Integrated Reservoir Characterization of the Subsurface Cambrian and Lower Ordovician Potsdam, Galway and Theresa Formations in New York

Final Report

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NOTICE

Abstract

Over the past decade, several successful wells have been drilled into subtle structural highs in the upper sandy member of the Galway Formation of western New York. Although it has long been called the Theresa Sandstone Play, recent paleontological and stratigraphic research indicates that the producing formation in western NY is actually the Rose Run Sandstone Member of the Late Cambrian Galway formation. The Galway Formation has is here subdivided into 7 members: the Rose Run Upper Interbedded, Rose Run Clean Sandstone, Rose Run Lower Interbedded, A Dolomite, B Sand, B Dolomite, B Interbedded and C Sand. Cuttings from three wells were used to refine log interpretation and determine porosity types. Wireline logs were used to develop a series of maps and cross sections to illustrate the complex relationship between the Knox Unconformity and underlying units. Thin sections made from cuttings and cores reveal that the majority of the porosity is secondary in nature and consists of leached dolomite, feldspar and quartz. Meteoric diagenesis may be responsible for enhancing porosity where the Rose Run subcrops under the Knox Unconformity, however there are porous wells away from the subcrop belt with a significant thickness of Little Falls between the Galway and exposure surface. Erosional remnants are believed to be the main trapping mechanism where the Rose Run just below the Knox Unconformity, but discoveries in the area to the south east of the subcrop cannot be related to erosion and must be structural closures. Large unexplored areas both where the Rose Run lies immediately beneath the Knox Unconformity and away from the subcrop belt leave much potential for future discoveries.

Key words: Theresa Sandstone, Rose Run Sandstone, Galway Formation, natural gas, New York State

TABLE OF CONTENTS

List of Figures

List of Tables

Executive Summary

Section 1
INTRODUCTION

Over the past decade, several successful wells have been drilled to the Theresa (Galway) Sandstone in western New York. This is the first production from that interval in New York, which has been prolific in neighboring Ohio where it is called the Rose Run Sandstone. The reservoirs occur in subtle structural highs that are visible on seismic and may be detectable on hi-resolution aeromagnetic data (Copley and Mohar, 1998).

Early success has brought up many questions on the Theresa play here in New York that need to be answered in order to reduce geologic risk and attract more drilling and investment. Questions include: Can productive structural highs be consistently identified on aeromagnetic data? What is the age of the sand that produces…Ordovician or Cambrian? What are the lithologies and depositional environments of the productive sands? How do the Potsdam, Galway and Theresa differ and how can they be distinguished in the subsurface? What are the pore types, how well are they connected and what are the permeability values for different rock types? Are the traps structural, stratigraphic or a combination of both? What is the role of the Knox unconformity in creating traps and enhancing or destroying reservoir properties? How laterally extensive are the Theresa, Galway and Potsdam and do their reservoir quality also vary laterally? Do they pinch out in the subcrop? Is what is called the Theresa in the subsurface actually the equivalent to the Galway in outcrop and the Rose Run in Ohio?

These questions and more are addressed in detail in this report. This could be a big play in New York with the potential for hundreds of wells and tens to hundreds of BCF of gas produced. It appears that there are many areas with great potential that have not been tested.

TECTONIC AND PALEOGEOGRAPHIC SETTING

New York's sedimentary strata are underlain by the Grenville Basement, which was emplaced approximately 1.1 billion years ago during the Grenville Orogeny which was part of the assembly of a supercontinent. That supercontinent rifted apart in the Late Precambrian/Early Cambrian and by the Late Cambrian/Early Ordovician, New York was situated south of the equator on a south-facing passive margin of the Iapetus Ocean (Figure 1). This passive margin setting is thought to have continued until the Late Ordovician Taconic Orogeny (when the island arc shown to the south in Figure 1 collided with North America). The approach of the island arc appears to have had an impact on the subsidence/uplift patterns in NY prior to the actual collision.

