysis). All of these rock types can be dolomitized, but dolomitization of the peloidal grainstones and packstones may be more common. The clay drapes superficially resemble stylolites but are unrelated to pressure solution. Burrowing is common in most rock types. The Black River Group carbonates are remarkably consistent in rock type across much of eastern North America. None of these rock types is a reservoir facies in the absence of dolomitization.

The Trenton has grainstones and packstones that are coarser and more fossiliferous than those in the underlying Black River and also has common dark gray to black shale (Brett and Baird, 2002). Deeper water rock types include black or dark gray shale, fossiliferous shale and skeletal wackestone. Shallower water facies occur in some locations and they include coarse-grained skeletal grainstone and packstone. The Trenton in central New York is generally more argillaceous than it is in Ohio, Michigan and Ontario. This may be the primary reason that the Trenton is rarely dolomitized in central New York. There is virtually no porosity in the limestone facies of both the Trenton and Black River facies and these impermeable limestones are thought to form a vertical and lateral seal on the hydrocarbon reservoirs.

MATRIX DOLOMITE DESCRIPTION

The reservoir rock types in the Trenton-Black River are hosted in laterally discontinuous dolomites. There is both matrix dolomitization and void filling saddle dolomite. Analysis of stained, impregnated thin sections from the cores shows that more than 95% of the dolomite is medium to coarse (50-400 micron) matrix-replacive dolomite. The matrix dolomite has little or no porosity in the cores studied from New York. Matrix porosity may occur in other wells, but was not present in the cores studied. This lack of matrix porosity is in contrast to Trenton-Black River dolomitized reservoirs in Ontario and Ohio where matrix porosity is more common and makes up a significant part of the reservoir (Wickstrom et al., 1992; Colquhoun, 1991).

Much of the matrix dolomitization is fabric-destructive, anhedral and nonplanar (*sensu* Sibley and Gregg, 1986). Finer dolomites are here interpreted to have been mudstones and mud-dominated wackestones and the coarser dolomites are interpreted to have been peloidal or pelletal grainstones and packstones (c.f. Lucia, 1995).

Even though this play has significant structural and diagenetic aspects, stratigraphy is still important. Strata with higher porosity and permeability remaining at the time of dolomitization were probably more likely to have been dolomitized and to have had some porosity preserved after dolomitization. As more core data is collected, a major emphasis will be placed on learning what each of the dolomitized rock types were prior to dolomitization and what the impact of original facies is on reservoir quality.

RESERVOIR FACIES DESCRIPTION

Most of the open pores in the Black River dolomites occur in saddle dolomite-lined fractures, vugs, zebra fabrics, boxwork fabrics and between clasts in breccias (Figures 10 and 11). Some vugs are sub-spherical and several cm in diameter. Other vugs are elongate (a few mm wide and several cm long) and may be solution-enlarged fractures. Some of these elongate vugs are horizontal while others are inclined. Porous zebra fabrics and boxwork fabrics are both present (Figure 10). Breccias are common but not abundant and consist of mm-to cm-scale angular to corroded clasts cemented with saddle dolomite.

The Matejka #1 core (Figure 9) was drilled in Chemung County (Figure 2) in 1975, eleven years before the first official discovery. It encountered dolomite in the Black River and heavily fractured limestone in the overlying Trenton Group. There is some porosity in fractures in the basal Trenton limestone that are mostly cemented with coarse calcite cement (Figure 9A). The dolomite in the Black River has no porosity (Figures 9B and 9C) and no open vugs, fractures or breccias. Saddle dolomite and calcite plug fractures within the dolomitized interval. The well was plugged as a dry hole, but it is located within a few hundred meters of a producing dolomitized well and may have produced from the fractures in the basal Trenton limestone.

The Gray #1 core (Figure 10) was drilled to the west of Muck Farms Field and did not produce economic quantities of gas. The matrix in the upper half of the core is dolomitized and the lower half is predominantly limestone. Saddle dolomite-lined vugs occur in the dolomitized interval (Figure 10) but

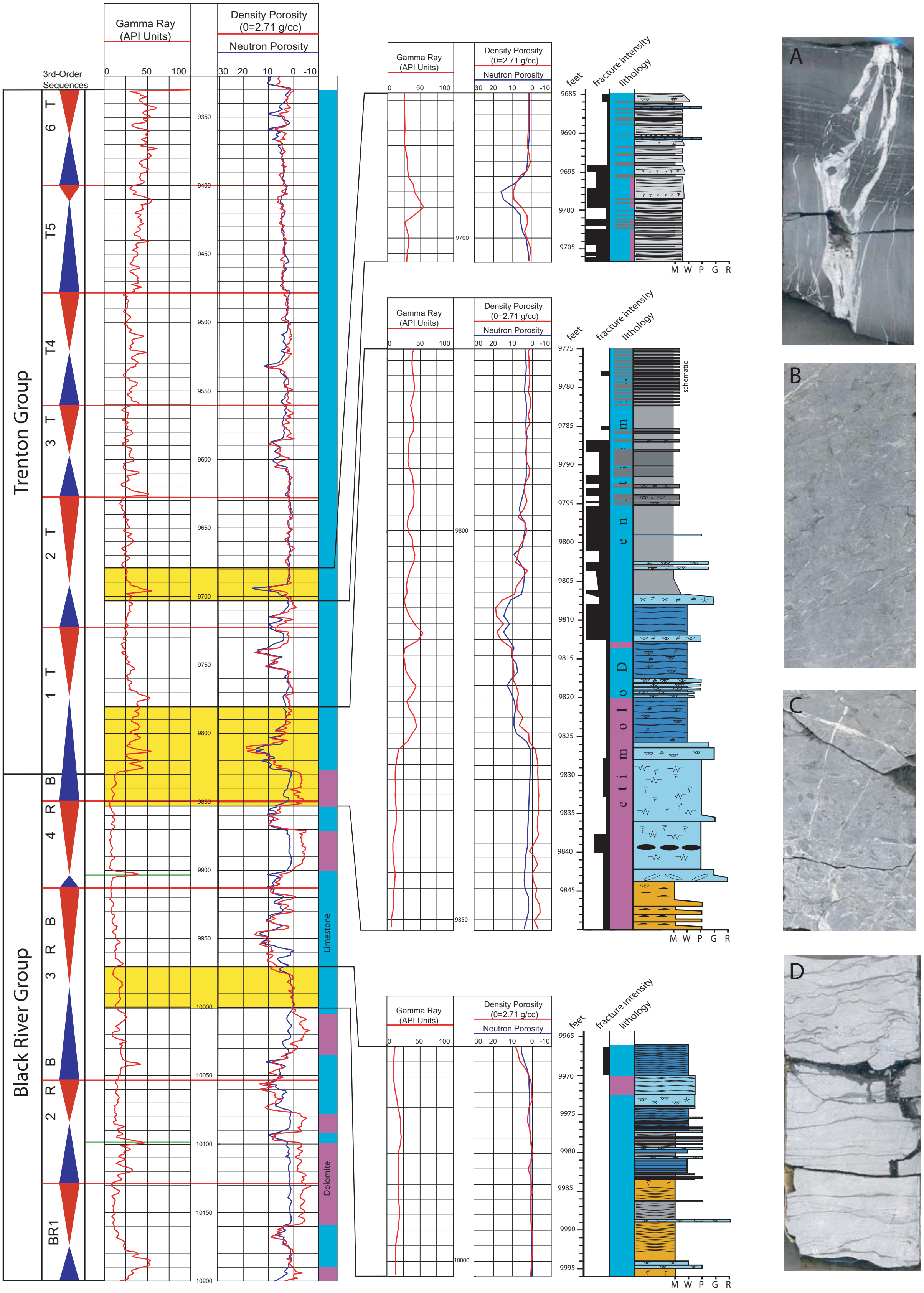


Figure 9. Core description with logs and photos from Matejka # 1 well, Chemung County, New York. Dolomitized intervals in core match with intervals where density log reads 5% less porosity than the neutron log. Color code for core description: grays are deeper water mudstone, wackestone and shale, dark blue is mid ramp skeletal wackestone, light blue is shallow marine peloidal and skeletal grainstone (interpreted in dolomitized interval), tan is shallow marine argillaceous mudstone and wackestone. (M = mudstone; W = wackestone; P = packstone; G = grainstone) Photographs are lettered: A) Lower Trenton Group interbedded fossiliferous shale and mudstone is faulted and cemented with calcite. This samples is from 9787' and has some porosity in the fracture. B) Uppermost Black River dolomite with relict clay fills, minor fractures and tight, gray matrix dolomite. C) Dolomitized conglomerate from upper Black River Group with calcite cemented fractures and no porosity. D) Typical Black River Limestone from lower core is shallow marine mudstone with clay laminae.

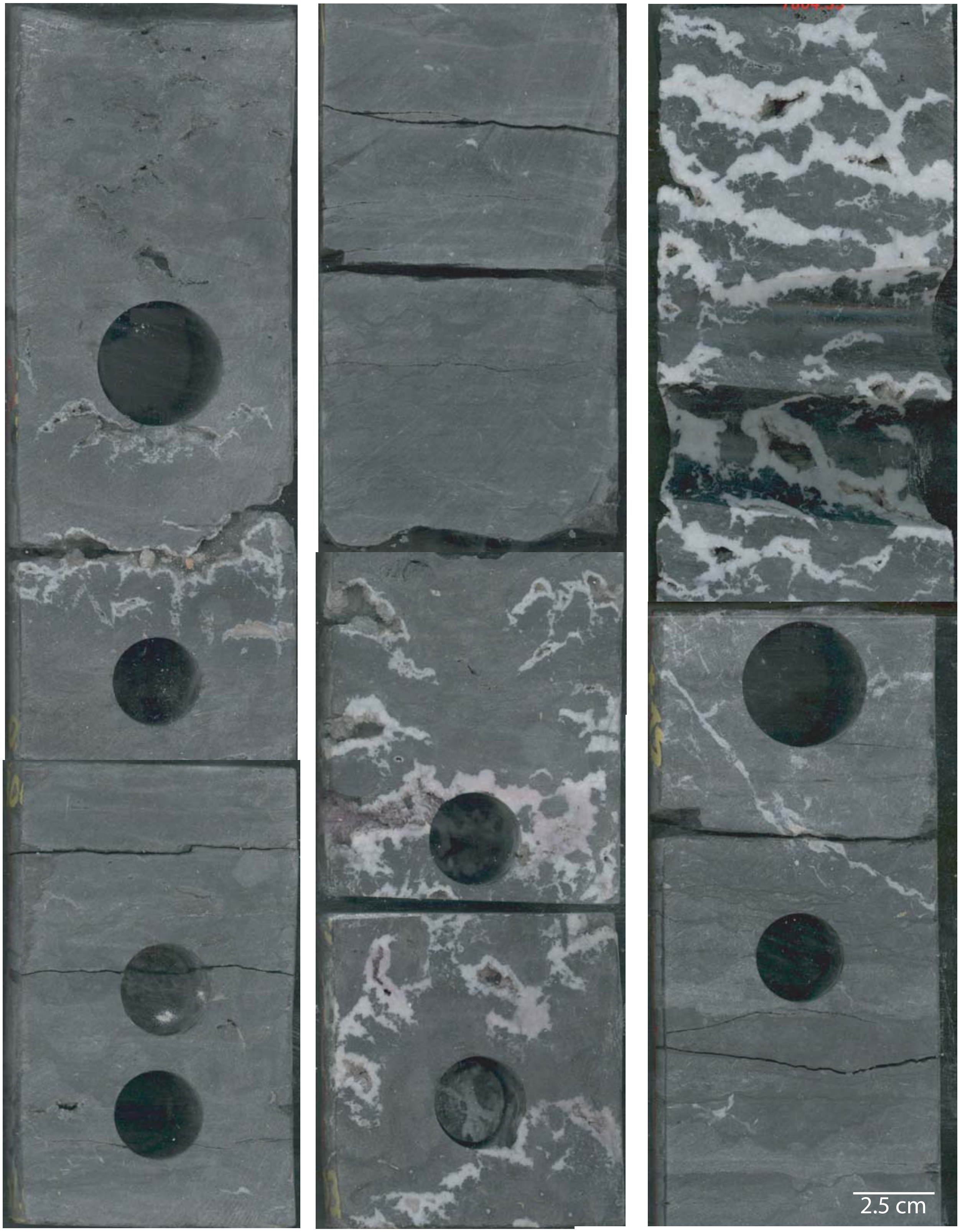


Figure 10. Core photographs from Gray #1 well, Steuben County, NY. Gray matrix dolomite with vugs lined with white saddle dolomite. Core is 9 cm (3.7 inches) wide.

Figure 11. Core photographs from Whiteman #1 well, Chemung County, NY. This core has common fractures, vugs, zebra fabrics (ZF), boxwork fabric (BF) and an overall brecciated appearance. White saddle dolomite lines vugs and fractures in gray matrix dolomite. Core is 5cm (2 inches) wide.

there are no open fractures or breccias. This well tested a very small amount of gas but not enough to justify facility costs and may be sidetracked.

The Whiteman #1 core (Figure 11) is pervasively dolomitized and has common saddle dolomite-lined vugs, zebra fabrics, breccias and fractures. Porosity primarily occurs in vugs and fractures, and there is little or no matrix porosity. The well has produced approximately 0.5 BCF as of the end of 2004 and is still producing today.

PARAGENETIC SEQUENCE

The paragenetic sequence of the Black River dolomitized reservoirs is presented in Figure 12 and supported with photographs in Figure 13. Prior to dolomitization, some early marine and shallow burial calcite cementation and compaction occurred along with some minor grain suturing. This early diagenesis was followed by matrix dolomitization (Figure 13A), faulting, fracturing and brecciation (Figure 11), then saddle dolomite (Figure 13A), quartz (Figure 13B), rare authigenic feldspar (Figure 13C), pyrite, bitumen and calcite precipitation (Figure 13D). In some cases, the late calcite and/or saddle dolomite are leached by a later event (Figure 13E). Figure 13E shows bitumen in a pore that apparently was precipitated between dolomite rhombs that were later leached. Major stylolitization follows all mineralization (Figure 13F). There are no dolomite filled fractures that cut across major stylolites and matrix and saddle dolomite rhombs are clearly consumed at stylolites. All these are postdated by hydrocarbon migration, which likely occurred in the Late Paleozoic. The bitumen found lining many pores and fractures is not thought to represent a full-scale migration event.

The timing of the development of the vugs is equivocal. It may be that most vugs formed before the matrix dolomitization (the preferred interpretation) during a period of pre-dolomitization leaching. Or it may be that they formed after matrix dolomitization but before saddle dolomite was precipitated through matrix dolomite dissolution. There is no evidence of significant dolomite dissolution such as corroded rhombs lining the vugs. In some cases, vugs appear to be enlarged fractures (Figure 11), which would make their development syn- or post-fracturing.

GEOCHEMISTRY AND FLUID INCLUSIONS

Geochemical and fluid inclusion analysis of the dolomites helps to understand their origin (Allan and Wiggins, 1993). We have conducted stable isotope, strontium isotope, trace element of the saddle dolomite, blocky calcite, matrix dolomite and matrix limestone and fluid inclusion analysis of the saddle and matrix dolomite and blocky calcite.

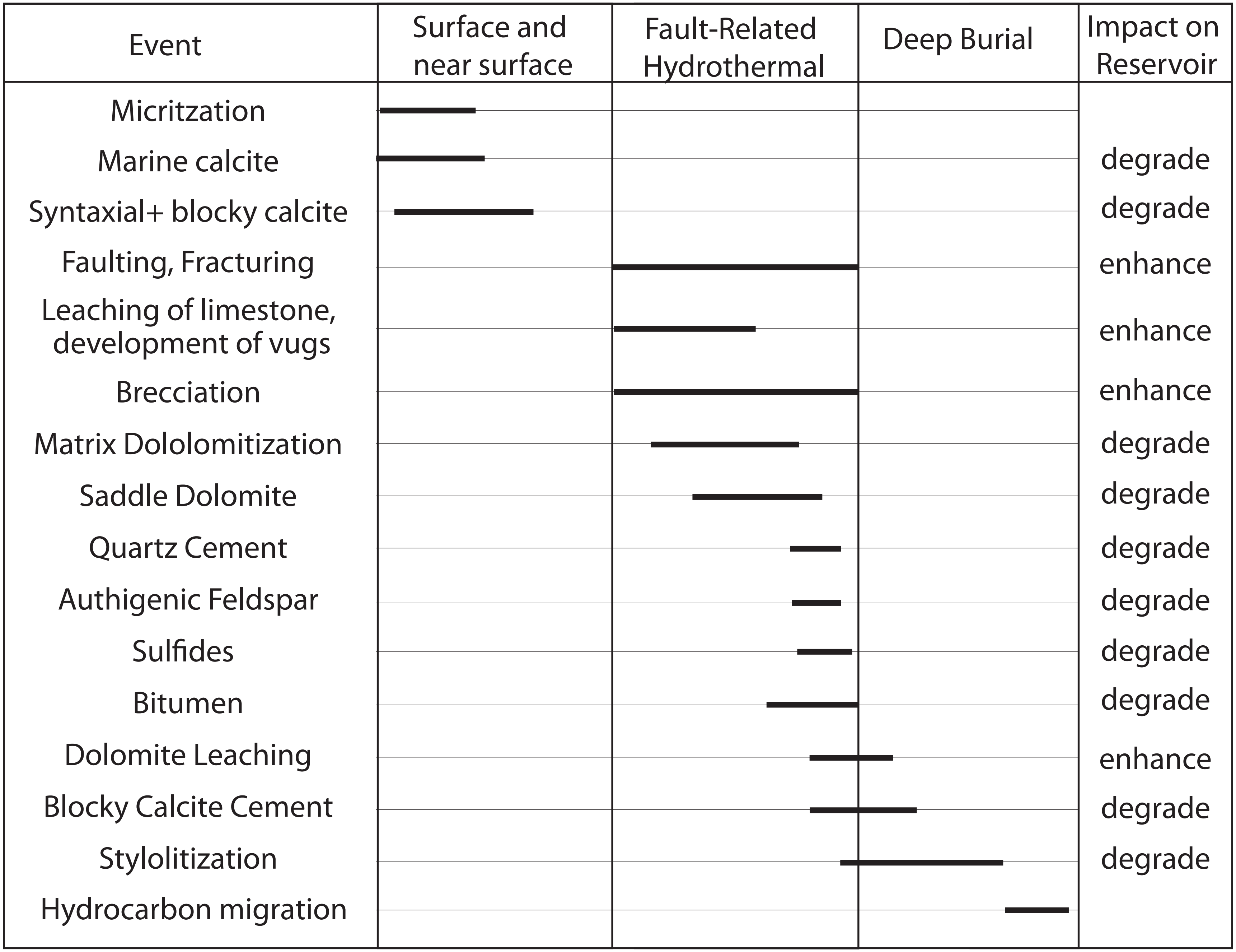


Figure 12. Paragenetic sequence of events in dolomitized cores from Black River Group of New York.

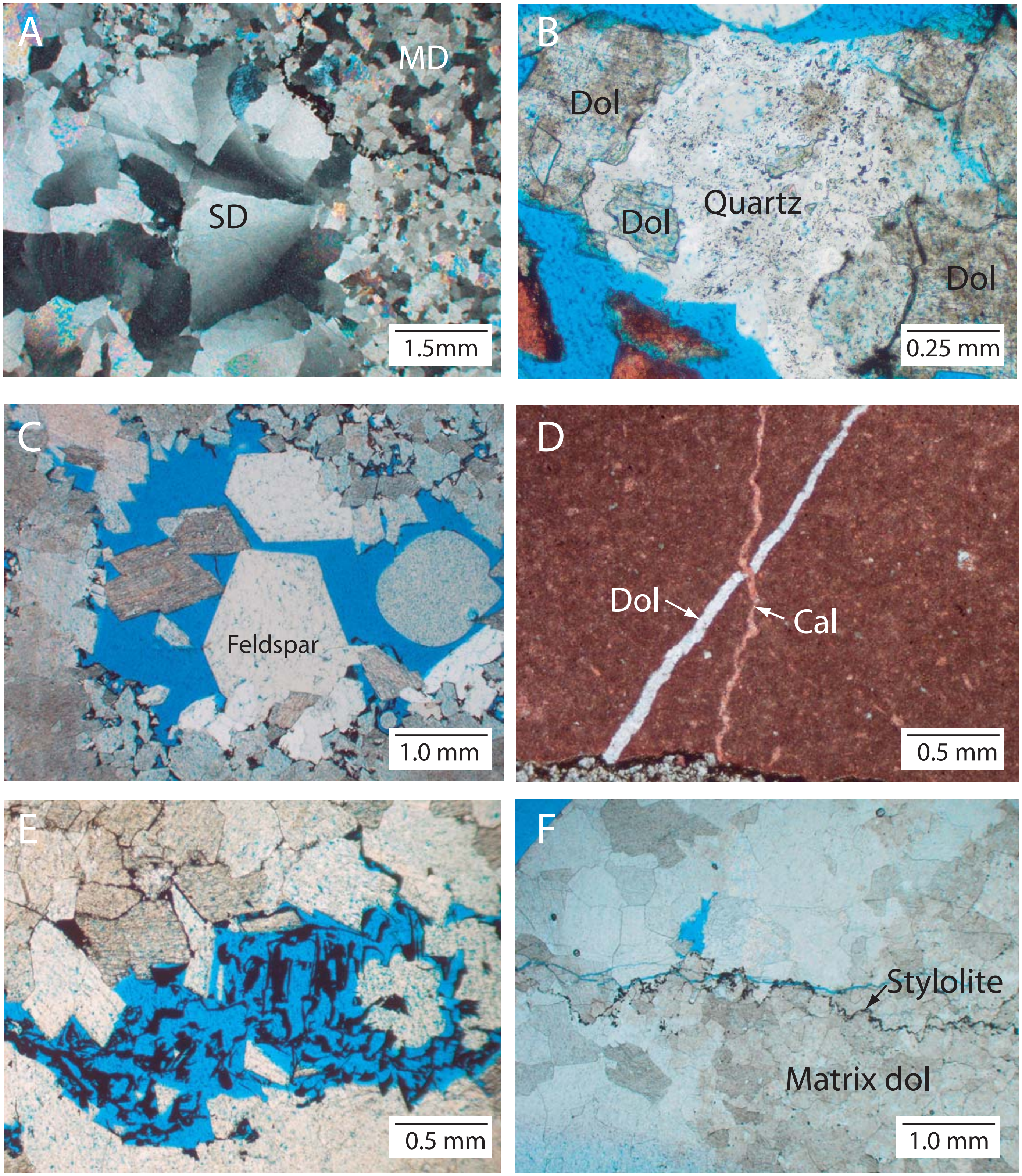


Figure 13. Thin section photographs from Black River Group, New York. A) Saddle (SD) and matrix (MD) dolomite. Gray #1 core, 7802 feet. B) Quartz cement in fractured ferroan dolomite. Auburn geothermal well cuttings, Onondaga County, NY, 4150 ft. C) Authigenic feldspar in vug. Whiteman #1 core, 9528.5 ft. D) Calcite-filled fracture clearly postdates dolomite-filled fracture. Late calcite commonly plugs porosity in Black River reservoirs. Gray #1 core, 7816 ft. E) Bitumen distribution in vug suggests that dolomite may have been leached after bitumen was precipitated. Whiteman #1 core, 9535 ft. F) Stylolite clearly postdates dolomitization. No dolomite grows across stylolites, all rhombs are consumed at stylolites. Gray #1, core 7803 ft.