The Paleogeographic map in Figure 2 (from Blakey website) shows two key features that affected deposition. One is the exposed land that trends from the Canadian Shield under present day Lake Ontario to the Adirondacks. This appears to have been exposed throughout the Cambrian and Lower Ordovician and was probably the source for the quartz, feldspar and mica in the Cambrian and Ordovician strata. The map also shows an elongate present-day NE-

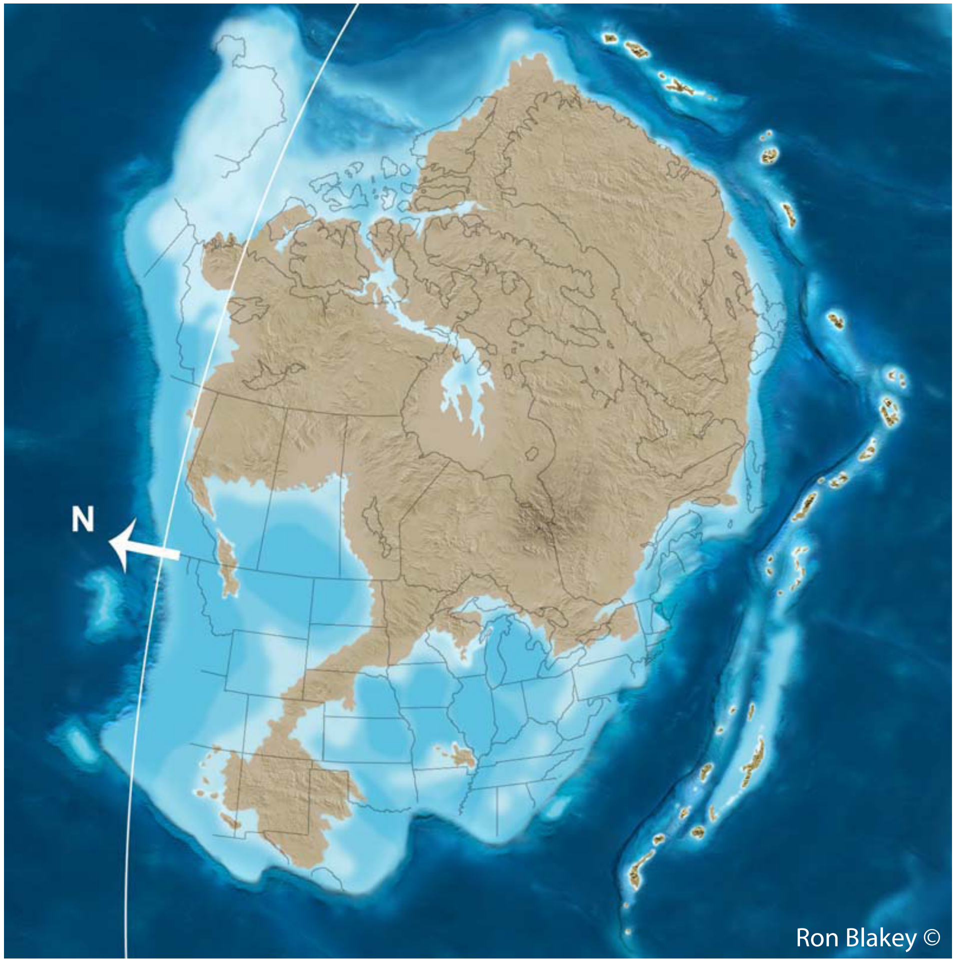


Figure 1. Paleogeographic map of North America in the Late Cambrian (from R. Blakey website) when the Galway and Little Falls Formations were deposited. New York was south of the equator and part of a south-facing passive margin. An island arc was approaching from the south. Basement was exposed in a present day E-W trend extending from Lake Ontario through Adirondacks.