Fluid Inclusions

Primary fluid inclusions from the saddle dolomite in the New York wells have homogenization temperatures between 110 and 170° C with an average of 130°C (Figure 14). Inclusions of an equivocal primary or secondary origin from the matrix have a similar range of homogenization temperatures with a higher average of 145°C. Secondary fluid inclusions from the saddle dolomites have homogenization temperatures up to 180°C with an average of 173°C. Matrix dolomites have equivocal primary/secondary inclusions with fluid inclusion homogenization temperatures that range from 135-165°C with an average of 145°C. Post-dolomite primary and secondary quartz fluid inclusions have homogenization temperatures ranging from 155° to more than 200°C with an average of 177°C. There were no petroleum inclusions found in any mineral.

The salinities of the primary fluid inclusions in both matrix and saddle dolomites range from 13.2 to 15.5 wt % with an average of approximately 14.4 wt % (approximately 4 times normal seawater). The salinity values of the equivocal inclusions in the matrix dolomites are similar with an average of 14.9 wt%. The secondary fluid inclusions in the post-dolomite quartz cement average 16.7 wt. %. These values show that the fluid that made the dolomites and quartz were saline brines. The values for the New York dolomites are not as saline as many brines thought to have precipitated hydrothermal dolomite in the Trenton-Black River in Ontario, Ohio and Michigan and elsewhere in the world, which average closer to 20 wt.% (Allan and Wiggins, 1993; Coniglio et al., 1994).

Stable Isotopes

Stable isotopes of carbon and oxygen were analyzed from matrix dolomite, saddle dolomite and limestone where present (Figure 15). The limestones in the Black River of NY have consistent $\delta^{18}O$ values around –6.5‰. Due to fractionation, dolomite that precipitated from the same water at the same temperature should have $\delta^{18}O$ values of around –3.5 ‰ (Friedman and O'Neil, 1977). The matrix and saddle dolomites in the Black River have $\delta^{18}O$ values between –9 and –12.5 ‰. Increased temperature and mixing of fresh water can both drive $\delta^{18}O$ values toward more negative values. The salinity of the primary fluid inclusions in the dolomites averages 4 times greater than seawater, which eliminates fresh water as a source of lighter (more negative) $\delta^{18}O$ values. Increased temperature is then the likely source for the depletion of $\delta^{18}O$.

The actual temperature of formation cannot be determined without first plotting the $\delta^{18}O$ values vs. fluid inclusion homogenization temperatures from the same samples and backing out the oxygen isotope composition of the fluid. Figure 16 shows the $\delta^{18}O$ values and fluid inclusion homogenization temperatures for the matrix and saddle dolomites in the TBR in New York. The homogenization temperatures from each sample were averaged and plotted with $\delta^{18}O$. It suggests that the fluid was somewhere between 0 and +4 with an average of +2 ‰. Note that this is considerably heavier (more

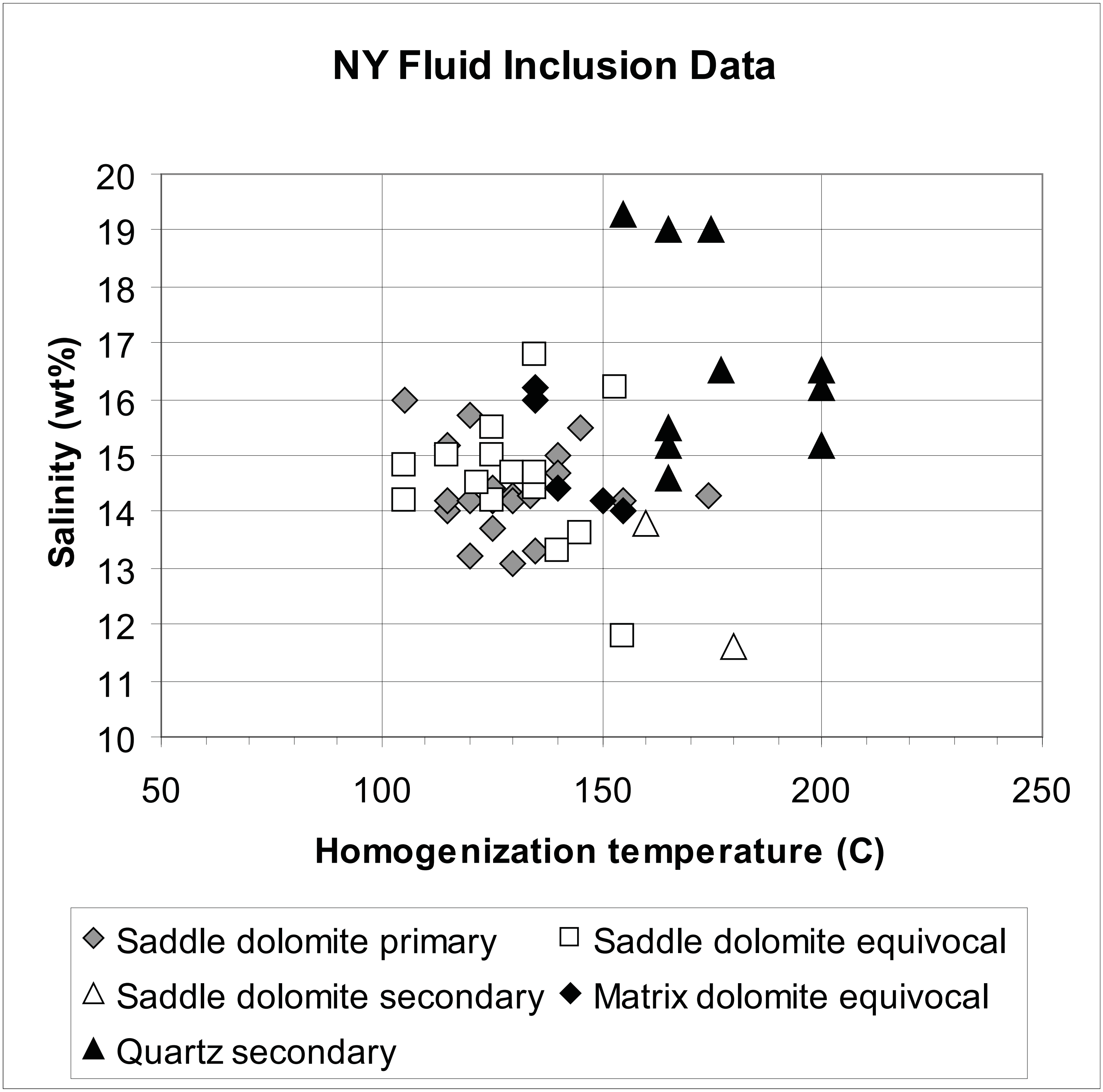


Figure 14. Fluid inclusion homogenization temperatures vs. salinity for samples from the Whiteman #1 and Gray #1 cores.

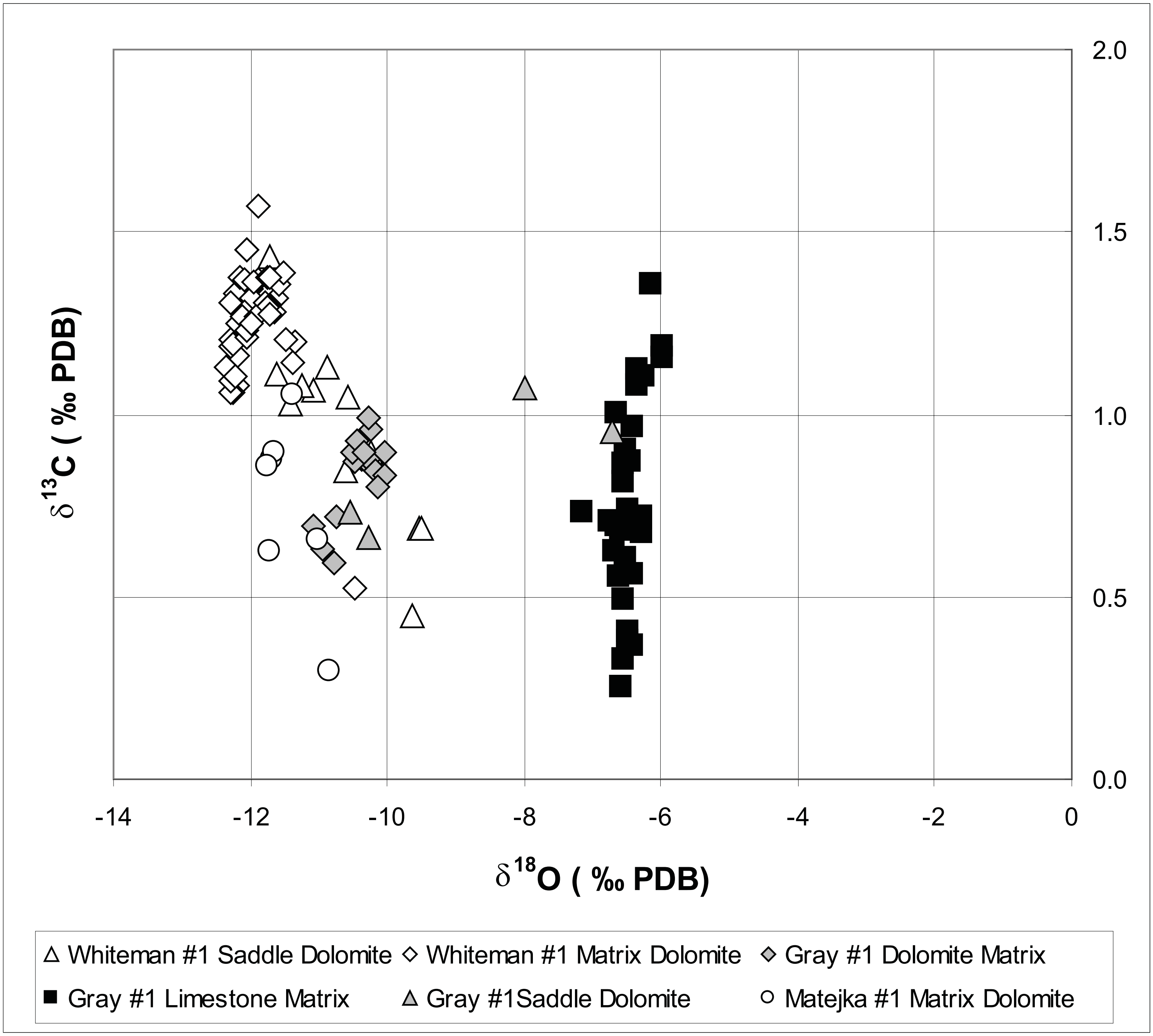


Figure 15. Stable isotope values for samples from the Whiteman #1, Gray #1 and Matejka #1 cores. Values reported versus PeeDee Belemnite standard (PDB).

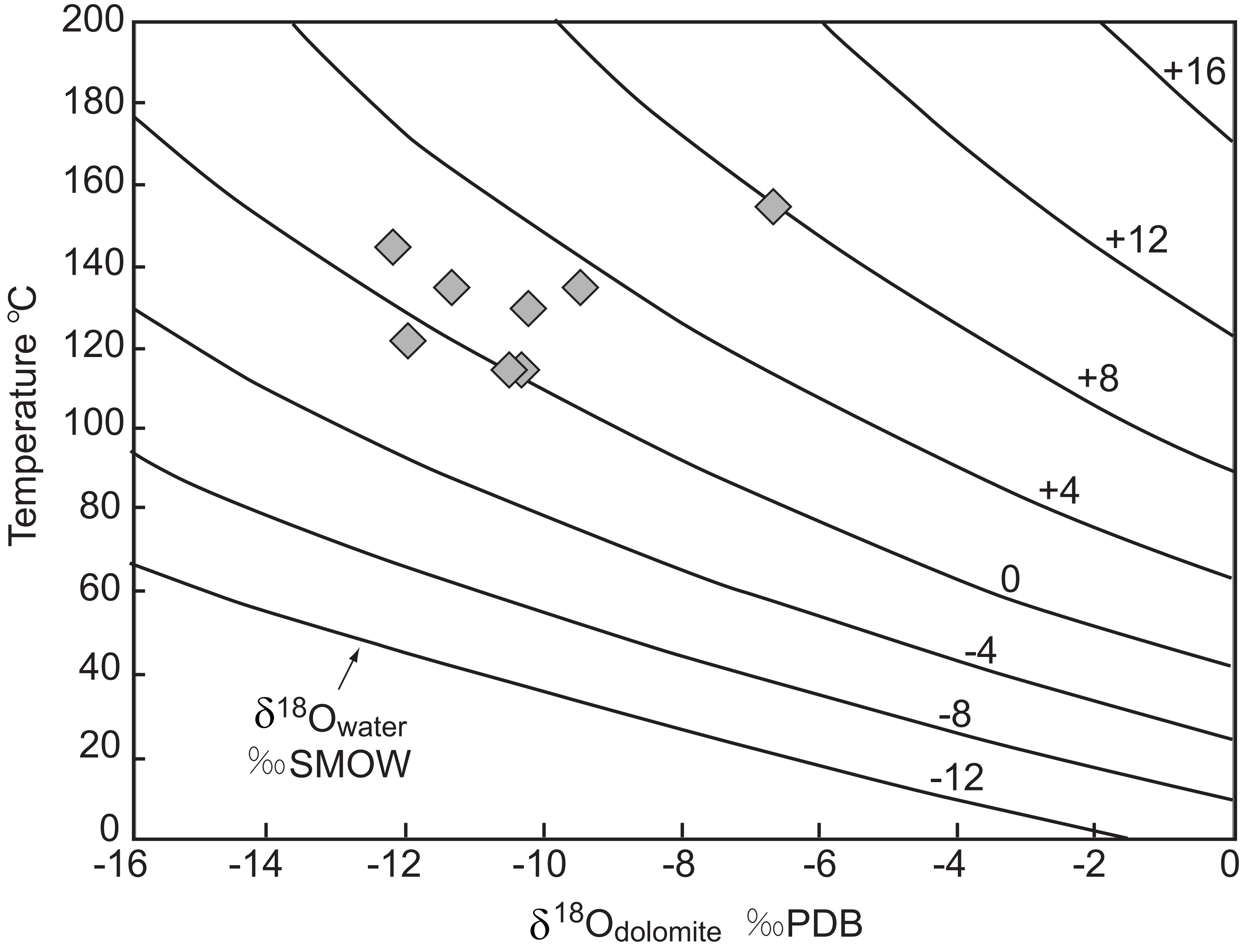


Figure 16. Average fluid inclusion homogenization temperature vs. δ18O for selected samples in Gray #1 and Whiteman #1 wells. Water values measured versus standard mean ocean water (SMOW).

positive) than the calculated composition of Late Ordovician seawater (around –6 ‰ based on limestone values). If one assumes that the fluid composition did not vary much from around +2 ‰, the temperature of formation can be estimated with some degree of precision using stable isotope values alone and the graph in Figure 16.

Trace Elements

The trace element data show that the Trenton-Black River dolomites are enriched in iron and manganese relative to the limestones (Figure 17). The iron content of the dolomites ranges from 1600 to 13,804 ppm and has a median value of ~4250 ppm. In contrast to the dolomites, the limestones from the same cores have a median value of ~550 ppm Fe. The dolomites are also enriched in manganese and have a median value of 880 ppm Mn while the median value for the limestones is only 52 ppm. The relatively high Mn and Fe values of the dolomites support a subsurface origin for the dolomites (*c.f.* Montanez, 1994).

Strontium Isotopes

Dolomites that formed from subsurface brines commonly (but not always) have $^{87}Sr/^{86}Sr$ ratios that are higher (more radiogenic) than seawater for the time that they formed (Allan and Wiggins, 1993). The range of $^{87}Sr/^{86}Sr$ ratios of seawater for Trenton and Black River time is between 0.7078 and 0.7085 (Burke et al., 1982). The strontium isotope values for the dolomites in the Black River range from 0.7085 and 0.7092 for both the matrix and saddle dolomites and are above the range for this time interval. While not strongly radiogenic (enriched in ^{87}Sr), the dolomites do plot above the range for seawater at the time of deposition, which suggests that the fluid that formed the dolomite passed through basement rocks or immature feldspar-rich siliciclastics prior to precipitating the dolomite.

Summary of Geochemistry

The geochemical and fluid inclusion data suggest that the dolomites formed from a hot (110-200°C), saline (3-6 times normal seawater), iron- and manganese-rich fluid that passed through basement rocks or immature siliciclastics prior to making the dolomite.

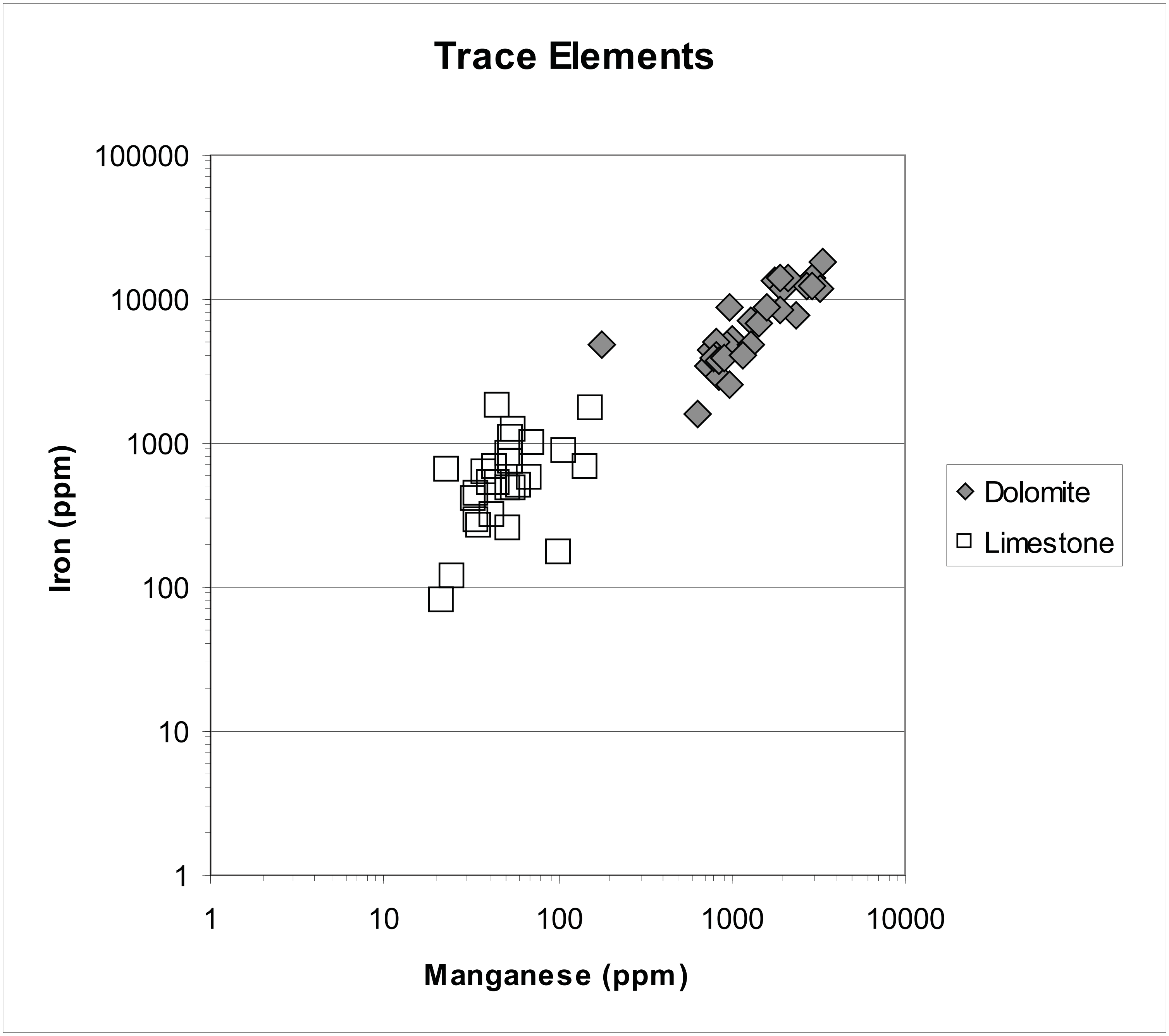


Figure 17. Trace element composition of limestones and dolomites in Gray #1 and Whiteman #1 wells. Dolomites strongly enriched in Mn and Fe relative to limestones.