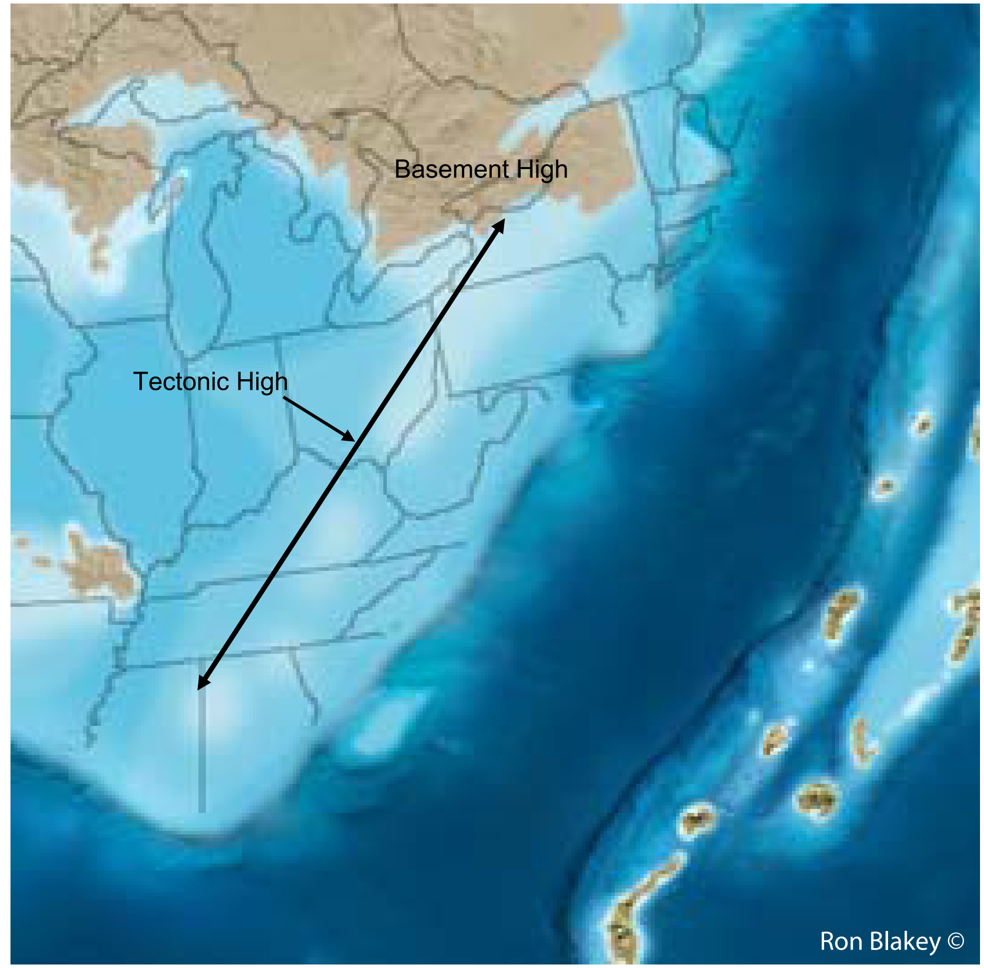


Figure 2. Closeup of Late Cambrian paleogeography from Figure 1 shows basement high that extended from present-day Adirondacks across Lake Ontario and into Canadian Shield. Th eexact limits of this high are probably not accurately represented but the idea is correct. Also note NY-Alabama trend of shallower marine conditions that runs parallel to island arc. These features played a major role in the distribution of Late Cambrian sediments.

SW trending area of shallower marine conditions in lighter blue which runs parallel to the approaching island arc and extends from western NY down to Alabama. There is good evidence for that area being a high, especially during Knox Unconformity time where the erosion patterns appear to run parallel to that high with progressively more erosion to the present day northwest. This may be an early expression of a peripheral bulge or activation of old structural features caused by the approaching island arc (Bradley and Kidd, 1991; Jacobi and Mitchell, 2002).

The depositional environment for the Potsdam, Galway, Little Falls and Tribes Hill Formations was shallow marine in the study area. The siliciclastics appear to have been beach and possibly barrier island sediments and the carbonates appear to be shallow marine oolitic, tidal flat and lagoonal facies.

STRATIGRAPHIC SETTING

The Paleozoic sedimentary rocks of New York are underlain by Proterozoic Grenville metamorphic and igneous basement rocks (Figure 3). There was significant relief on the Precambrian surface which generally dipped from north to south. An isopach map of the Sauk Sequence from the Knox Unconformity to Basement (Cambrian and Lower Ordovician) shows gradual thickening from zero near Lake Ontario to as much as 3600 feet along the Pennsylvania border (Figure 4).

The lowermost sedimentary unit in the Appalachian Basin study area is the Potsdam Sandstone (Figure 3) which is thickest in the basin axis and pinches out to the north, west, and east. The Potsdam can be feldspathic at the base and composed of cleaner quartz sandstones toward the top.

The Potsdam is overlain by the Upper Cambrian Galway Formation (Figure 3), which is composed of interbedded shallow marine sandstone and dolomite. This unit has long been called the Theresa Formation in the subsurface, but the name Theresa is incorrect in a strict stratigraphic sense as the Theresa Sandstone in outcrop is thought to be Lower Ordovician in age. This will be discussed in the following section on nomenclature.