Section 7
DISCUSSION

Hydrothermal diagenesis occurs when fluids are introduced to a given formation at a temperature that exceeds the ambient temperature of that formation (*sensu* White, 1957; Davies, 2004). By this definition, there is not a set temperature range at which hydrothermal alteration occurs, the water simply must be warmer than the ambient temperature of the formation due to the local geothermal gradient. For example, if a formation is buried to a depth where the ambient temperature is 50°C and a fluid is introduced that is 60°C, that fluid would here be called a hydrothermal fluid. In the absence of local igneous intrusions, the most likely way for a hydrothermal fluid to be introduced to a formation is via rapid upward fluid flow from greater depths through high-permeability faults and fractures (Deming, 1992). Lateral and vertical unfocused fluid flow through porous and permeable formations, in the absence of faults and fractures, is in most cases too slow to generate hydrothermal conditions because fluids equilibrate with the ambient temperature as they migrate through the formation (Deming, 1994).

Hydrothermal dolomitization is here thought to occur when relatively high-pressure, high-temperature Mg-rich fluids flow up active transtensional faults and into permeable formations that underlie sealing shales or other low permeability strata. Solubility of carbonates (and other minerals) is directly affected by changes in temperature, pressure, P_{CO2}, pH, and salinity and all of these are fluctuating on short time scales in fault-related hydrothermal systems (Rimstidt, 1997). Subsurface fluids flowing rapidly up faults and fractures can maintain most of their physical and chemical attributes until they are introduced to the formation and where they are then capable of producing significant diagenesis in short periods of time.

TIMING AND DEPTH OF BURIAL DURING ALTERATION

Hydrothermal fluid flow is thought to be most common while faults are active and much less common during periods of tectonic quiescence (Sibson, 1990, 2000; Davies, 2001; Knipe, 1993; Muir Wood, 1994; Davies and Smith, 2006). Therefore, the timing of hydrothermal alteration is closely linked to the timing of fault movement.

Most of the faults that have associated dolomitization in New York appear to have been active during Trenton and Utica time (during the Late Ordovician Taconic Orogeny) and largely inactive after that time (Smith et al., 2003a, 2003b). On seismic data, most dolomitized wrench faults in New York die out in the Trenton and Utica and sags are commonly filled in during Trenton or Utica time (Figure 8). This suggests that most of these faults were active during the Taconic Orogeny but were not reactivated during subsequent mountain building events. Some fractures and faults have multiple generations of cement lining them suggesting that they were filled episodically when the faults were moving, which ties mineralization to the time of fault movement.

Further support for significant Trenton and Utica-aged faulting comes from the Mohawk Valley to the northeast of the producing area where normal growth faults with up to 500 feet of throw were active during Trenton and Utica time (Bird and Dewey, 1970; Bradley and Kidd, 1991; Jacobi and Mitchell, 2002; Joy et al., 2000) and from seismites in the Trenton and Utica and equivalents in New York (Baird et al., 1992), Kentucky and Ohio (Pope et al., 1997; McLaughlin et al., 2002; Ettenshohn et al., 2002).

During Trenton and Utica time, when most of the faulting appears to have occurred, the Black River was buried to depths of less than 350 meters (1100 feet) in New York. Therefore, if hydrothermal alteration occurred during the period of active faulting, the Black River would have been relatively shallowly buried (less than 350 meters).

DEMONSTRATION OF A HYDROTHERMAL ORIGIN

As a first pass, if dolomitization is highly localized and patchy, the patchiness can be linked to faults, and the geochemistry and fluid inclusions support a high-temperature subsurface origin, then the mineralization is likely to be hydrothermal in origin. This is the case with the Black River dolomites in New York. The dolomite is patchy, only occurs near faults visible on seismic, and has geochemical attributes that suggest a hot, subsurface origin. This strongly suggests that fluids flowed up the faults and precipitated dolomite. The sags associated with the faults were filled in during Trenton and Utica time when the Black River was only buried to a depth of a few hundred meters. If fluid flow up faults is most likely to occur when the faults are active, as has been suggested by many who study this process (Knipe, 1993; Sibson, 2000; Muir Wood and King, 1993; many others), dolomitization of the Black River is likely to have occurred as a result of fault-related hydrothermal fluid flow during the first few hundred meters of burial.

The field relations between the faults and dolomitization and the hot subsurface origin of the dolomite strongly suggest a fault-controlled hydrothermal origin, but some academics require more rigorous proof (Machel and Lonee, 2002). The more strict way to demonstrate a hydrothermal origin for dolomite is to determine the burial and thermal history of the formation in question and compare that to the fluid inclusion homogenization temperatures in the dolomites (Davies, 2001; Machel and Lonee, 2002). If the homogenization temperatures exceed the maximum temperatures that the formation has ever been exposed to during burial, or the known depth at the time of dolomitization, the dolomite or other minerals can be called unequivocally hydrothermal. Furthermore, if the timing of dolomitization can be constrained through crosscutting relationships and the fluid inclusion homogenization temperatures exceed the maximum burial temperature at the known time of dolomitization, these dolomites can also be said to be unequivocally hydrothermal.

Weary et al. (2001) showed that the area where the dolomite fields are located in New York has seen very high burial depths and temperatures using conodont alteration indices (CAI) from the overlying Utica Shale. All of the cores are located in the area where the CAI values from the overlying Utica Shale were 4.5, which suggests that the Utica was heated to between 187-354°C (Hulver, 1997) or 150-300°C (Harris, 1979). Therefore, in this case, the Black River was buried to a depth where the temperature was equal to or greater than the fluid inclusion homogenization temperatures in the dolomites (Figure 18). This does not mean that the dolomites in New York are not hydrothermal in origin, just that the formation was, at some point in time, buried to a temperature that exceeded the temperature at which the dolomites formed. If the dolomitization occurred during early burial, when the ambient temperature was still <100°C (which it appears to have been based on the timing of fault movement) the dolomite would still be considered to be hydrothermal in origin.

Confirmation of hydrothermal origin for similar Trenton-Black River dolomites comes from Ontario, Michigan and northwest Ohio (Figure 18). In most respects, the dolomitized horizons look the same with matrix dolomitization, breccias, saddle dolomite, fractures and vugs, and the clear link to faults. At the Hillman Field in Ontario, fluid inclusion homogenization temperatures for the dolomites ranged from 100-220°C (Coniglio et al., 1994), but CAI analysis in that area suggests that the Trenton Group was never buried more than a kilometer in that area (Colquhoun, 1991). Using a geothermal gradient of 25-30°C/km and a surface temperature of 20°C, the maximum burial temperature was 45-50°C. The homogenization temperatures exceed the maximum ambient burial temperature by 50-170°C. A similar scenario occurs in Michigan where fluid inclusion homogenization temperatures from Trenton-Black River dolomites at the Albion Scipio Field exceed the maximum burial temperature by 40-90°C (using fluid inclusion data from Allan and Wiggins (1993) and CAI data from Repetski et al. (2004)). In Ohio, fluid inclusion homogenization temperatures exceed the maximum burial temperature by 50-110°C. Fluid inclusion homogenization temperatures from the Lima-Indiana Trend in NW Ohio for matrix and saddle dolomites range from 100-160°C, but the Trenton was never buried more than 800-1000 meters in this area (fluid inclusions analyzed for this report from core in Bowling Green Fault Trend and CAI data from Rowan et al., 2004). Therefore, the Trenton-Black River dolomites are unequivocally hydrothermal in Ohio, Michigan and Ontario.

The dolomites from the fields in Ohio, Michigan and Ontario are virtually identical to those found in New York in appearance, association with wrench faults, and geochemical attributes. It is unlikely that they would have formed by a different process.

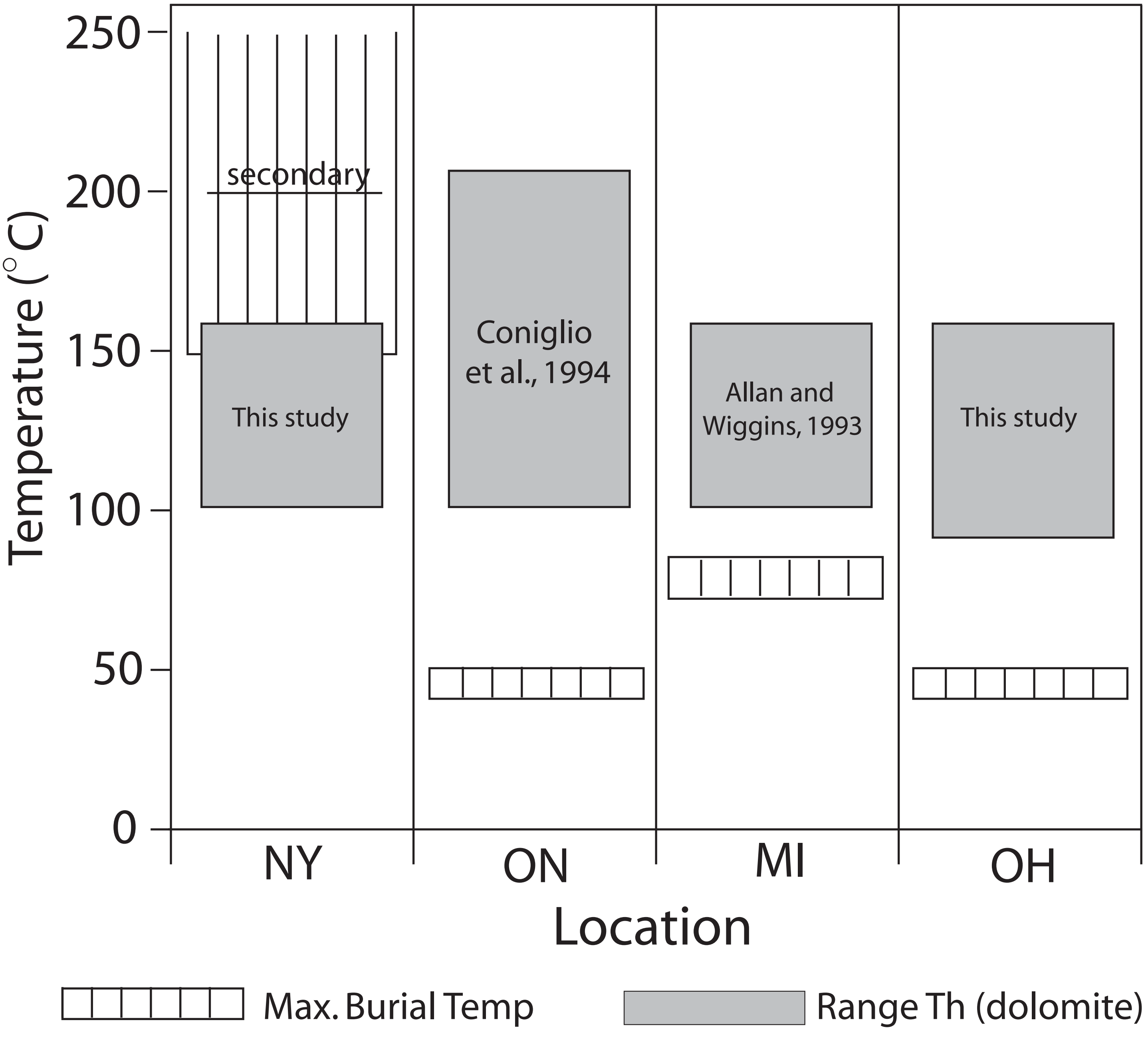


Figure 18. Fluid inclusion homogenization temperature vs. maximum burial depth. Ohio CAI data from Rowan et al., 2004. Ontario fluid inclusion data from Coniglio et al., 1994 and CAI data from Colquhoun, 1991. Michigan fluid inclusion data from Allan and Wiggins, 1993 and CAI data from Repetski et al., 2004.

ORIGIN OF SAGS

The structural sags associated with these features could form as a result of the combination of the development of negative flower structures, dissolution of limestone or dolomite, and/or the volume reduction associated with the dolomitization of limestone. Negative flower structures form in transtensional parts of strike-slip fault zones and can show an apparent volume loss because strata are displaced laterally as well as vertically (Dooley and McClay, 1997; many others). It has been convincingly demonstrated that many Trenton-Black River Fields form in structural sags associated with strike-slip faults and negative flower structures (Prouty, 1988; Hurley and Budros, 1990; Davies, 2001; others). This model can explain all of the sag development in the Trenton-Black River reservoirs.

The occurrence of vuggy porosity in most or all Trenton-Black River hydrothermal dolomite fields shows that there has been significant dissolution of limestone, dolomite or both during hydrothermal diagenesis. If the dissolved carbonate was carried away by fluids exiting the altered zone, or was precipitated in tight matrix dolomite and limestone outside of the sag, it is possible that some volume loss may have occurred due to dissolution. It is difficult to assess the amount of section that may have been dissolved, but this could certainly have played a role, particularly where breccias and cavernous porosity occur.

Mole-for mole replacement of limestone with dolomite results in a volume loss of 12-13% because dolomite molecules are smaller than calcite molecules (Weyl, 1960). This has been argued as a possible origin of porosity in dolomite (Weyl, 1960). The argument against this concept is that in an open system, fluids that are rich in magnesium are in many cases also rich in carbonate anions and rather than developing porosity or reducing the volume, more moles of dolomite will form than there were originally moles of calcite and the mineral volume will be retained or even increased (Halley and Schmoker, 1983; Sun, 1995). This process would have a minor impact on sag development, if any. In many wells, only 33 feet (10 meters) of section are dolomitized, but they still occur in sags visible on seismic. Assuming a volume loss of 13%, 10 meters of dolomite would be left after dolomitization of 11.3 meters of limestone, this minor volume loss (1.3 meters) would not be detectable on a seismic line.

There is no evidence that the Black River has collapsed into underlying caves in the Beekmantown as was suggested by Loucks (2003a, 2003b). This model is not supported by the seismic (Figure 8B) and can be discarded based on field relations in Ontario where the Beekmantown and equivalents are absent and the Black River Group directly overlies Cambrian siliciclastics which sit directly on the basement. If there is no Beekmantown, there can be no caves in the Beekmantown into which the overlying Black River might collapse. The sags, breccias and mineralization in the Trenton and Black River in Ontario are virtually identical to those in New York, Michigan and Ohio (Colquhoun, 1991; Coniglio et al., 1996; Bonnar, 2001). Furthermore, there is little or no offset on the top of the Beekmantown underlying many of the sags in the Black River play in New York (see Figure 8).

FAULT STYLE

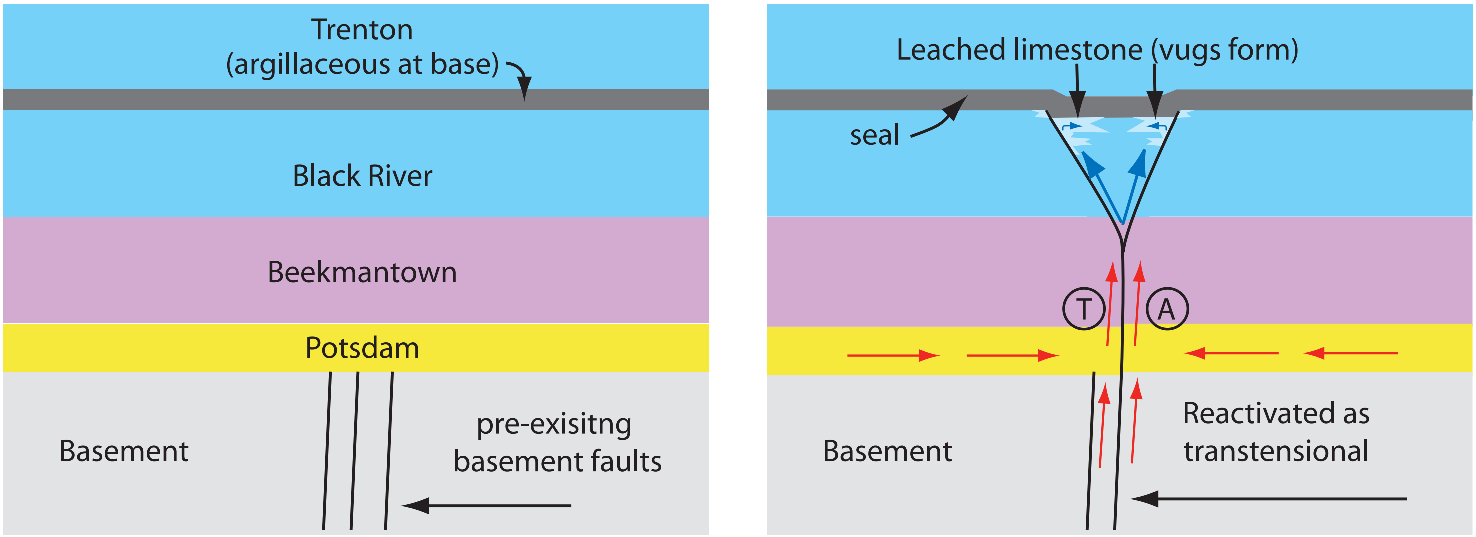
The *en echelon* sags in Figure 7 are interpreted to have formed as a result of oblique divergent slip (Smith and Nyahay, 2005) as initially proposed by Harding (1974) for similar *en echelon* sags at the Albion Scipio Field. The main component of fault movement is thought to be strike-slip, but with a very important extensional component. The individual sags are interpreted to be negative flower structures that formed over synthetic shear faults that tie back to a master transtensional fault at depth. The extensional component would tend to open the synthetic fractures and make them conduits for upward flowing hydrothermal fluids (Harding, 1974). This might occur at a dilational jog on a longer strike-slip fault or on a reactivated pre-existing fault that is slightly misaligned with respect to the principle compressive stress.

It appears that there are many variations on this theme in the Trenton Black River Play. There may be both right-lateral and left-lateral fault movement (Smith et al., 2003) on different faults and in different parts of the basin associated with the same tectonic event. The axes of *en echelon* grabens may occur at a range of angles to the overall trend from very low angle to as high as 15°(Smith and Nyahay, 2005). Fault intersections are common locations for sag development and hydrothermal alteration because they commonly set up zones of transtension and transpression. Many of the fields may occur where faults of differing orientation intersect and zones of transtension occur. The common thread between all of the successful wells in New York to date is that they have occurred within structural depressions that are likely to have been produced by transtensional faulting.

FAULT-RELATED HYDROTHERMAL ALTERATION MODEL

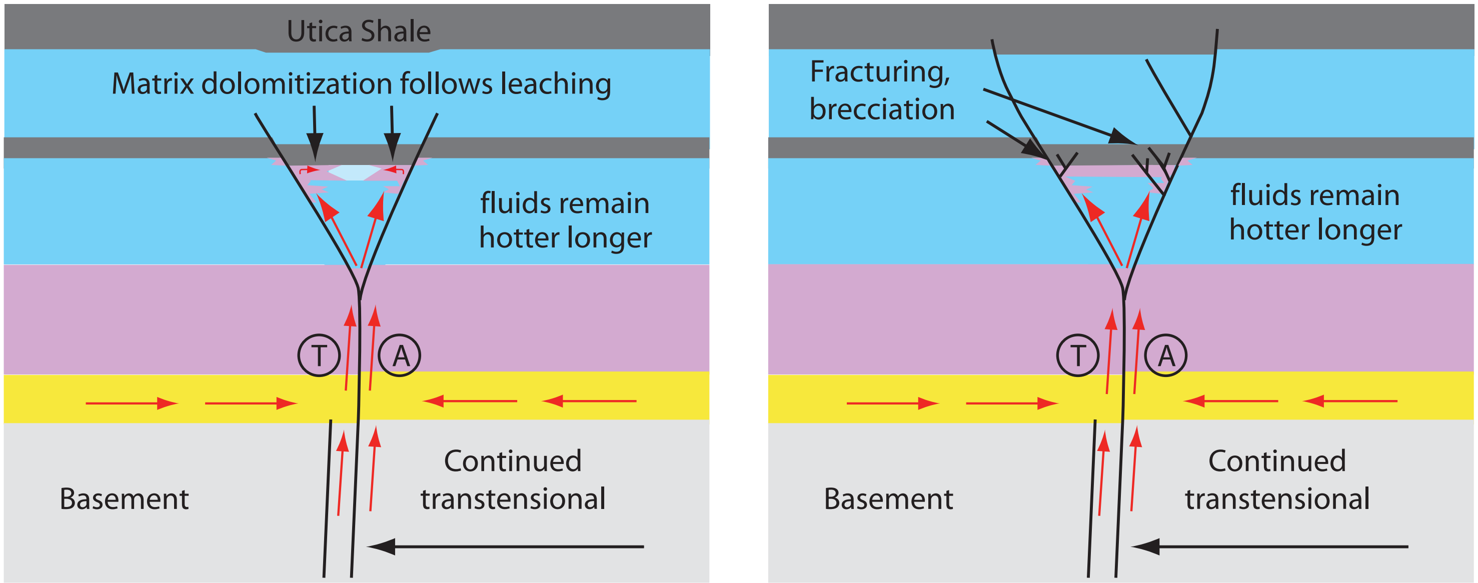
This model is speculative, but is supported by all of the known facts at this time (Figure 19). Black River Group carbonates were deposited on a relatively stable craton (Figure 19A). Major collision between North America and the Taconic Island Arc begins during earliest Trenton time and continues through the Late Ordovician and into the Silurian (Ettensohn and Brett, 2002). This collision leads to reactivation of appropriately oriented older faults or activation of new faults. Near the thrust front, thrust-loading leads to normal faulting oriented subparallel to orogenic belt (Bradley and Kidd, 1991). In the more distal parts of the craton, strike-slip faulting is initiated along appropriately oriented faults.