The Galway Formation also onlaps the Precambrian surface, with progressively younger units overlying the basement to the north, east and west. The Formation has been divided into several informal member names in this paper. The basal part of the Galway Formation consists of sandstone with thin beds of sandy dolomite (here called the C Sand). The C Sand is overlain by an interval that is dominantly composed of dolomite with some dolomitic sandstone beds (here called the B Dolomite). This unit is overlain by a second interval of sandstone and sandy dolomite (here called the B Sand), which directly overlies the basement in portions of the study area. The B Sand is overlain by a thick, predominantly dolomitic interval here called the A Dolomite. There is some reservoir potential in all of these units, especially where they directly overlie the basement or are directly beneath the Knox Unconformity.

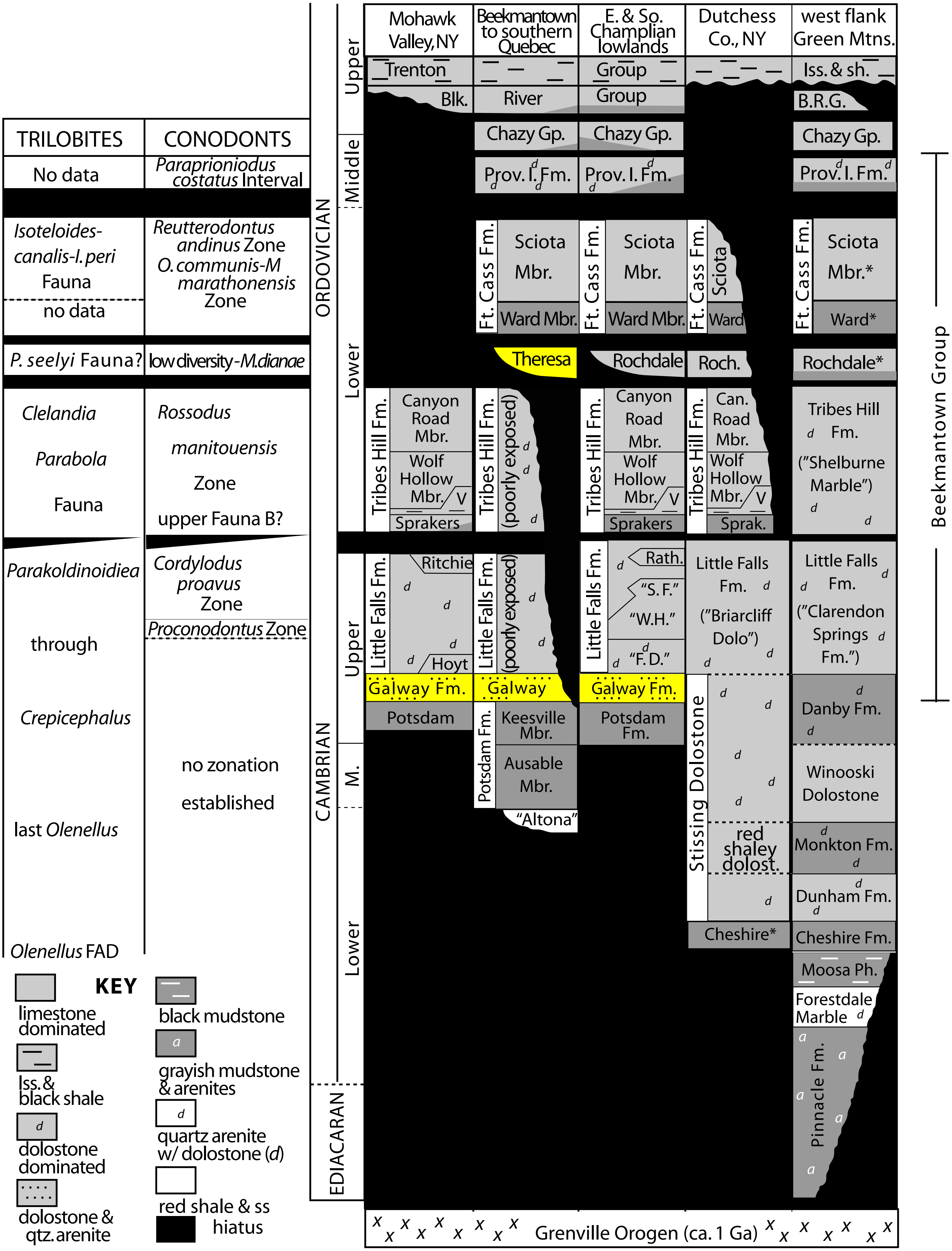


Figure 3. Stratifraphic nomenclature from outcrop belt surrounding the Adirondack Mountains (from Landing, 2007). The Galway Formation is an Upper Cambrian unit that includes sandtone and dolomite and is the foucs of this study. The Theresa Sandstone is Lower Ordovician and found in southern Quebec.

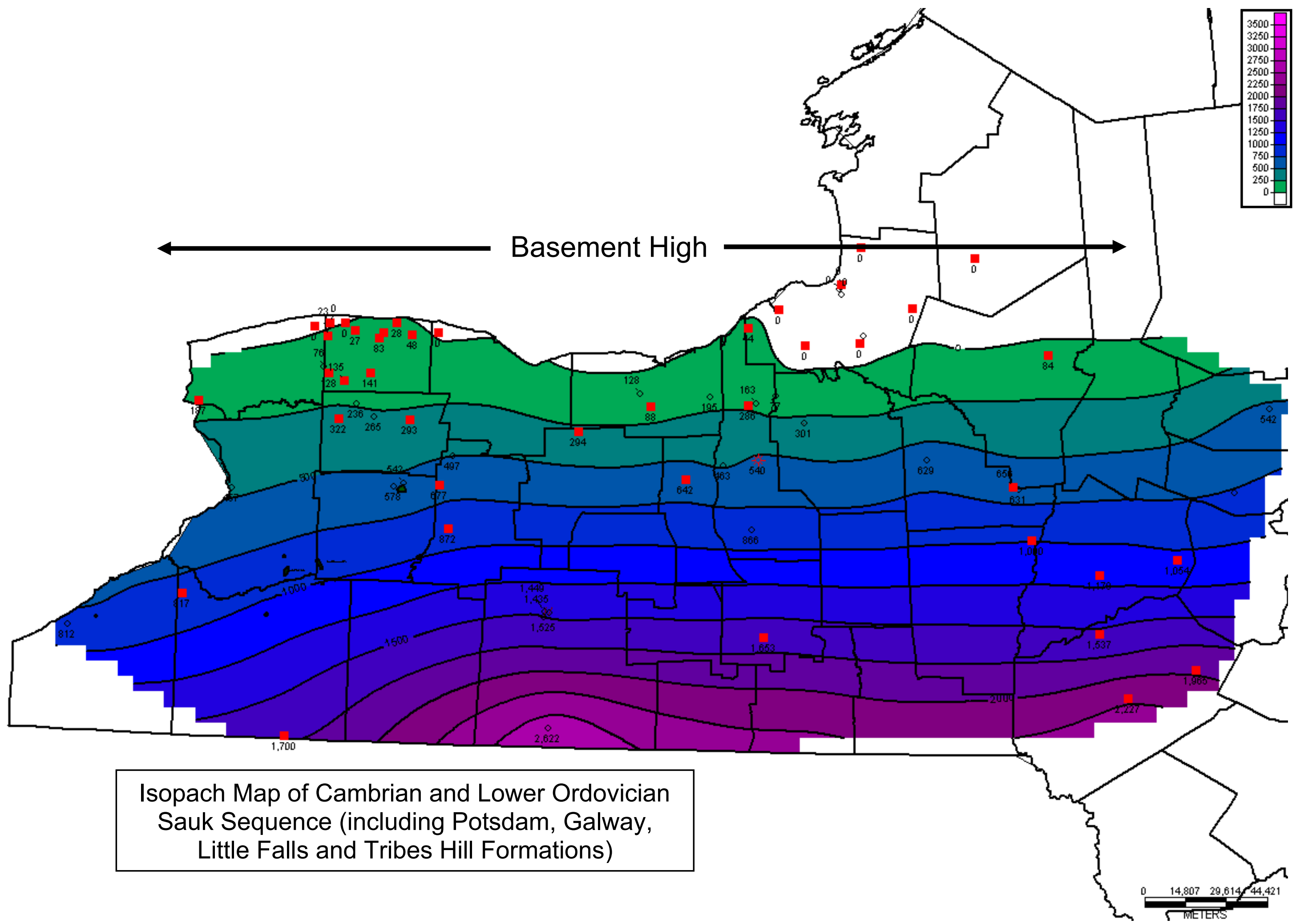


Figure 4. Knox Unconformity-Basement isopach thickness map shows Cambrian-Lower Ordovician interval thickening to south and pinching out on basement high to north trending parallel to shore of Lake Ontario.