High-pressure, high-temperature fluids flowed up active basement-rooted strike-slip and transtensional faults (particularly in dilational parts of fault zones) hit low permeability beds at the base of the Trenton and flowed out laterally into the more permeable limestones of the Black River. Cooling hydrothermal fluids leached the limestone and produced vugs in a migrating front moving away from the fault zone



A) Trenton time

B) Onset of faulting (Trenton time), cooling fluids leach limestone



C) Faulting continues (Utica time); hotter fluids dolomitize leached matrix

D) Faulting continues (Utica, later?); Matrix fractured, vugs, breccias and fractures filled with saddle, etc.

Figure 19. Schematic fault-related hydrothermal alteration model for Black River Group dolomite reservoirs, New York.

(Figure 19B). As permeability was enhanced by fracturing and leaching, warmer dolomite-supersaturated fluids migrated farther from fault zone precipitating dolomite (Figure 19C). These fluids first produced a halo of matrix dolomite, particularly on the downthrown sides of faults in negative flower structures. Because the fluids flowed up from greater depths where pressures are higher, the elevated pressure of the fluids may have led to hydro-fracturing (*sensu* Phillips, 1972), enlargement of existing fractures and further brecciation. Some dissolution vugs may have formed prior to and during matrix dolomitization. Matrix dolomitization was followed by further fracturing, brecciation and vug development as tectonic activity continued (Figure 19D). Fractures and vugs were lined or filled with saddle dolomite soon after their formation. This later mineralization occurred during active fracturing as is demonstrated by episodic filling of fractures as they opened.

As time passed, fluids evolved and precipitated a range of other minerals including quartz, bitumen, sulfides and calcite. Bitumen may have formed when kerogen within the altered formation and near the faults was heated by the hydrothermal fluids and small quantities of oil formed that coated some pores and fractures ("forced maturation" of Davies, 2001). If the faulting was over by Late Ordovician or Early Silurian time (as it appears to be on many seismic lines), that would make most or all of the diagenesis Taconic (Late Ordovician-Early Silurian) in age. If the faulting continued or recurred during the Devonian Acadian or Pennsylvanian Alleghenian Orogenies some of the later stages of mineralization may have occurred during those times. Some calcite cementation may have occurred during later pressure solution of the adjacent limestones under normal burial conditions.

RESERVOIR HETEROGENEITY

All producing wells in the Black River produce from dolomitized intervals, but not all wells with dolomite are porous and/or productive. Some exploration wells are "geological" successes but economic failures because they find dolomite but no effective porosity or they flow water instead of gas. Out of 175 wells that have encountered dolomite in the Black River, only 48 have produced gas (27%). Understanding why some dolomite wells are tight and non-productive while others are porous and produce at higher rates is one of the main challenges in characterization of the Black River play. Some wells could be tight because they are too close to faults and were completely cemented, while others could be too far from faults and do not penetrate enough open faults and fractures. It is also possible that only a certain rock type ends up with matrix porosity after dolomitization and that this rock type is absent in the tight dolomite wells.

The Matejka #1 core (Figure 10) and the Gray #1 core (Figure 11) presented in this paper are both considered "tight" dolomite wells in that they have significant quantities of dolomite, but very low permeability. Most of the dolomite in these wells is matrix dolomite with little or no porosity. The Matejka well has tens of feet of dolomite but no vugs and few open fractures. The Gray #1 core (Figure

11) does have numerous open vugs, but they are isolated because there are few fractures and the matrix dolomite between them has little or no permeability. In many cases, bitumen, quartz or other minerals occur between the dolomite rhombs and may plug what would otherwise be effective porosity.

The Whiteman #1 core has high permeability in several beds that have vuggy and fracture porosity (Figure 11) and the well has been a good producer. This suggests that penetration of at least some open fractures may be essential to drilling a productive well in the Black River dolomite play in New York. The abundance of fractures and saddle dolomite suggest that the Whiteman core may be closer to a fault than the Matejka #1 and Gray #1 wells.

The cores studied for this paper suggest that penetrating open faults, fractures, and breccias and vugs connected by fractures may be the key to drilling a successful well in this play. Most of the early wells in the trend were vertical wells that were commonly sidetracked once or twice after encountering tight dolomite or limestone. The probability of success on a vertical development well was about 35% (Bob Bonnar, Talisman Energy, pers. comm). This may be because the wells were less likely to penetrate faults and fractures. More recently, a series of horizontal wells have been drilled that have a more consistent level of success (about 60%) along with much higher initial production rates and greater cumulative production (Bob Bonnar, pers. comm.). Because horizontal wells cut across the fault and fracture zones and penetrate the formation at a range of distances from the faults, they have a much higher probability of success. It may also be the case that some successful producers have good matrix porosity, but that no cores have been acquired from these wells. Further research is required in order to fully understand all potential sources of heterogeneity.

EXPLORATION MODEL

Hydrothermal dolomite (and leached limestone) reservoirs represent one of the most significant remaining resources in North America and other mature regions of the world. These reservoirs are likely to have been bypassed in many cases because of their common occurrence in structural lows, which are unlikely to have been drilled during earlier exploration phases. The exploration model for Trenton and Black River hydrothermal dolomite reservoirs is to look for subtle basement-rooted wrench faults and negative flower structures that cut the regional limestone with evidence for movement in the first kilometer of burial. Faults with relatively minor offset that do not extend far above the target formation are typically the best candidates because the faults have not breached the seal for the hydrothermal fluids or the hydrocarbons.

Most documented hydrothermal dolomite reservoirs occur in regional limestones, but that does not mean that hydrothermal alteration is restricted to this scenario. The effects of the hydrothermal alteration may be less obvious where entire formations are dolomitized regionally, but saddle dolomite cemented breccias, fractures and vugs, and sulfide ore deposits are very common in regional dolomites and in most cases are probably fault-related hydrothermal in origin (Smith, 2004a). Hydrothermal leached limestone reservoirs may be as common or more common than hydrothermal dolomite. Although leached limestone is not a common component of the Trenton-Black River Play, it does occur in many other settings and similar exploration strategies may lead to success in leached limestone plays as well (Davies and Smith, 2006; Wierzbicki et al, 2006).

Section 8
CONCLUSIONS

1. Newly discovered natural gas reservoirs in the Black River Group carbonates of New York occur in laterally discontinuous, linear, fractured, vuggy dolomite bodies that occur in structural lows associated with wrench faults.
2. Both matrix and saddle dolomite formed from hot (110-170°C), saline (14.5 wt.%), Fe- and Mn-rich brines with radiogenic strontium isotope values. All of these support a subsurface origin for the dolomitizing fluids.
3. In Ohio and Michigan, fluid inclusions from similar fault-related dolomitized bodies in the Trenton and Black River have homogenization temperatures that exceed the maximum ambient burial temperature by 40-120°C. That makes the dolomite there unequivocally hydrothermal in origin. In New York, the Black River was buried to a temperature equal to or greater than the homogenization temperatures in the dolomites so the origin of the dolomite is equivocal in that sense. However, the New York dolomites are similar in their appearance, geochemical attributes, and association with wrench faulting to those in Ohio and Michigan. They are here interpreted to have formed in the same way and at roughly the same time.
4. The dolomite, vugs, breccias and fractures are interpreted to have formed when high-pressure high-temperature fluids flowed up dilational portions of active strike-slip faults, hit sealing units at the base of the Trenton and flowed laterally, altering the formation. Vugs formed when limestone was leached by a front of cooling hydrothermal fluids and dolomitization and other mineralization followed soon after. Alteration is thought to have occurred during the Late Ordovician Taconic Orogeny when the formation was buried to a depth of less than 350 meters.
5. Because these reservoirs occur in structural lows, they have been bypassed for many years. More of these reservoirs (and associated leached limestone reservoirs) can and will be found in the Trenton and Black River Groups and in carbonates around the world using the appropriate integrated structural-stratigraphic diagenetic model.

REFERNCES

Allan, J. R. and W. D. Wiggins, 1993, Dolomite reservoirs: Geochemical techniques for evaluating origin and distribution, AAPG Continuing Education Course Notes No. 36, 129p.

Baird, G.C., Brett, C.E., and D. Lehmann, 1992, The Trenton - Utica Problem Revisited: new Observations and Ideas Regarding Middle - Late Ordovician Stratigraphy and Depositional Environments in Central New York: New York State Geological Association Guidebook, p.1-40.

Bird, J. M., and J. F. Dewey, 1970, Lithosphere Plate-Continental Margin Tectonics and the Evolution of the Appalachian Orogeny. Geological Society of America Bulletin, 81:1031-1060

Bonnar, B., 2001, Talisman Energy Inc. and the Ontario Oil Patch: Does the Shoe Fit? *in:* Ontario Petroleum Institute (OPI) 2001 Annual Meeting Program.

Bradley, D.C., and Kidd, W.S.F., 1991, Flexural Extension of the Upper Continental Crust in Collisional Foredeeps: Geological Society of America Bulletin, v.103, p. 1416–1438.

Brett C. E., and G. C. Baird, 2002, Revised stratigraphy of the Trenton Group in the type area, central New York State: sedimentology, and tectonics of a Middle Ordovician shelf-to-basin succession, p. 231-263. *in:* C. E . Mitchell and R. Jacobi (eds.), Taconic Convergence: Orogen, Foreland Basin and Craton. Physics and Chemistry of the Earth, v. 27.

Burke K., and J. F. Dewey, 1973, Plume-generated triple junctions: key indicators of applying plate tectonics to old rocks: Journal of Geology, v. 81, p. 406-433.

Burke, W. H., Denison, R. E., Hetherington, E. A., Koepnick, R. B., Nelson, H. F. and J. B. Otto, 1982, Variation of seawater ^{87}Sr/^{86}Sr throughout Phanerozoic time *in:* Geology, v. 10, p. 516-519.

Colquhoun, I.M., 1991, Paragenetic history of the Ordovician Trenton Group carbonates, Southwestern Ontario [unpublished M.S. thesis], Brock University, St. Catherines, Ontario, 250p.

Coniglio, M., Sherlock, R., Williams-Jones, A.E. Middleton, K. and S.K. Frape, 1994, Burial and hydrothermal diagenesis of Ordovician carbonates from the Michigan Basin, Ontario, Canada in B. Purser, M.Tucker and D. Zenger (eds.), Dolomites, International Association of Sedimentologists Special Publication 21, p. 231-254.

Cornell, S. R. 2001. Sequence Stratigraphy and Event Correlations of upper Black River and lower Trenton Group Carbonates of northern New York State and southern Ontario, Canada, unpublished M.S. Thesis, University of Cincinnati, Cincinnati, Ohio.

Cornell, S. R., and C. E. Brett. 2000. K-Bentonite and sequence correlations of Upper Black River and lower Trenton Limestones from Lake Simcoe, southern Ontario Canada to Watertown, northern New York State. American Association for Petroleum Geologists Bulletin, vol. 84(9):1381.

Davies, G.R., 2001, Hydrothermal (thermobaric) dolomite reservoir facies: Global and western Canadian perspectives, unpublished report, Graham Davies Geological Consultants Ltd, Calgary, 548p.

Davies, G.R., 2004, Hydrothermal (thermobaric) dolomite and leached limestone reservoirs: general principles, genetic connections and economic significance in Canada. American Association of Petroleum Geologists, Annual Convention, Dallas, Abstracts Vol., p. A32.

Davies, G.R. and Smith, Jr., L.B., 2006, Structurally controlled hydrothermal dolomtie reservoir facies: an overview in: AAPG Bulletin, v.90, no.11, p.1641-1690

Deming, D., 1992, Catastrophic release of heat and fluid flow in the continental crust, Geology, v. 20, p. 83-86.

Dooley, T. and K. McClay, 1997, Analog modeling of pull-apart basins, AAPG Bulletin, v. 81, p. 1804-1826.

Ettensohn, F.R., Kulp, M.A., and Rast, N., 2002, Interpreting ancient marine seismites and apparent epicentral areas for paleo-earthquakes, Middle Ordovician Lexington Limestone, central Kentucky, in Ettensohn, F.R., Rast, N., and Brett, C.E., eds., Ancient seismites: Geological Society of America Special Paper 359, p. 177-190.

Ettensohn, F.R., and Brett, C.E., 2002, Stratigraphic evidence for continuation of Taconian Orogeny into Early Silurian time: in Mitchell, C.E., and Jacobi, R., eds., Taconic convergence: Orogen, foreland basin, and craton: Physics and Chemistry of the Earth, v. 27, p. 279-288.

Gregg, J.M. and D.F Sibley, 1984, Epigenetic dolomitization and the origin of xenotopic dolomite texture, Journal of Sedimentary Petrology, v. 54, p.908-931.

Gonzalez, L.A., Carpenter, S.J. and K.C. Lohmann, 1992, Inorganic calcite morphology: the role of fluid chemistry and fluid flow, Journal of Sedimentary Petrology, v. 62, p. 382-399.

Harding, T.P., 1974, Petroleum traps associated with wrench faults in: AAPG Bulletin, v. 58, p.1290-1304.

Horvath, E., Davies, L. and M. Molgat, 2004, Example of a Trenton-Black River reservoir: a case study of the Rochester Pools, Ontario [abstract], Ontario Petroleum Institute Annual Meeting Program with abstracts.

Hulver, M. L., 1997, Post-orogenic evolution of the Appalachian Basin Mountain system and its foreland [unpublished Ph.D. thesis], University of Chicago, 917p.

Hurley, N.F. and R. Budros, 1990;Albion-Scipio and Stoney Point Fields-USA Michigan Basin in: E.A. Beaumont and N.H. Foster (eds.), Stratigraphic Traps I, Treatise of Petroleum Geology, Atlas of Oil and Gas Fields, A.A.P.G., p. 1-37.

Jacobi, R. D., and Mitchell, C. E., 2002, Geodynamical interpretation of a major unconformity in the Taconic Foredeep: slide scar or onlap unconformity?, Physics and Chemistry of the Earth, v. 27, p. 169-201.

Joy, M.P., Mitchell, C.E., and Adhya, S., 2000, Evidence of a tectonically driven sequence succession in the Middle Ordovician Taconic Foredeep *in:* Geology, v. 28, p. 727-730.

Knipe, R.J., The influence of fault zone processes and diagenesis on fluid flow in: Horbury, A.D., and A.G. Robinson, eds., Diagenesis and basin development, AAPG Studies in Geology #26, p. 131-156.

Landing, E. Westrop, S.R., and Knox, L.A., 1996, Conodonts, stratigraphy and relative sea-level changes of the Tribes Hill Formation (Lower Ordovician, east-central New York) *in*: Journal of Paleontology, v. 70, p. 656-680.

Lavoie, D., 1994. Diachronic collapse of the Ordovician continental margin, eastern Canada: comparison between the Québec Reentrant and the St. Lawrence Promontory. Canadian Journal of Earth Sciences, 31: 1309-1319.

Loucks, R.G., 2003a, Origin of Lower Ordovician Ellenburger Group Brecciated and Fractured Reservoirs in West Texas: paleocave, thermobaric, tectonic or all of the above? [abstract]: AAPG National Meeting Program with Abstracts.

Loucks, R. G., 2003b, Understanding the development of breccias and fractures in Ordovician carbonate reservoirs, in Hunt, T. J., and Lufholm, P. H., The Permian Basin: back to basics: West Texas Geological Society Fall Symposium: West Texas Geological Society Publication #03-112, p. 231–252.

Loucks, R. G., 1999, Paleocave carbonate reservoirs: origins, burial-depth modifications, spatial complexity, and reservoir implications: American Association of Petroleum Geologists Bulletin, v. 83, p. 1795–1834.

Lucia, F.J., 1995, Rock-Fabric/Petrophysical Classification of Carbonate Pore Space for Reservoir Characterization: Bulletin of the American Association of Petroleum Geologists, v. 79, p. 1275-1300.

Machel, H. G., and J. Lonee, 2002, Hydrothermal dolomite- a product of poor definition and imagination, Sedimentary Geology, v. 152, p. 163-171.

Machel, H.G., 2004, Concepts and models of dolomitization: a critical reappraisal in: Braithwaite, C. J. R.,Rizzi, G. and Darke, G., eds., The Geometry and Petrogenesis of Dolomite Hydrocarbon Reservoirs. Geological Society, London, Special Publications, no. 235, p. 7–63.

McLaughlin, P.I., Brett, C.E., 2002. Upper Ordovician seismites of Kentucky: a sedimentological and sequence stratigraphic approach, Abstracts with Programs - Geological Society of America v.36, p. 102.

Moore, J.M., 1986, Introduction: the 'Grenville Problem' Then and Now in: Moore, J. M., Davidson, A., and A.J. Baer, eds., The Grenville Province, Geological association of Canada Special Paper 31, p. 1-12.

Nyahay, R. E., and L. B. Smith, 2003, Vertical and Lateral Distribution of Hydrothermal Dolomite in Trenton-Black River carbonates of New York [abstract], AAPG Eastern Section Program with abstracts

Pope, M.C., Read, J.F., Bambach, R.K., Hofmann, H.J., 1997. Late Middle to Late Ordovician seismites of Kentucky, southwest Ohio and Virginia: sedimentary recorders of earthquakes in the Appalachian basin. Geological Society of America Bulletin v. 109, p. 489– 503.

Prouty, C.E., 1988, Trenton exploration and wrenching tectonics in Michigan Basin and environs in B.D. Keith, (ed.), The Trenton Group (Upper Ordovician Series) of eastern North America, A.A.P.G. Studies in Geology 29, p.207-236.

Repetski, J. E., Ruppert, L. F., Ryder, R. T., Weary, D. J., Rowan, E. L. and Trippi, M. H., 2004, Thermal Maturity Patterns for Ordovician, Devonian, and Pennsylvanian Rocks of the Central Appalachian Basin, Based on CAI and Vitrinite Reflectance (%Ro)[abstract], AAPG Eastern Section Meeting Program with abstracts.

Rickard, L.V., 1973, Stratigraphy and Structure of the Subsurface Cambrian and Ordovician Carbonates of New York: New York State Museum Map & Chart No. 18, 77p.

Rowan, E. L., Ryder, R. T., Swezey, C. S., Repetski, J. E., Crangle, R. D., Trippi, M. H. and L. F. Ruppert., 2004, Burial and Thermal History Model of a Cross-Section through the Central Appalachian Basin, Ohio and West Virginia [abstract], AAPG Program with Abstracts

Rimstidt, J.D., 1997, Gangue mineral transport and deposition *in:* H.L. Barnes, ed., Geochemistry of Hydrothermal Ore Deposits, John Wiley and Sons, New York, p. 487-516.

Sibson, R.H., 1990, Faulting and fluid flow *in:* B.E. Nesbitt, ed., Fluids in tectonically active regimes of the continental crust, Mineralogical Association of Canada, Short Course Handbook, v. 18, p. 93-132.

Sibson, R.H., 2000, Fluid movement in normal faulting, Journal of Geodynamics, v. 29, p. 469-499.

Smith, L.B. and R.E. Nyahay, 2005, Wrench fault architecture of Trenton Black River Hydrothermal Dolomite Reservoirs, in AAPG Eastern Section Meeting Program with Abstracts

Smith, L.B., 2004a, Hydrothermal Alteration of Carbonate Reservoirs: How Common is it? *in:* AAPG National Meeting Program with Abstracts, p. A130.

Smith, L.B. Nyahay, R.E. and B. Slater, 2004b, Outcrop Analogs for Hydrothermal Dolomite Reservoirs, Mohawk Valley, New York, *in* Program with Abstracts, AAPG Eastern Section Meeting

Smith, L. B., Lugert, C. M., and R . E. Nyahay, 2003a, Integrated Characterization of Hydrothermal Dolomite Reservoirs in Trenton-Black River Carbonates of New York (abstract): AAPG National Meeting Program with Abstracts.

Smith L.B. and R.E. Nyahay, 2003b, Trenton-Black River Hydrothermal Dolomite Reservoirs: An Integrated Structural Stratigraphic Diagenetic Play in AAPG Eastern Section Program with Abstracts

Taylor, T.R. and D. F. Sibley, 1986, Petrographic and geochemical characteristics of dolomite types and the origin of ferroan dolomite in the Trenton Formation, Ordovician, Michigan Basin, Sedimentology, v. 33, p. 61-86.

Thomas, W. A., 1991, The Appalachian-Ouachita rifted margin of southeastern North America, Geological Society of America Bulletin, v. 103 p. 415-431.

Van Staal, C.R., 2005. The Northern Appalachians. In: Encyclopedia of Geology. R.C. Selley, L. Robin, M. Cocks and I.R. Plimer (Editors). Elsevier, Oxford, Vol. 4: 81-91.

Weyl, P.K.1960, Porosity through dolomitization: conservation of mass requirements: Journal of Sedimentary Petrology, v. 30, p.85-90.

Weary, D. J., Ryder, R. T., and R. E. Nyahay, 2001, Thermal maturity patterns in New York State using CAI and %R_O, Northeastern Geology and Environmental Science, v. 23, p. 356-376.

White, D. E., Thermal waters of volcanic origin, Geological Society of America Bulletin, v. 68, p. 1637-1658.

Wickstrom, L.H., Gray, J.D., and R. D. Stieglitz, 1992, Stratigraphy, structure, and production history of the Trenton Limestone (Ordovician) and adjacent strata in northwestern Ohio, Ohio Geological Survey Report of Investigation 143, 78 p.

Wierzbicki, R., Dravis, J.J., Al Aasm, I. And N. Harland, in review, Dolomitization and porosity evolution of Upper Jurassic Abenaki platform carbonates, Deep Panuke Reservoir, Nova Scotia: Hydrothermal or Deep Burial diagenetic processes or both?, submitted to AAPG Bulletin

Appendix
FIELD STUDIES

LOCATION AND PRODUCTION HISTORY

This summary focuses on more recent hydrothermal dolomite discoveries in New York. The first discovery in New York was inadvertent. A well drilled in 1982 as a geothermal test in the town of Auburn in Cayuga County found gas in what is now known to be a hydrothermal dolomite zone in the uppermost Black River. This well is still producing today. The first intentional discovery was in 1985 in laterally discontinuous dolomite in the Black River Group in the Glodes Corners Road Field of south-central New York. Since then, at least twenty-five new fields have been discovered in laterally discontinuous dolomites of the Trenton-Black River. Most of the fields are between 7000 and 10,000 feet deep. Several wells have produced at sustained rates of >10MMcf/d, and the most prolific producer (Reed #1 in Quackenbush Hill Field) made 35MMcf/d for several months. As of the end of 2004, the well with the best cumulative production had produced more than 15 Bcf and is still flowing at a high rate. Overall, the trend in New York has produced 45.7 Bcf as of the end of 2004.

Things to consider as the fields are reviewed are: Where does the porous dolomite occur in each field? What makes more sense in this field, vertical or horizontal wells? Our belief is that in New York, horizontal wells make sense in most cases because if a well is going to be a good producer it almost always has porosity in the upper 40-50 feet of the Black River. Thus, this interval is a target zone for horizontal wells. Horizontal wells help reduce the chance of hitting a tight dolomite or limestone zone within a productive feature.

In the York Field in Ohio, however, porosity occurs in many different zones. It would be very difficult to choose an interval in which one would drill horizontally. Vertical wells almost certainly would be better in this setting. Exploration wells drilled in areas outside known dolomite intervals should probably be drilled vertically or on a slanted well path. It may be that in different areas, other stratigraphic intervals are more likely to be dolomitized and once they are identified, horizontal drilling may again be preferable.

DESCRIPTION OF KEY FIELDS

This appendix includes brief descriptions of each field along with a cross section of the wells in each field. The cross-sections used in the figures were generated using data imported into Petra software by Geoplus from New York's ESOGIS database. These included formation tops and .las files. On the cross sections, dolomite is picked using PEF, density and neutron logs. Any strata in the Trenton or Black River that are not picked as dolomite are either composed of limestone, argillaceous limestone or bentonite. The PEF curve typically reads between 3 and 3.5 in dolomitized intervals whereas it reads 4.5 or 5 in limestones. Dolomite (2.86 g/cc) is denser than limestone (2.71 g/cc). When logs are plotted using a limestone density of 2.71 g/cc = 0% neutron porosity, the density log will plot to the right of the neutron log in dolomitized intervals and plot on top of the neutron in limestone intervals. This should be true in both porous and tight dolomitized intervals. Sometimes in very vuggy, high-porosity zones, it is hard to tell if the density plots to the right of the neutron, but if a zone has very high porosity in the Black River it is almost certainly dolomitized.

The figures include mostly vertical wells. Whenever possible, directional wells have been presented in a TVD format so that it doesn't look like the section is thickened. Where fields are mostly developed by horizontal wells, such as Quackenbush Hill Field, it is difficult to make a meaningful cross section. We plan to make map view cross sections of these fields eventually, but were not able to prepare them for this study. We have only included wells that are publicly available as of April 2006. Some of these fields almost certainly have or will have more wells drilled in them over time.

Auburn Geothermal Field (Figure A1)

Discovered in 1982, this is a one-well field that has produced behind pipe for more than twenty years. Thin sections made from well cuttings confirm that the productive interval is dolomitized and that there is at least a component of saddle dolomite. The dolomite interval occurs at the top of the Black River Group at depths of 4150 to 4176 feet. As of 2004, the well had officially produced 42 MMcf, but that only includes production since 1994. It is thought that the well has produced more than 200 MMcf since it was first placed on line. The older log suite confirms the dolomite interval. The density log reads higher than 2.71 and the neutron log registers porosity values between 2% and 9% through the twenty six foot interval. This is the northern-most producing field. The occurrence of gas this far north suggests that there may be many other productive fields between the main producing area and this field.

Ballyhack Creek (Figure A2)

Discovered in 2002, this is a three-well field with only one well, the Beagell #2, producing from dolomitized Black River. The well has produced 340 MMcf as of 2004. Well 23078-02 only made it to the Trenton and well 23056-01 is similar to the producing well with the exception of porosities being less than 3%. The producing well is a directional well whose bottom location is to the SSE of its surface location. Surface trend of the three wells are NE – SW. The dolomitized units correlate from well-to-well suggesting that a horizontal approach may work in this area. This is the easternmost producing field, again suggesting that there may be potential between this field and the main producing area.

Beans Station (Figure A3)

Discovered in 2002, this is a one-well field. The Gray # 1 well was cored and results of analysis of that core are included in this report. The original well tested a small amount of gas but was never hooked up. It has recently been sidetracked with promising results. This is a directional well whose bottom hole position is WSW of the surface location.

Caton (Figure A4)

Discovered in 2002, this is a one-well field that produced 33 MMcf as of 2004. At this time we have no logs for the producing deviated sidetrack. In the vertical well the Black River interval is all dolomite, with a strange log response. The PEF is around 2.5 which is low for dolomite and the density jumps around significantly. The neutron log shows very little porosity. There may be a significant component of chert in this well. Quartz has a PEF response of ~2.5 and the density would be lower in a silica-rich well.

Cooper Hill (Figure A5)

Discovered in 2005, this is a one-well field. It is a directional well whose bottom hole position is NW of the surface location. The field had produced no gas as of the end of 2004. The dolomite section begins approximately 60 feet below the top of the Black River interval and is 61 feet thick with porosity up to 12%.

County Line (Figure A6)

Discovered in 2000, this field has three producing wells. The trend of the field is ENE-WSW and it produced 1.34 BCF as of the end of 2004. Three of the wells are almost completely dolomitized. The best producer through the end of 2004 was the Whiteman well which was cored and studied for this report. The Whiteman #1 well was deepened and no logs are available for the deeper interval. The Youmans well has the same problem that was encountered in the vertical well at Caton Field with a neutron log showing no porosity and a density log that is highly variable. This field has a lot of tight dolomite relative to the Wilson Hollow and Quackenbush Hill Fields to the south.

Cutler Creek (Figure A7)

Discovered in 2002, this is a two-well field with a deviated well and a horizontal well. The field has produced 3.5 Bcf as of the end of 2004. The Corning Game Club well is a deviated well that has produced over 3 Bcf to date. The bottom-hole location is SSW of the surface location. The Moss well, 23100-00, is a more recent horizontal well that trends to the northeast away from the Corning Game Club well towards

Quackenbush Hill. It went through 650 feet of limestone, then through several wide dolomitized zones and then back into limestone prior to reaching Quackenbush Hill.

Glodes Corner Road (Figure A8)

Discovered in 1985 by Columbia Natural Resources, this is the first field to be drilled in the hydrothermal dolomite play in a sag feature in New York. Currently, there are 12 producing wells, of which three are directional wells. The field has produced 7.5 Bcf of gas as of the end of 2004 and was probably overdrilled. Most of the wells do not go deeper than the top few feet of the Black River. The better producing wells have dolomite sections that are relatively thin, but have porosities between 5% and 12%. The best producing well, the Fox #1, 21706-00, has no log coverage. We have correlated several bentonite zones on this cross section which can most likely be correlated to many of the other wells in the area.

Guyanoga Valley (Figure A9)

Discovered in 1999, this field consists of one producing directional well. This well produced 330 MMcf of gas through the end of 2004. The producing interval has a relatively thin dolomite section at the top of the Black River Group in which porosity does not exceed 8%.

Langdon Hill (Figure A10)

Discovered in 2000, this field consists of three wells that produced significant amounts of gas through the end of 2004. This may have been the discovery field for the Black River hydrothermal dolomite play, but the Matejka #1 well that was drilled by Shell in 1974 either did not produce economic quantities of gas or the company was looking for oil at that time. The field has produced 2.1 Bcf as of the end of 2004. Not included on this cross section is the Konstantinides #1 horizontal well which has made 0.6 Bcf through the end of 2004.

Moreland Field

Discovered in 2003, this is a one-well field. The lone producing well is a directional well. No logs or directional surveys are available. The field has not produced to date.

Muck Farm (Figure A11)

Discovered in 1998, this field consists of five wells. Four have produced and one was not completed. Wells in the field have an average completion interval of only twenty seven feet of dolomite. The field is located just south of the Glodes Corners Road field and east of the Bean Station field. The Snyder #1 well, located at the north end of the field, is the highest producer with a dolomite section that is only 8 feet thick but has a porosity spike of 15%. The field has produced 7.25 Bcf as of the end of 2004, a volume comparable to the amount of gas produced from 12 wells in Glodes Corners Road field to the north.

Pine Hill (Figure A12)

Discovered in 1999, this field consists of four wells. The field has produced 401 MMcf as of the end of 2004. Production is at the low end of the scale as compared to other fields that have more than one producing well. This is the only field that trends NW-SE. The best producing well consists of dolomite developed at the top of the Black River and not near the bottom. There is one producing well that only has dolomite near the base of the Black River, but it has only produced 40 MMcf. All other wells that produce in this trend have porous dolomite at or near the top of the Black River.

Quackenbush Hill (Figures A13 and A14)

Discovered in 2000, this field has ten producing wells. The cross section is obviously very difficult to correlate because of the large number of deviated and horizontal wells. This field has produced 43 Bcf as of the end of 2004 and is the largest producing field in the trend. This field has the best producing well in the trend, the Lovell #1, a vertical well that produced over 15 Bcf in four years through the end of 2004. There are several long horizontal wells in this field (Figure A14). The Reed #1 well was the biggest onshore gas well in the U.S. in 2004. It has a 1650 foot lateral section, mostly in porous dolomite. The Hakes well, 23054-00 encountered 800 feet of limestone at the top of the Black River before cutting into porous dolomite zones. This well was drilled in a NNE direction and it looks like the limestone occurs within the middle of the field. The Andrews well, 230320-00, has a long section of porous dolomite with very little limestone. The Henkel well, 22871-00, has a thinner dolomite section with porosities ranging from 10% to 30% (Figure A13). This field contains more directional wells than any other Black River field in the state. The variability of most of the producing wells gives a hint of how complex this reservoir system is to understand.

Riverside (Figure A15)

Discovered in 2002, this is a one-well field. It consists of a directional well whose bottom-hole position is WSW of the surface location. There is a lot of chatter in the density log as there was in the Caton field. The top 140 feet and the bottom 200 feet of the Black River interval are dolomitized. The well produced 376 MMcf as of the end of 2004.

Seeley Creek (Figure A16)

Discovered in 2004, this is a one-well field. It is a directional well whose bottom hole position is ESE of the surface location. The well produced 872 MMcf as of the end of 2004. Dolomite occurs in at least 5 separate beds. The bed that is second from the top appears to have the most porosity in this well. This is the southernmost producing well in the trend in NY.

Sexton Hollow (Figure A17)

Discovered in 2000, this is another one-well field. The Sexton Hollow discovery well has produced 459 MMcf as of the end of 2004. There is a thick dolomite section in the upper Black River and some very high porosity spikes in the basal Trenton which may be bentonites or possibly high porosity zones.

South Corning (Figure A18)

Discovered in 2004, this is a one-well field. It is a directional well whose bottom hole position is SW of the surface location. The field had not produced as of the end of 2004. Dolomite is found at the top of the Black River interval.

Sugar Hill

Discovered in 2000, this is another one-well field. It is a directional well whose bottom hole position is WSW of the surface location that has produced 1.07 Bcf as of the end of 2004. We do not have a good set of logs for this well.

Terry Hill South (Figure A19)

Discovered in 2000, this field has seven producing wells. The field has produced more than 6.4 Bcf of gas as of the end of 2004. Wells on the south side of the field have produced better than those on the northern side. The Black River is dolomitized almost everywhere it was penetrated in the five wells.

West River (Figure A20)

Discovered in 2004, this is a one-well (22985-02) field. This well was sidetracked twice and the second sidetrack reportedly found gas. This is a directional well whose bottom hole position is SSW of the surface location. The well had not produced gas as of the end of 2004.

Whiskey Creek (Figure A21)

Discovered in 2003, this is a one-well field. The well produced 1.03 Bcf as of the end of 2004. This is a directional well whose bottom hole position is SE of the surface location. Dolomite is not found at the top of the Black River, but the PEF response suggests that there may be some open fractures or faults in that interval. The middle part of the Black River is pervasively dolomitized.

Wilson Hollow (Figure A22)

Discovered in 1999, the field consists of ten producing wells. The field has produced 30.6 Bcf as of the end of 2004 and is the second-best producing field in the trend after Quackenbush Hill which is just to the south and parallel to Wilson Hollow field. Most wells have dolomite throughout the Black River, and all of them have dolomite in the upper 50 feet, where some of the best porosity occurs. This is an ideal field for horizontal wells because of this consistent dolomite distribution. In some wells, the basal Trenton is dolomitized. The trend of the field is ENE-WSW.

Zimmer Hill (Figure A23)

Discovered in 2005, this is a one-well field. This is a horizontal well whose bottom position is NNE of the surface location. The well penetrated 360 feet of limestone, then a narrow dolomitized zone followed by another 200 feet of tight limestone before encountering a wider dolomitized zone with good porosity. Again, this well shows the lateral heterogeneity in this play and why horizontal wells are a good idea in most locations. The well did not have any production data for 2004 as it was not discovered until the following year.

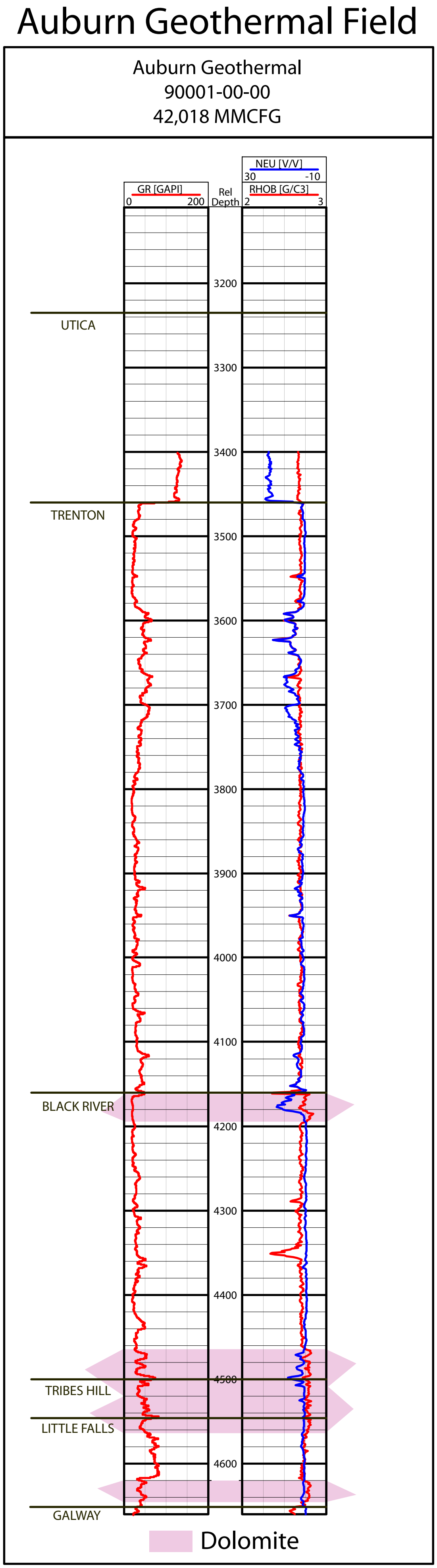


Figure A1 - Well log from the Auburn Geothermal field.

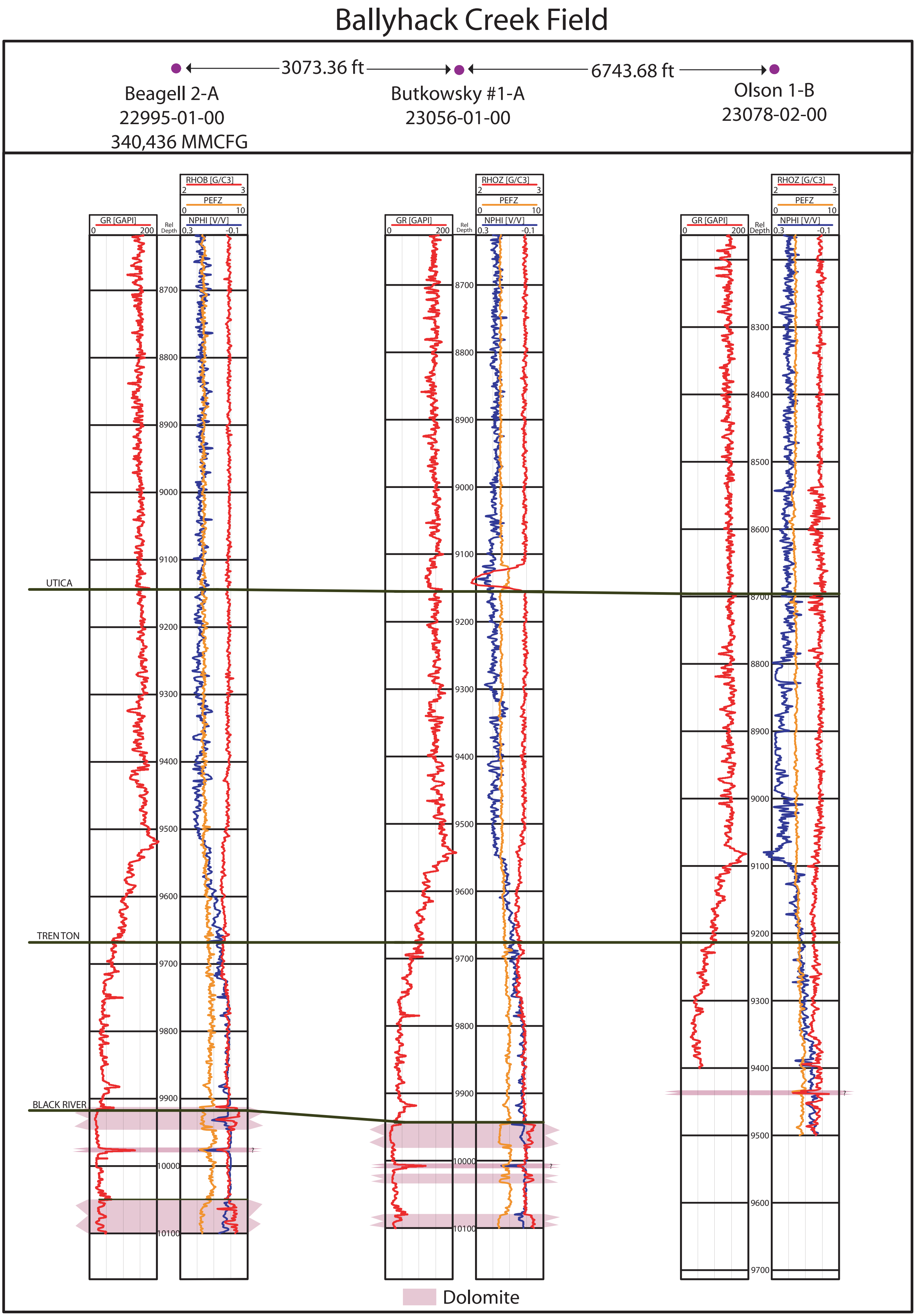


Figure A2 - Well logs from the Ballyhack Creek Field.

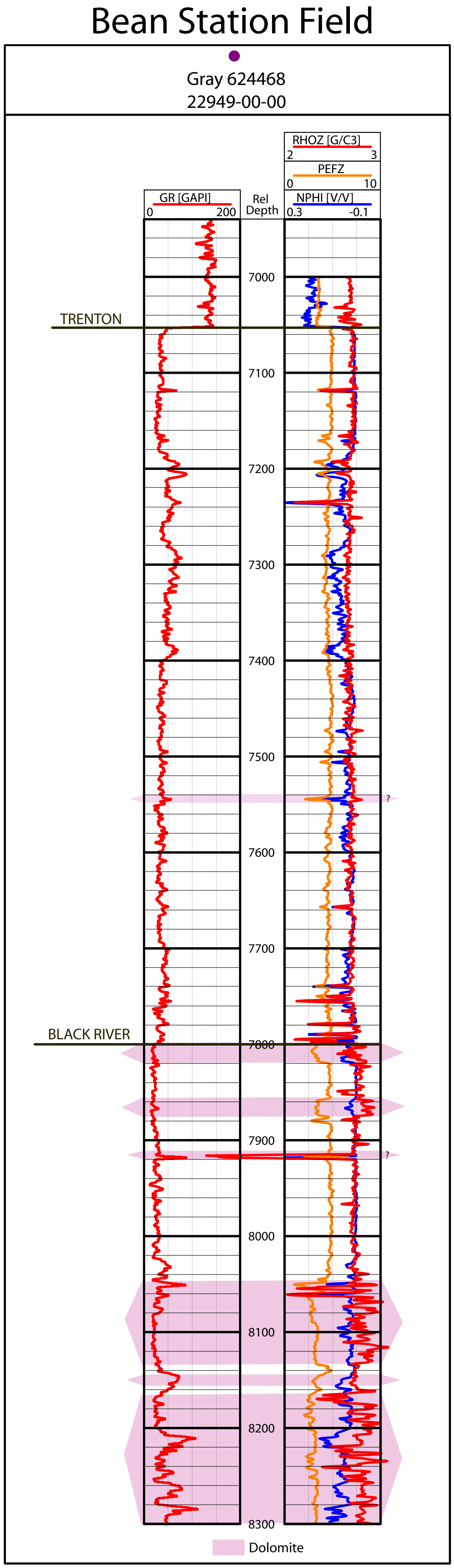


Figure A3 - Well logs from the Bean Station Field.