The upper part of the Galway consists of an interval of interbedded sandstone and dolomite, overlain in some areas by a massive clean sandstone and in some places a capping interbedded sandstone and dolomite unit. Together these units are called the Rose Run Sandstone Member as they are equivalent to the Rose Run Sandstone of Ohio where it is a prolific gas reservoir. The interbedded interval at the top marks a transition from the dolomite of the overlying Little Falls Formation into the sandstone of the underlying Rose Run. This interval can be porous and is here included as the uppermost part of the Galway Formation although it could just as easily be called basal Little Falls Formation.

The Galway Formation is overlain in the southern and eastern parts of the study area by the Cambrian Little Falls Dolomite, which has little or no porosity in the wells studied. Farther east, the Little Falls is overlain by the Lower Ordovician Tribes Hill Formation, which is mostly composed of limestone and shaly limestone. Together, the Galway, Little Falls and Tribes Hill Formations make up the Beekmantown Group.

Following deposition of the Tribes Hill Formation, sea level fell to much lower levels, leaving most of western New York exposed for tens of millions of years and producing the Knox Unconformity. The Knox Unconformity cuts progressively lower in the section to the north and west (Figure 5). In the eastern part of the New York Appalachian Basin, the Knox Unconformity overlies the Lower Ordovician Tribes Hill Formation. Moving west-northwest, the Tribes Hill is completely eroded/pinched out and the Knox Unconformity overlies the Upper Cambrian Little Falls Formation (Figure 5). Moving farther west, the Little Falls is also completely eroded/pinched out and the Knox Unconformity directly overlies the Galway Formation (Figure 5). The Knox Unconformity cuts progressively further down through the Galway to the northwest. There are wells along the southern and eastern shores of Lake Ontario where no Cambrian strata are found and the Knox Unconformity immediately overlies the basement. Some of the plays in the Galway (and possibly the Beekmantown carbonates as well) occur where these formations directly underlie the Knox Unconformity.

The Knox Unconformity is overlain by the Late Ordovician Black River Group carbonates. These blanket much of the state and correlate very well across the study area. The interval immediately overlying the unconformity is a shaly, sometimes sandy dolomite called the Pamelia Formation in New York and is equivalent to the Wells Creek in Ohio. The Pamelia has a higher quartz sand content in the area where the Black River immediately overlies the Precambrian Basement around Lake Ontario. The Black River thins significantly to the east.

The correlations presented here are similar but differ from Rickard, 1973 in one key way. In Rickard's study the Potsdam was picked as a time-transgressive unit that overlies the basement everywhere (Figure 6). Wherever there was sandstone overlying the basement, it was called Potsdam. This has been the convention for many years. In this paper, strata is called Potsdam where it clearly underlies the Galway and where it has no interbedded dolomites. Thus it is both a chronostratigraphic and lithostratigraphic pick. This has led to an interpretation where the Potsdam only occurs in a limited area in the deepest part of the basin.