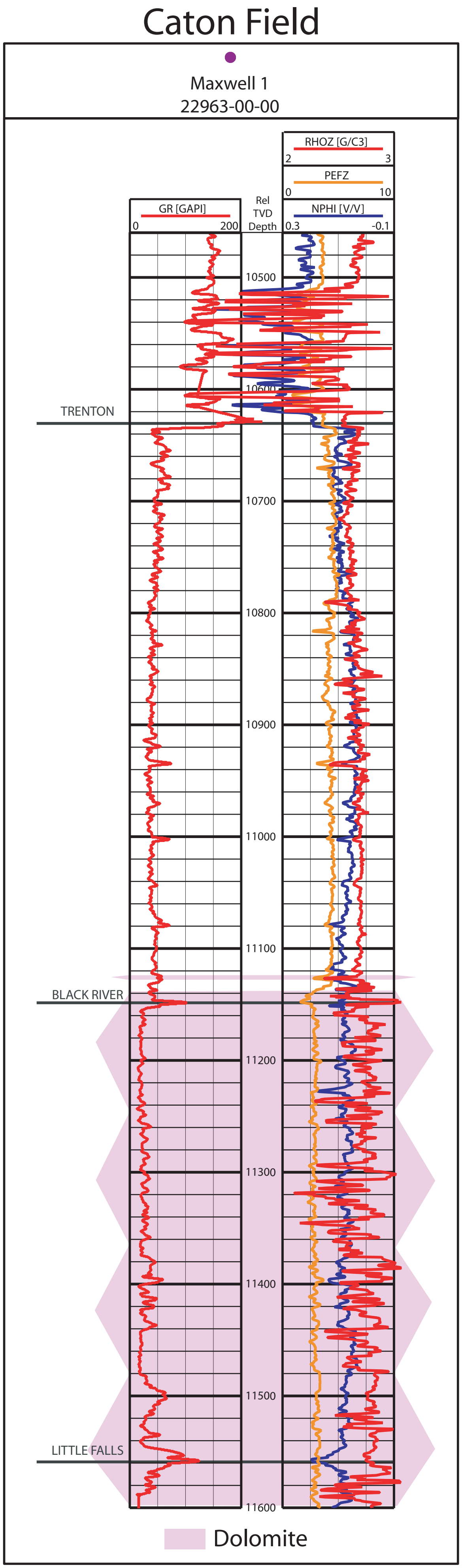


Figure A4 - Well log from the Caton Field.

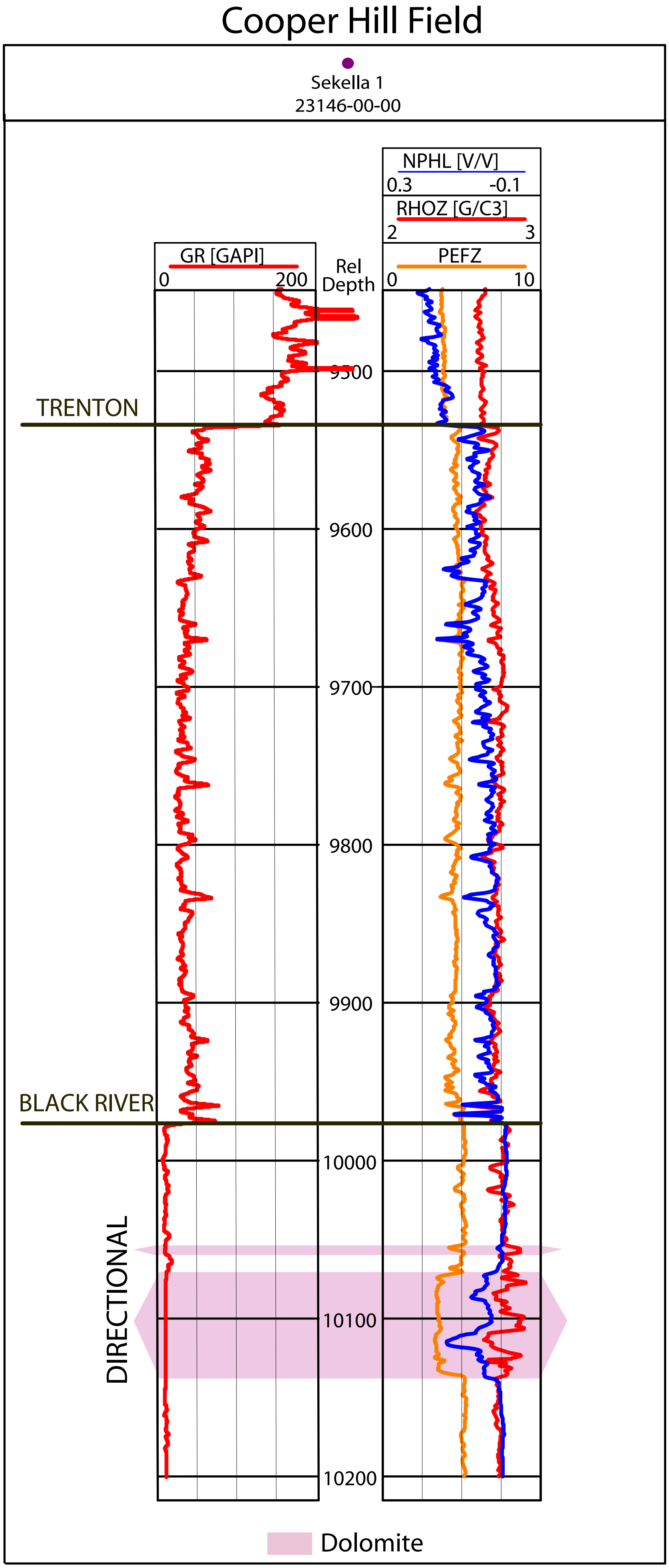


Figure A5 - Well log from the Cooper Hill Field.

County Line Field

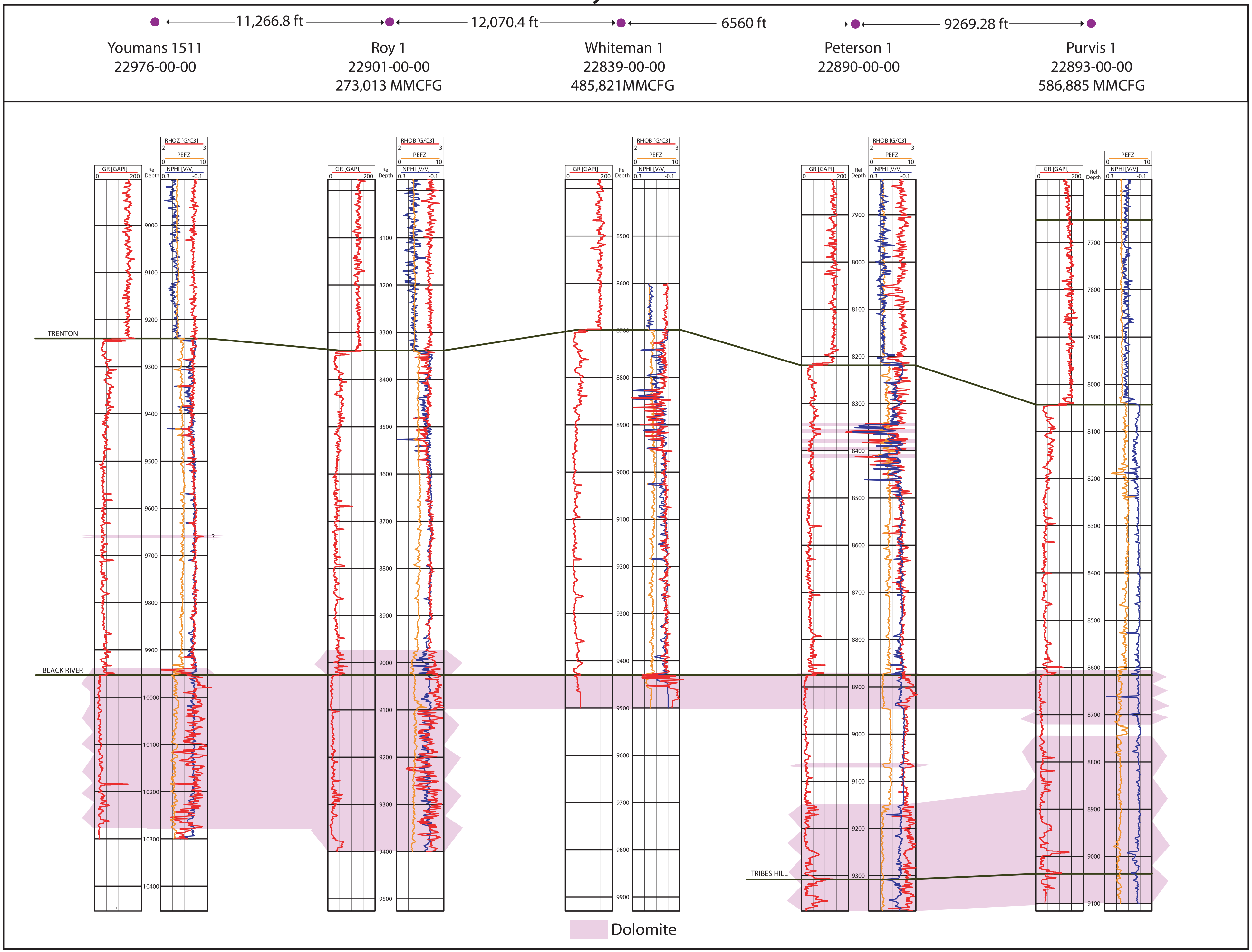


Figure A6 - Well logs from the County Line Field.

Cutler Creek Field

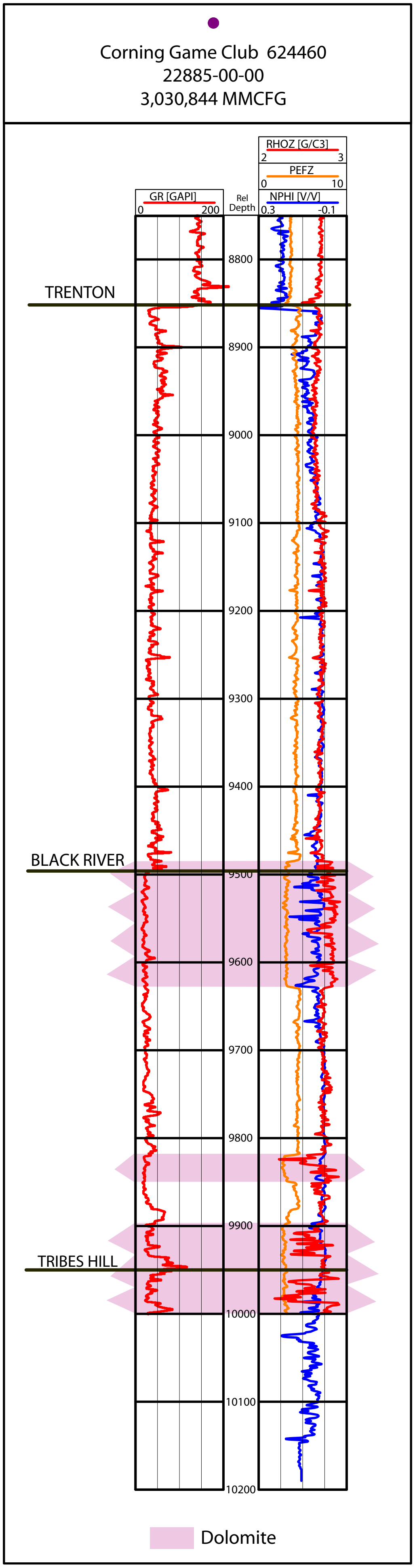


Figure A7 - Well log from the Cutler Creek Field.

Glodes Corners Road Field

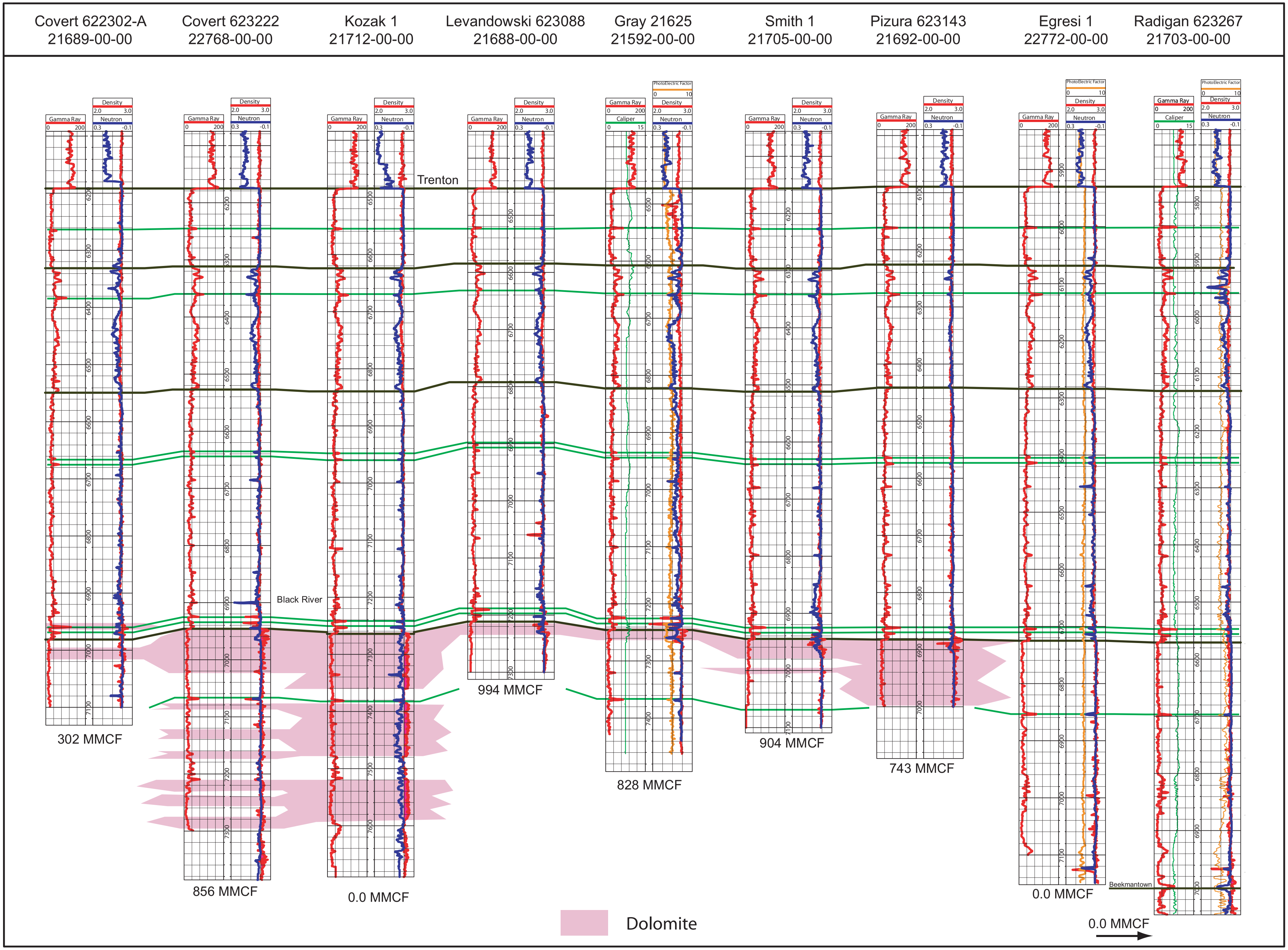


Figure A8 - Well log from the Glodes Corners Road Field.

Guyanoga Valley Field

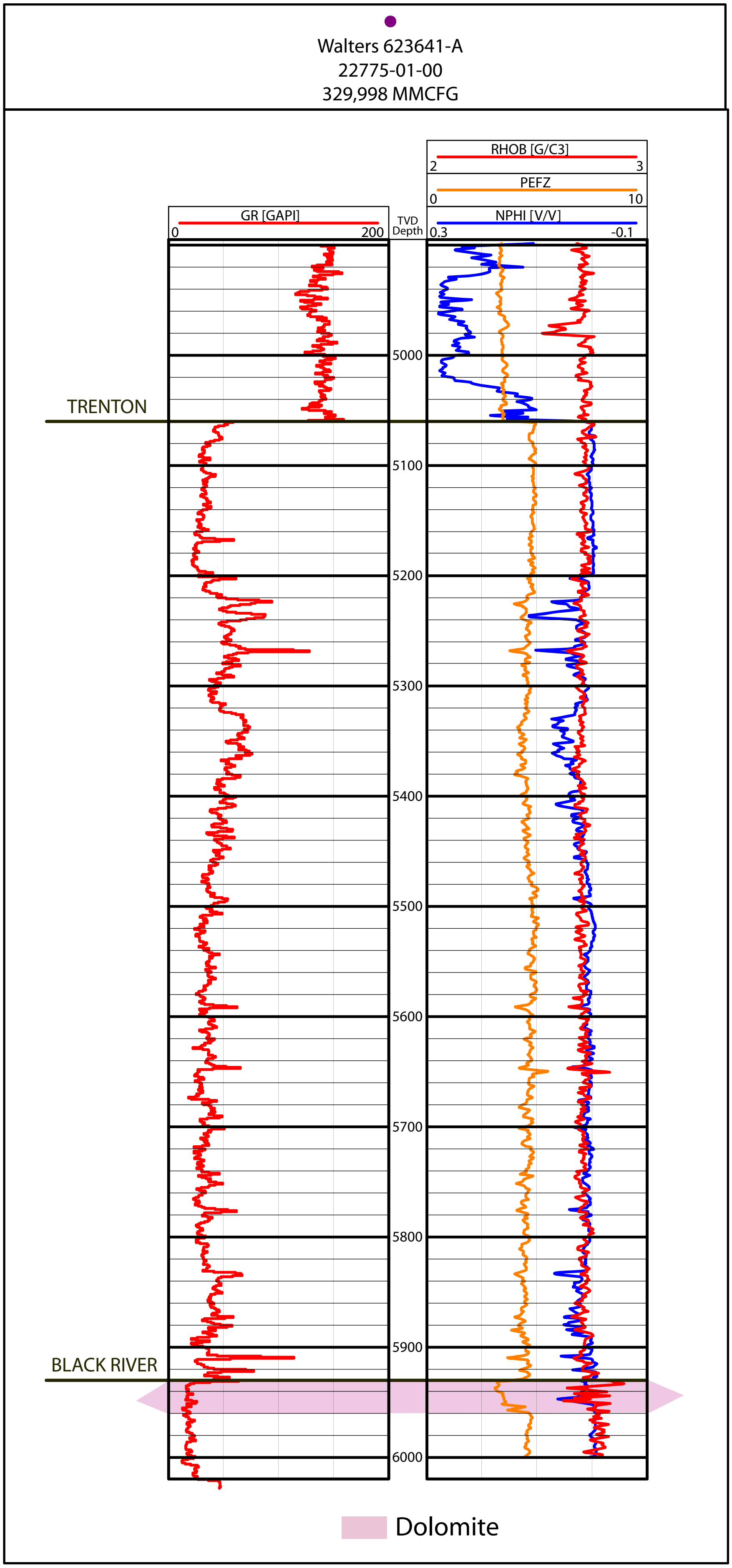


Figure A9 - Well log from the Guyanoga Valley Field.