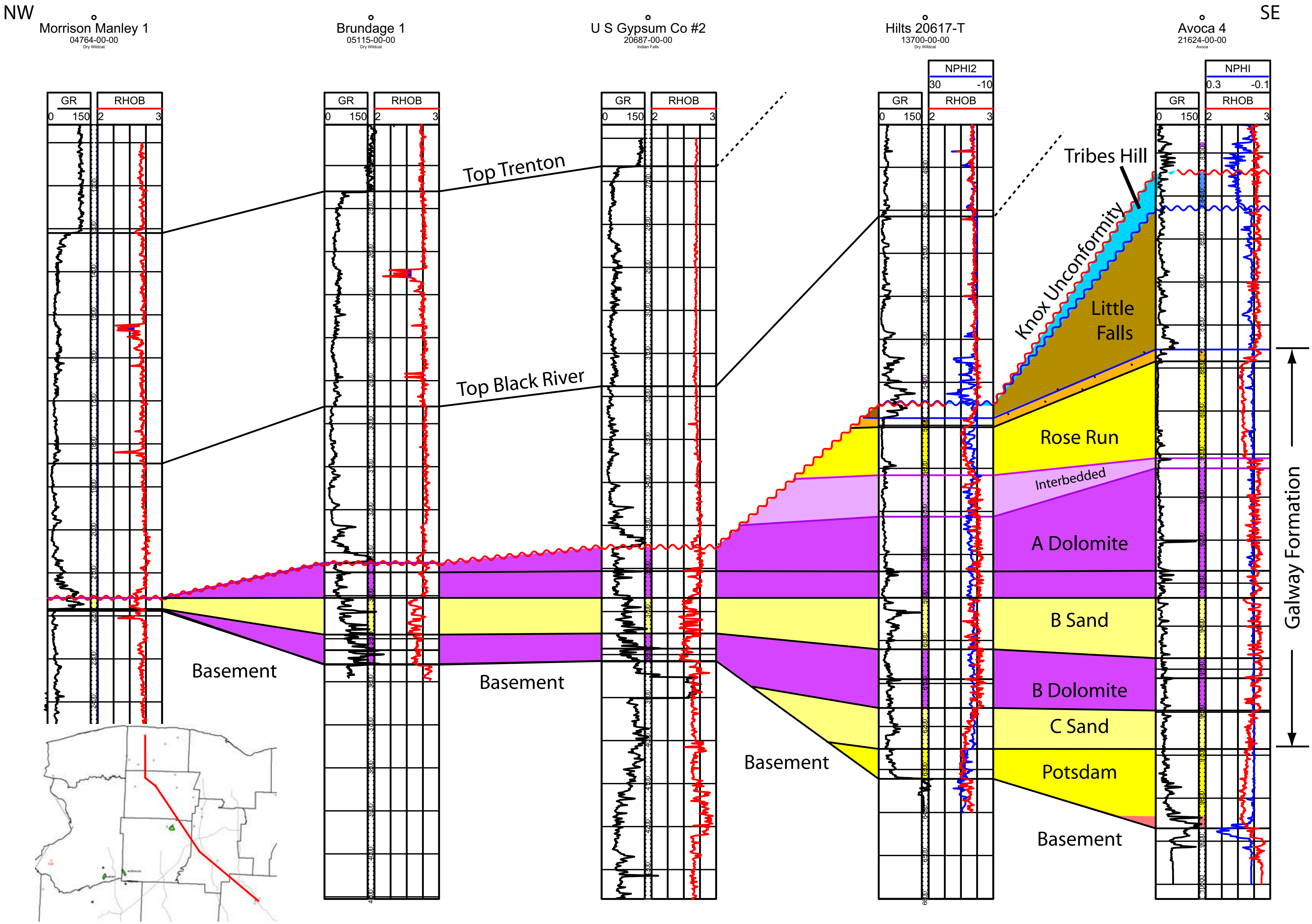


Figure 5. Cross section from Orleans County to Avoca shows onlap of Potsdam and lower Galway and erosion of the Little Falls and Upper Galway under the Knox Unconformity.