Langdon Hill Field

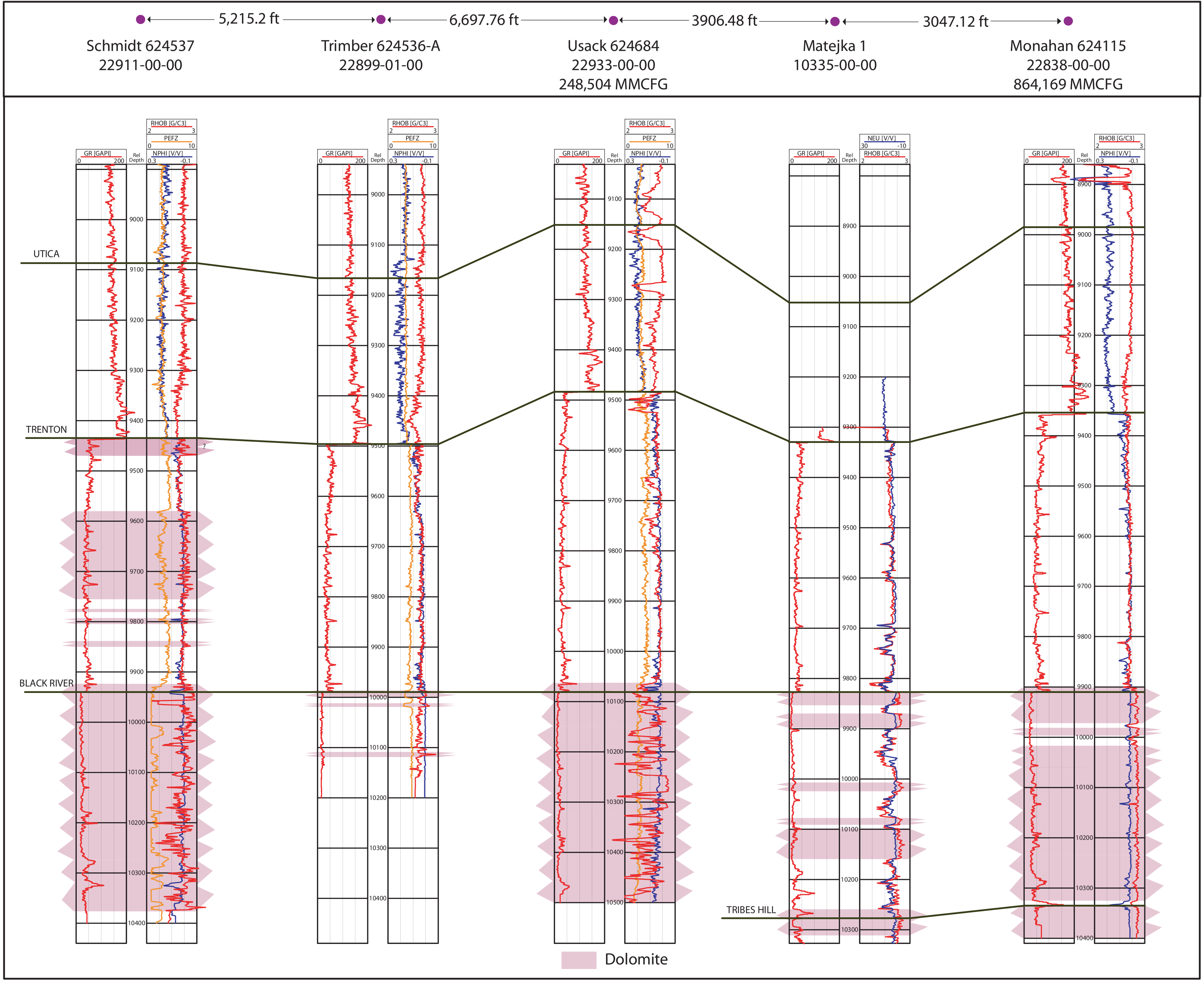


Figure A10 - Well logs from the Langdon Hill Field.

Muck Farm Field

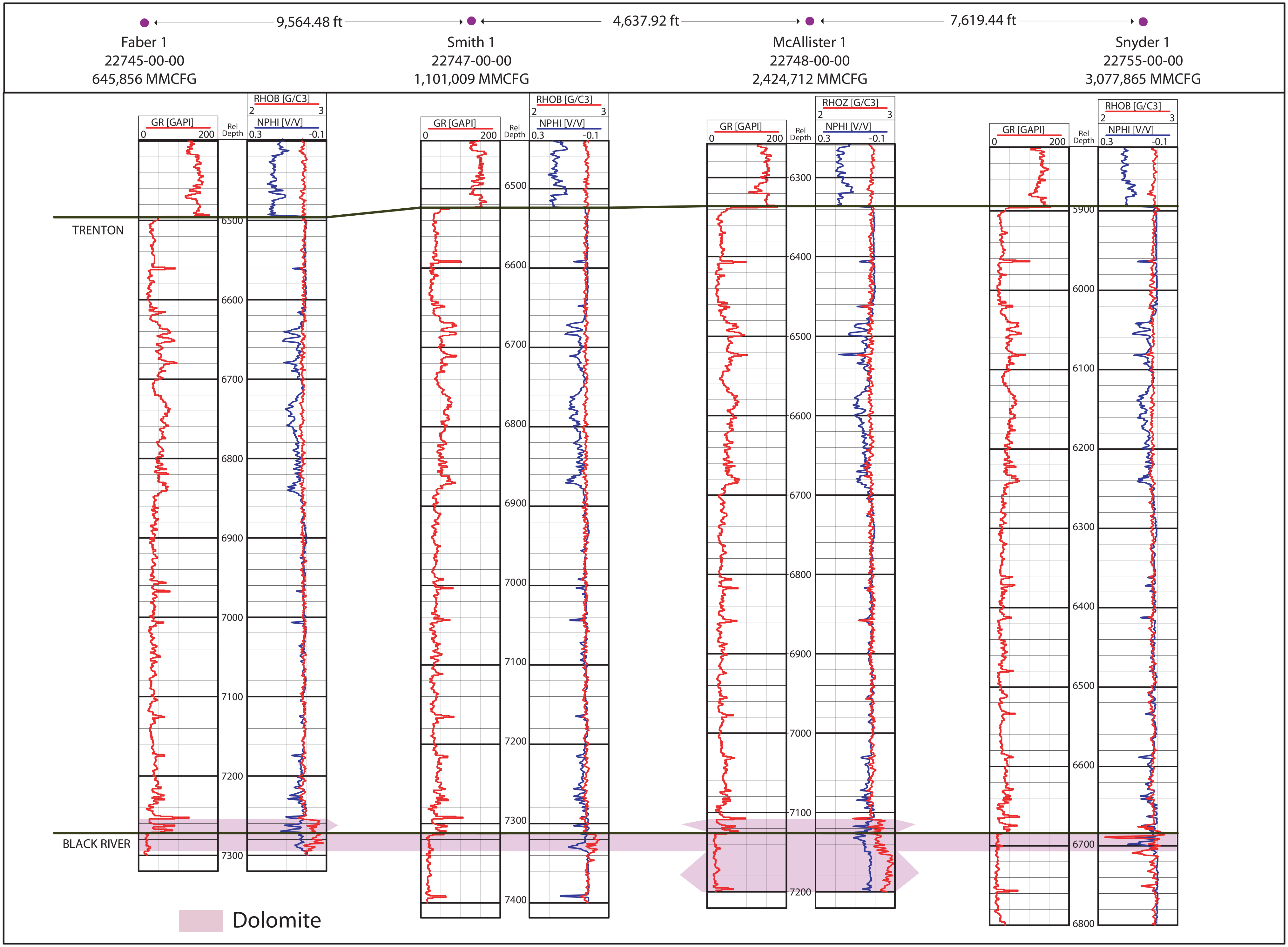


Figure A11 - Well log from the Muck Farm Field.

Pine Hill Field

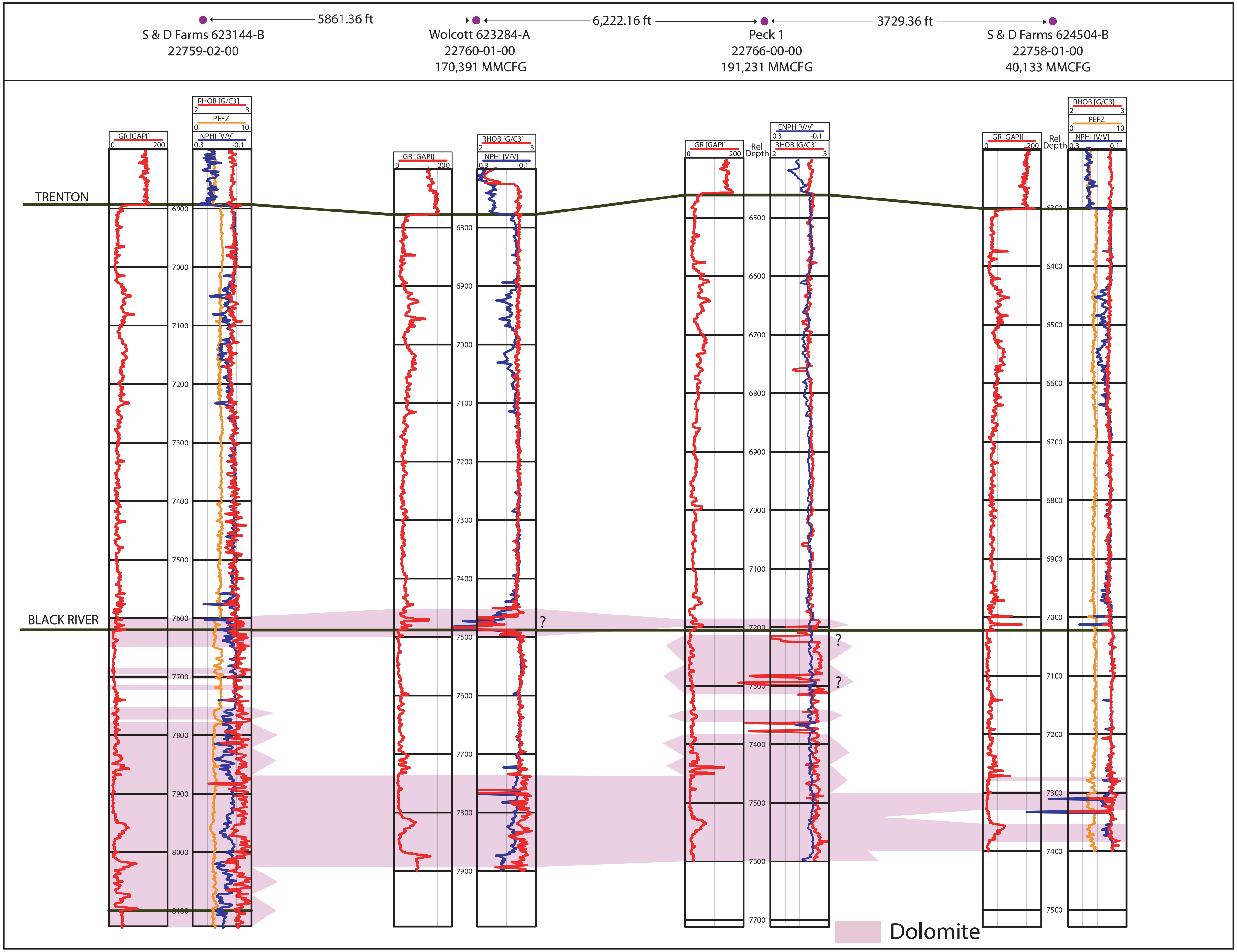


Figure A12 - Well logs from the Pine Hill Field.

Quackenbush Hill Field

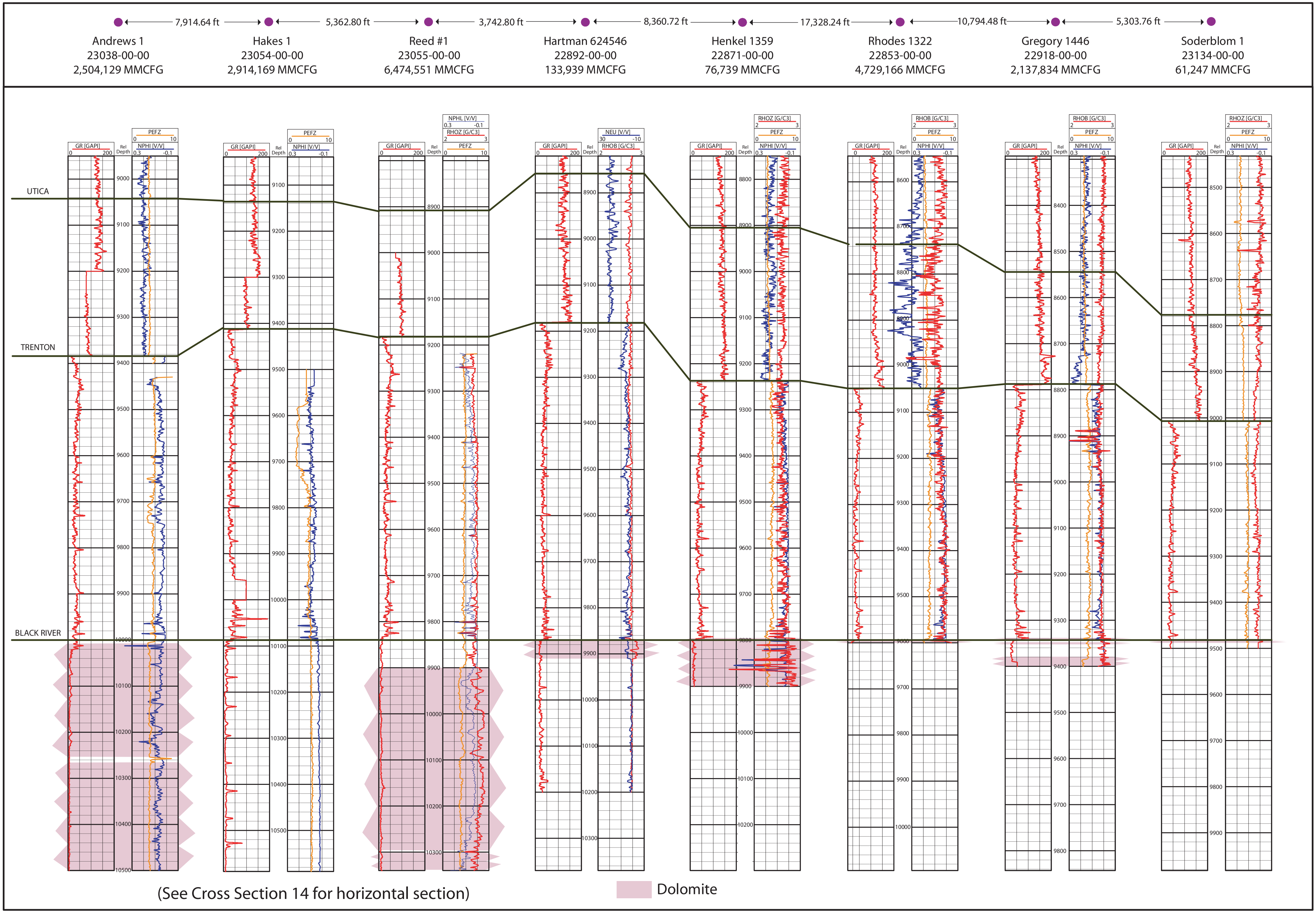


Figure A13 - Well logs from the Quackenbush Hill Field.

Quackenbush Hill Field

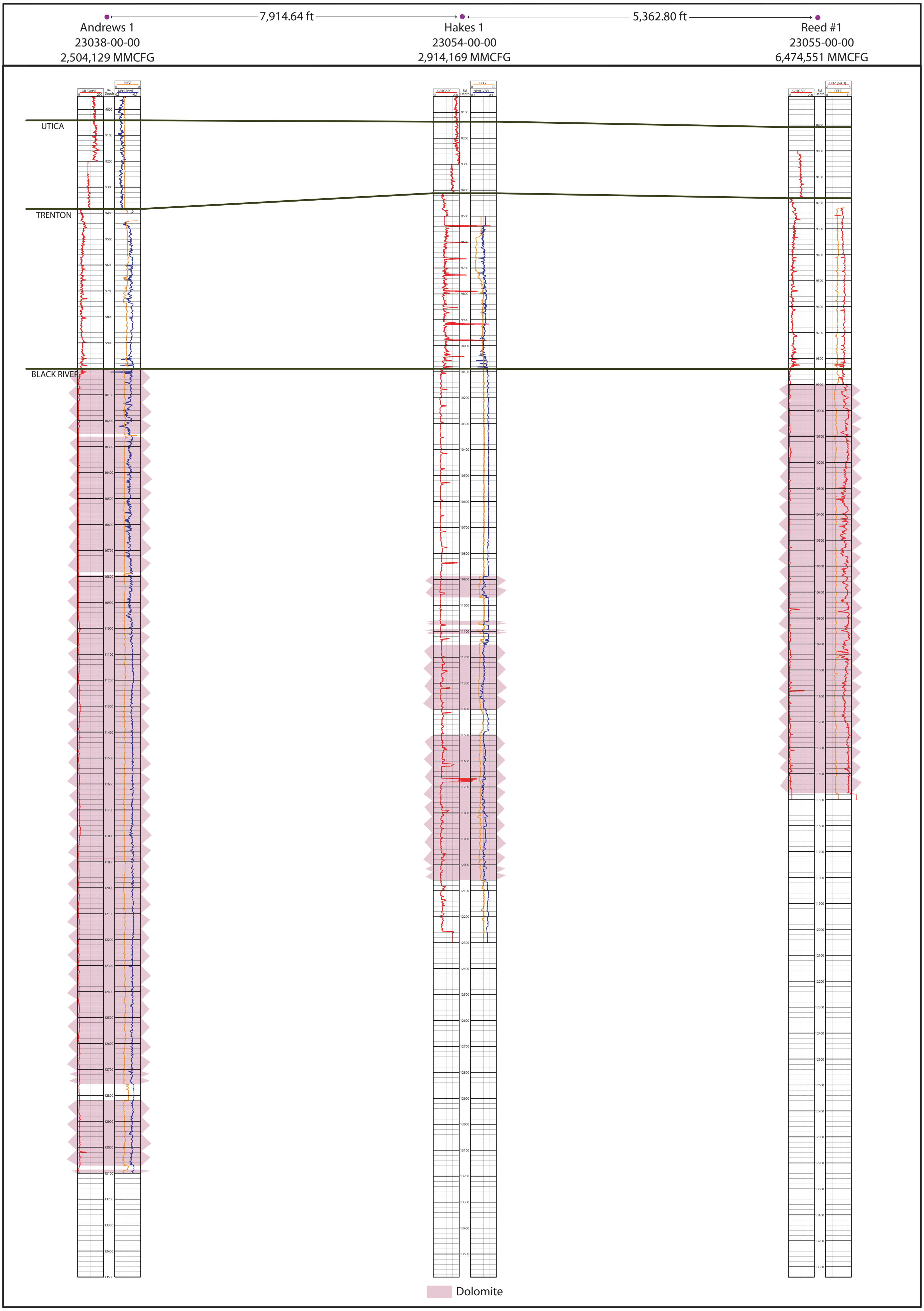
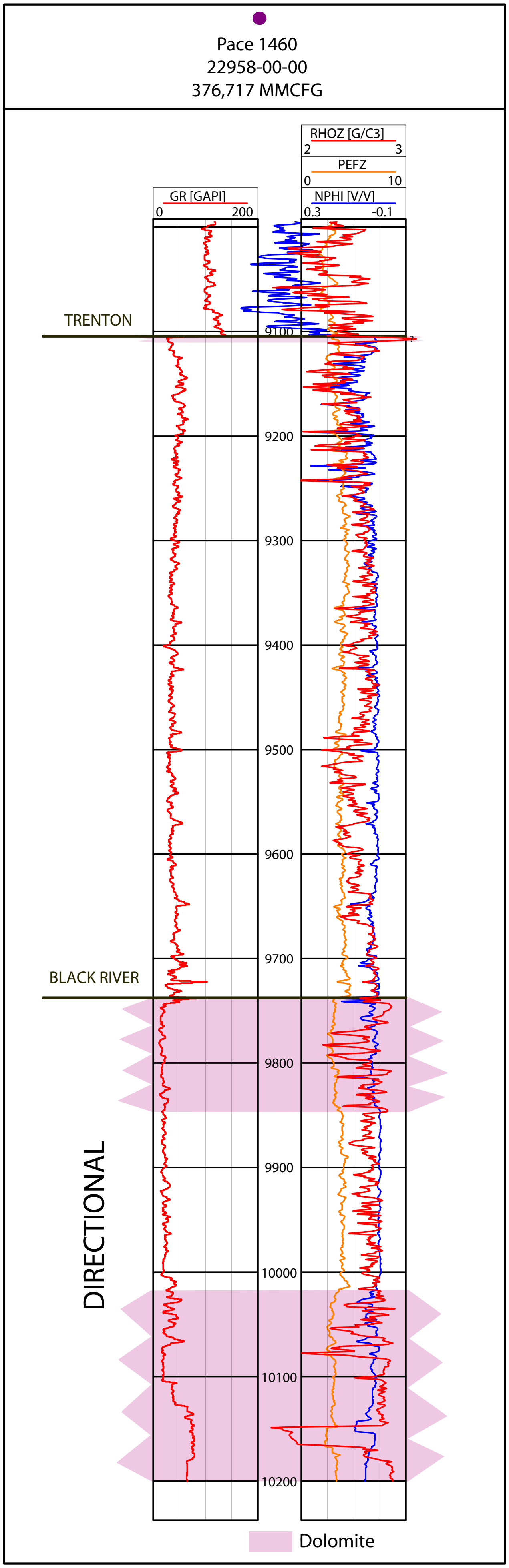


Figure A14 - Horizontal well logs from Quackenbush Hill Field.



Riverside Field

Figure A15 - Well log from the Riverside Field.

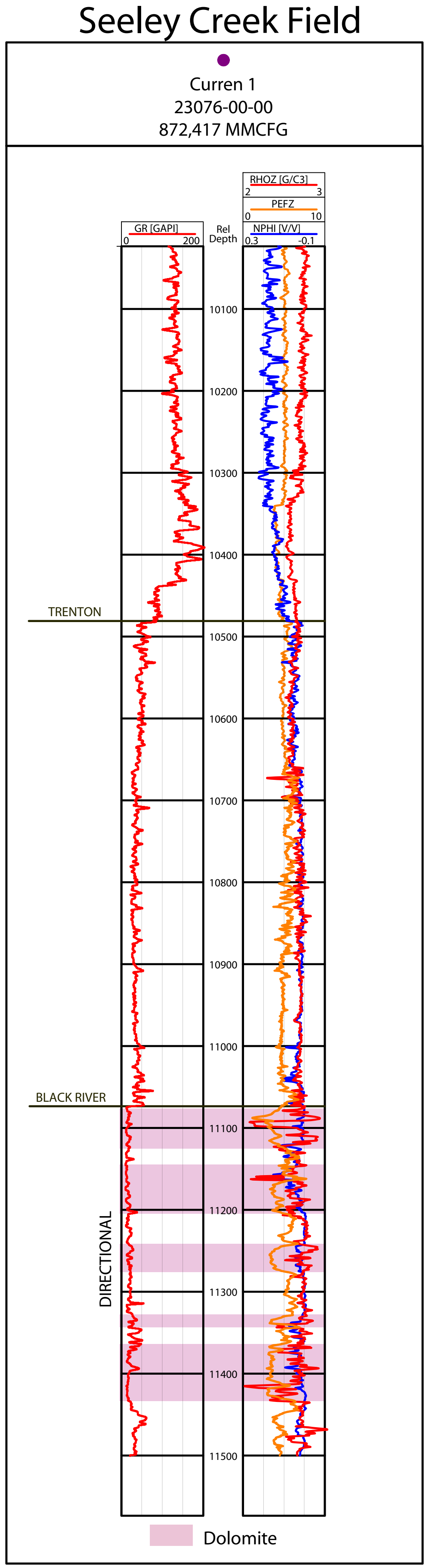


Figure A16 - Well log from the Seeley Creek Field.

Sexton Hollow Field

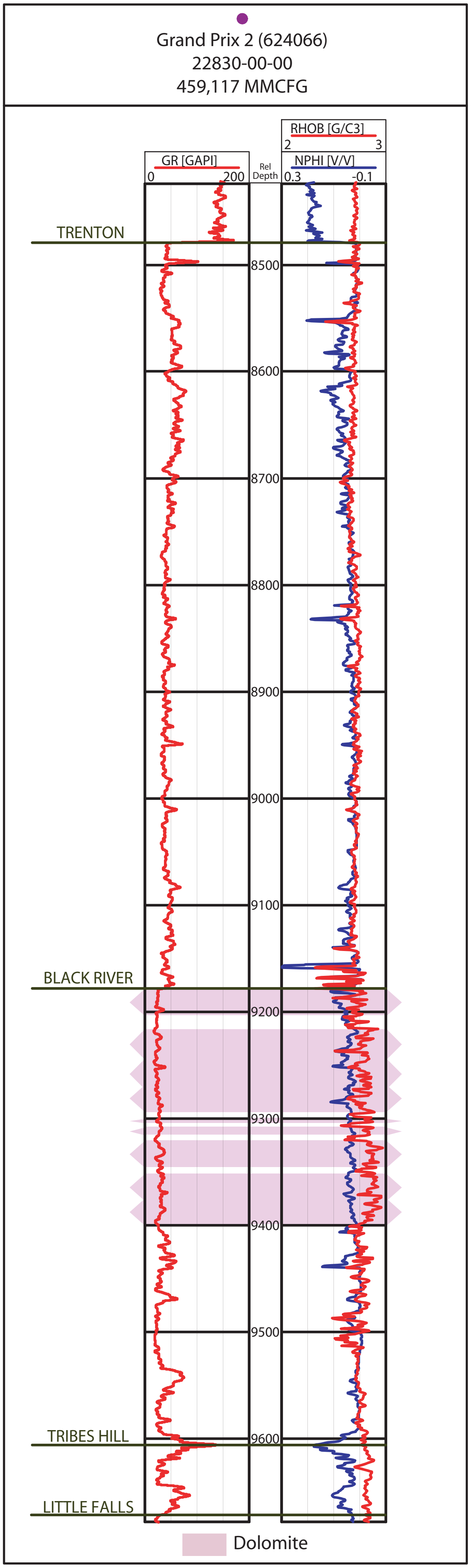


Figure A17 - Well log from the Sexton Hollow Field.

South Corning Field

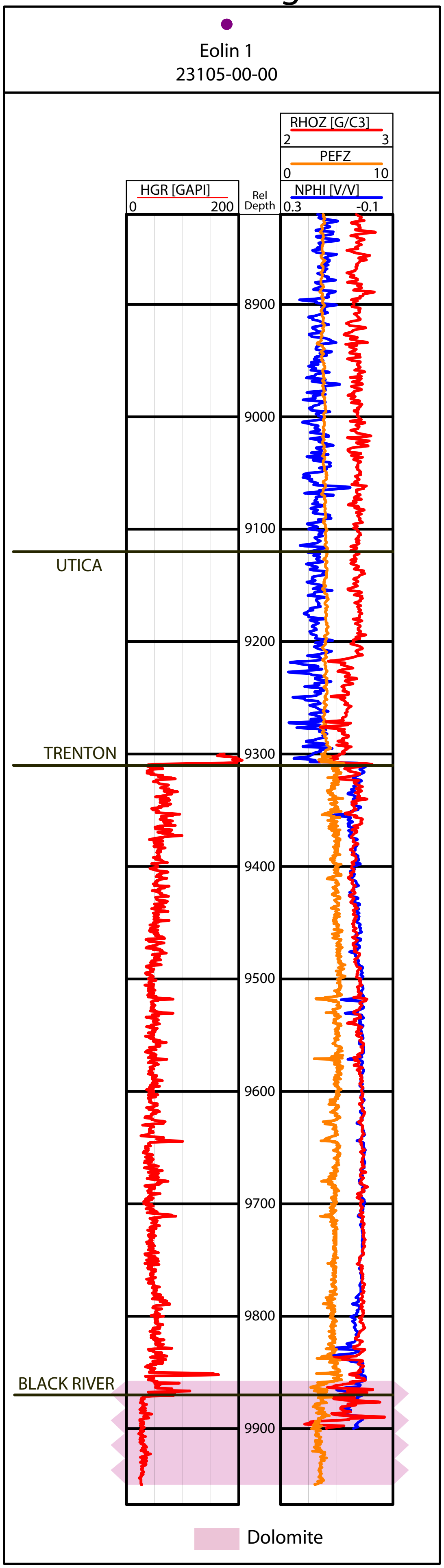


Figure A18 - Well log from the South Corning Field.

Terry Hill South Field

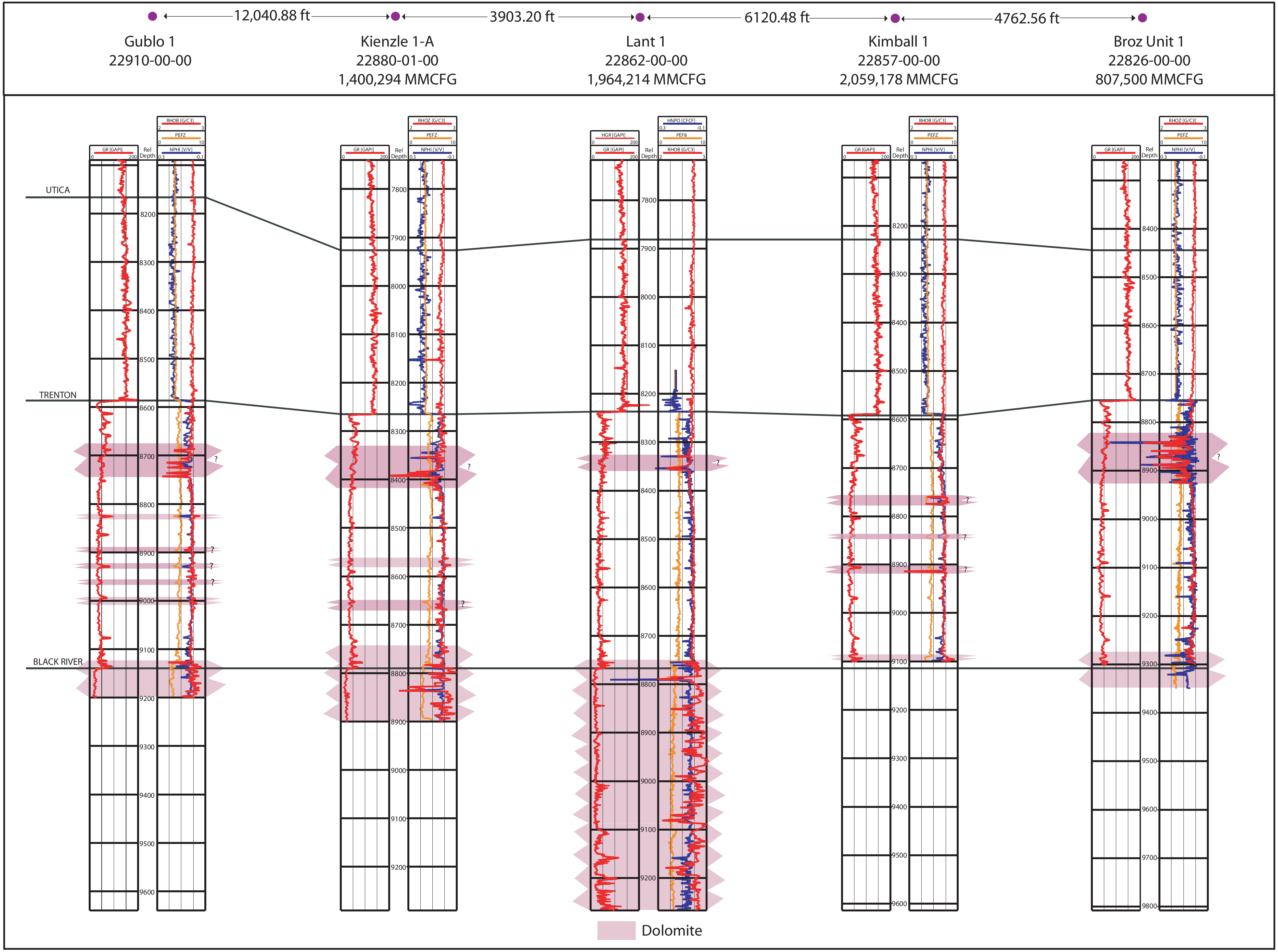


Figure A19 - Well logs from the Terry Hill South Field.

West River Field

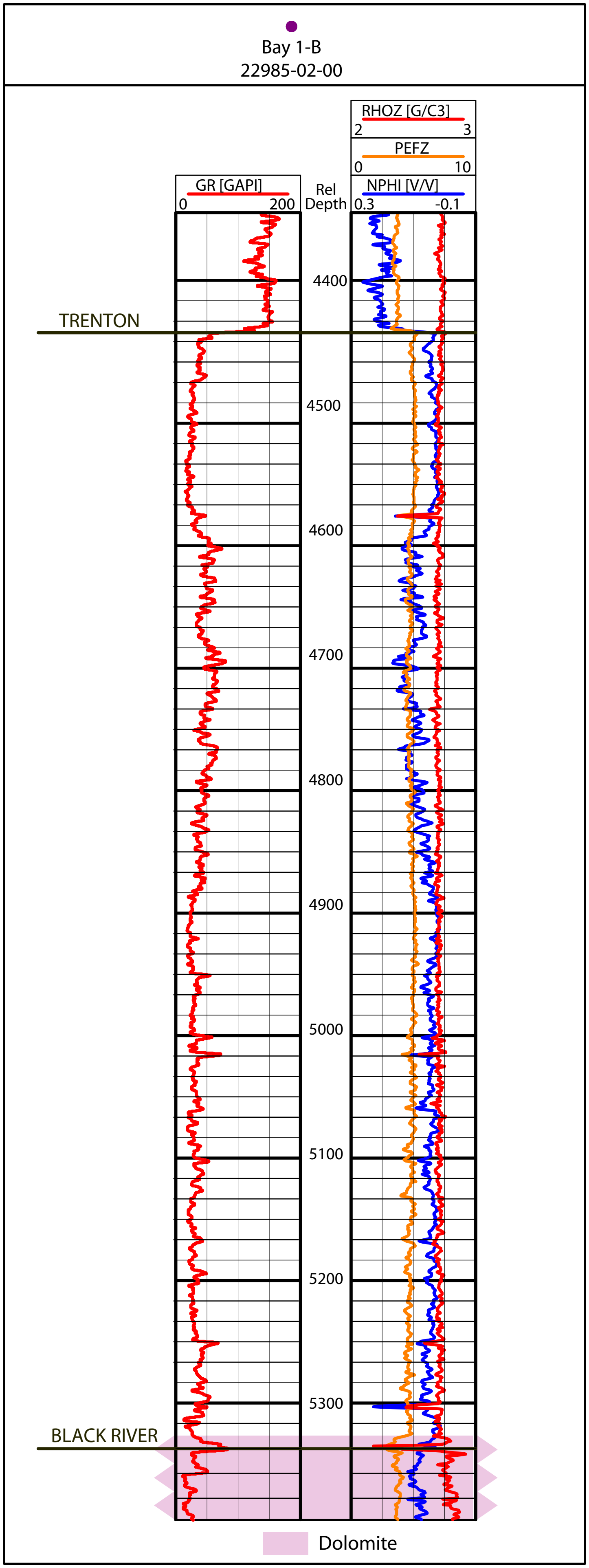


Figure A20 - Well log from the West River Field.

Whiskey Creek Field

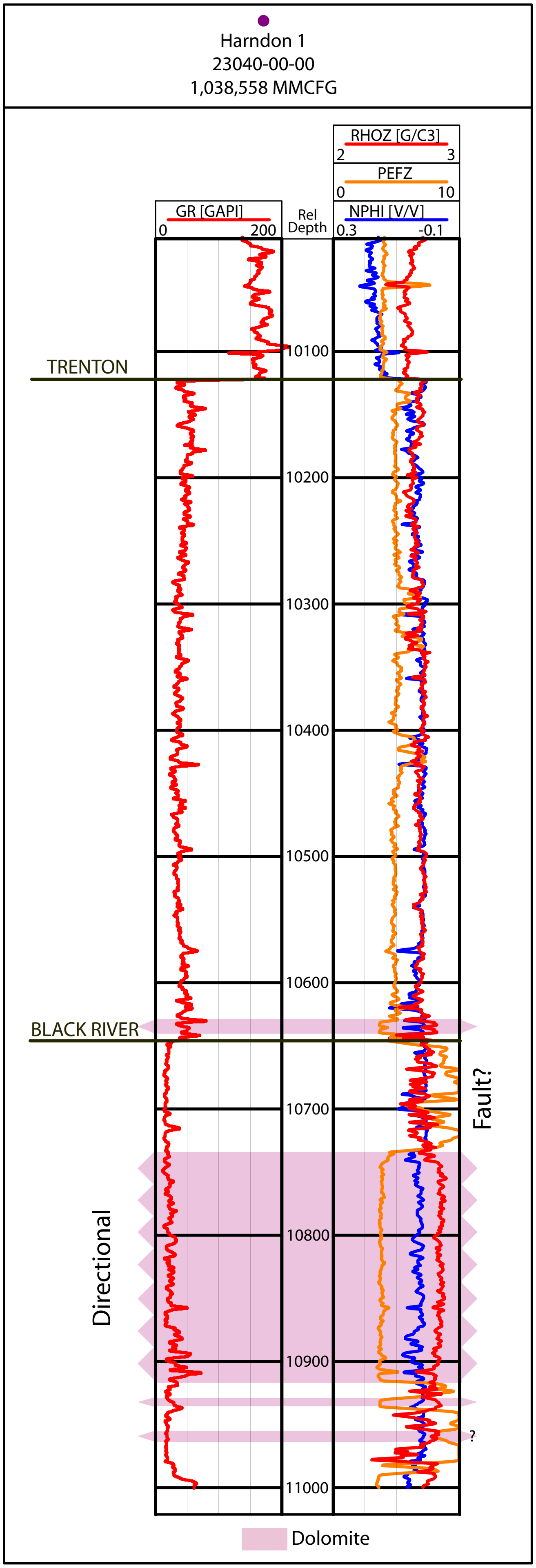


Figure A21 - Well log from the Whiskey Creek Field.

Wilson Hollow Field

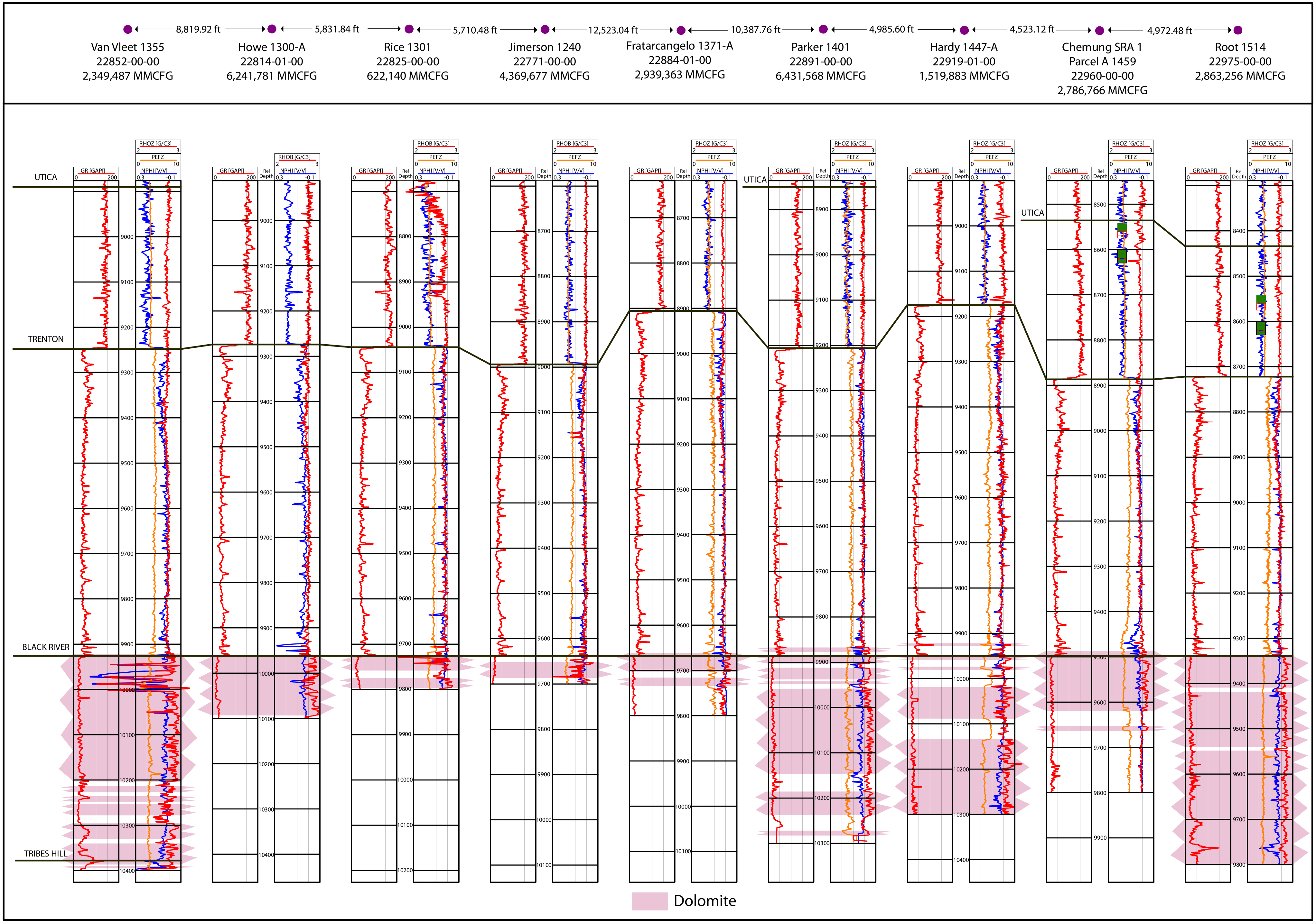


Figure A22 - Well logs from the Wilson Hollow Field.

Zimmer Hill Field

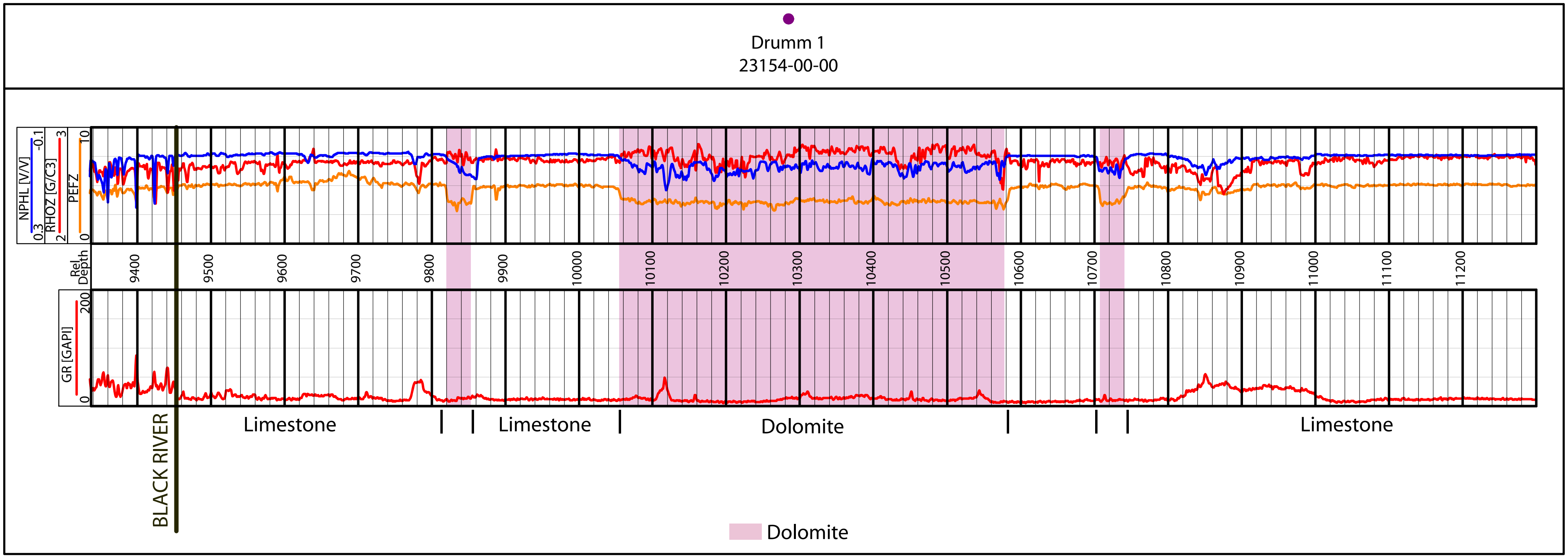


Figure A23 - Well log from the Zimmer Hill Field.