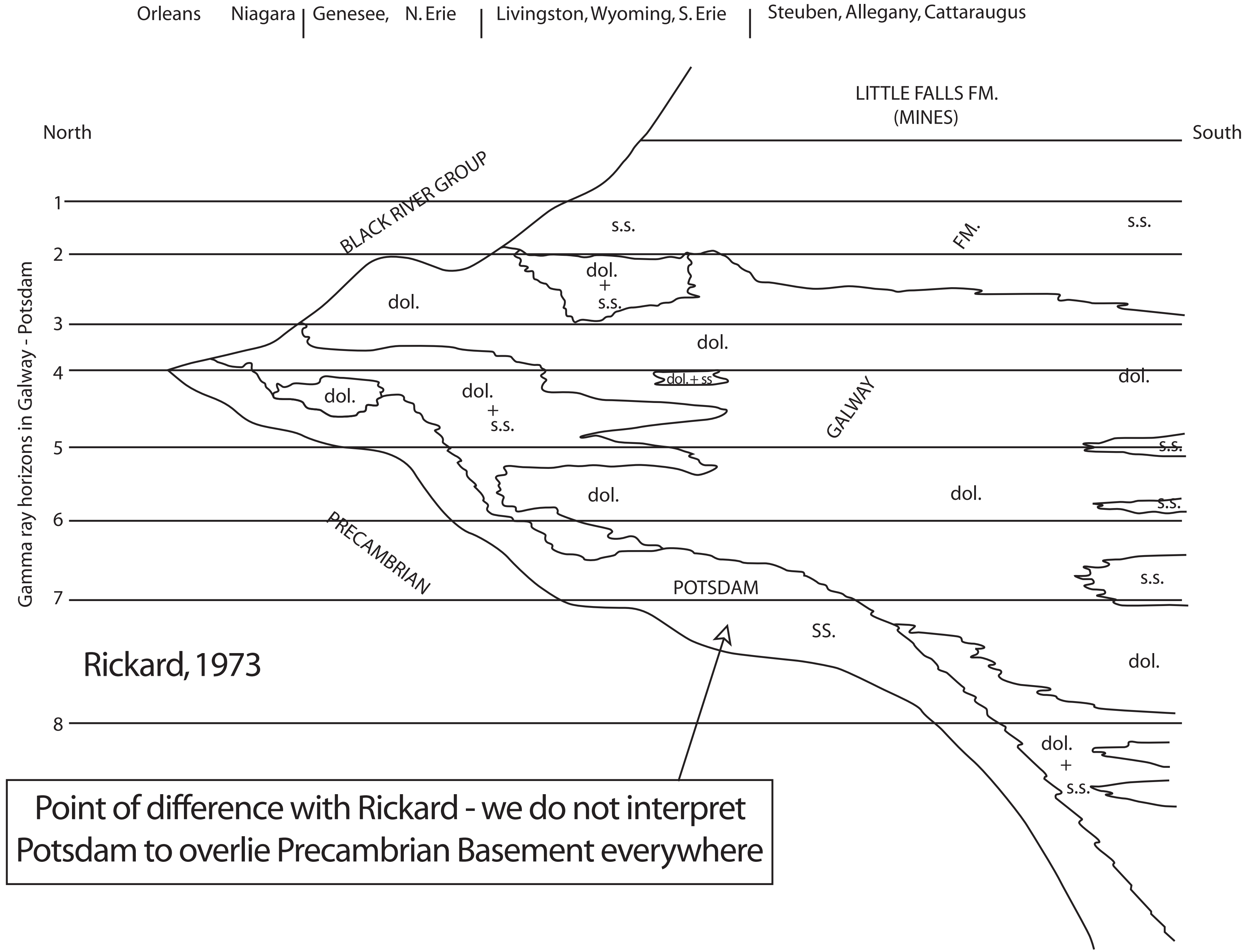


Figure 6. Rickard (1973) correlation scheme for Potsdam, Galway and Little Falls Formations. This is very similar to what we have found except the Potsdam here is interpreted to onlap the basement only in the deepest part of the basin (compar with Figure 5).

The previous approach has major problems as there are places where the sandstone that immediately overlies the basement immediately underlies the Black River Formation and where it may be as young as Late Ordovician in age. For future work, the best way to approach this problem might be to call whatever sandstone immediately overlies the basement the basal sandstone and to keep the name Potsdam as a unit that is demonstrably older than the Galway and free of dolomite interbeds.

NOMENCLATURE

The interval of interest in this study has long been called the Theresa Sandstone in the subsurface, but when compared to the outcrop stratigraphy it appears that name is probably inaccurate. This work shows that the interval of interest is Upper Cambrian in age and occurs above the Potsdam Sandstone (earliest Upper Cambrian in age) and below the Little Falls Formation (uppermost Cambrian in age). Landing of the New York State Museum recently revised all Cambrian and Lower Ordovician stratigraphy in New York State (Figure 3). Landing makes a convincing case that the Theresa Formation is Ordovician in age and is actually younger than even the Tribes Hill Formation. The Theresa only outcrops in the Ottawa Graben of northernmost New York. It may also occur in the subsurface along the eastern side of Lake Ontario where there is a siliciclastic unit overlying the basement that is immediately overlain by the Upper Ordovician Black River Limestone. This being the case, the Theresa, *sensu stricto,* probably never occurs in the subsurface in the central and western parts of the state. According to Landing, the Galway Formation occurs below the Little Falls and above the Potsdam. Using this work, it is clear that the producing formation in Western New York is the Galway Formation.

Until the publication of Landing's work, the state of the nomenclature for the Upper Cambrian and Lower Ordovician was extremely confusing. Fisher (1977) did a regional study of outcrops surrounding the Adirondacks and came up with a model that the Theresa and Galway had different ages but could actually be correlated as a time-transgressive unit. This is a quote on the age of the Theresa Formation from Fisher, 1977:

> "Along the southern and southeastern Adirondack border, the Theresa is wholly of Late Cambrian age. In the St. Lawrence Valley, the Lower Theresa is latest Cambrian (Trempeauleau) age and the upper Theresa is earliest Ordovician (Gasconadian) age. Along the northern Adirondack border, the Theresa is wholly lowermost Ordovician (Gasconadian). Thus the unit transgresses time in a northerly direction."

The Fisher (1977) correlations strain credulity. The idea was that the depositional environment where the Galway was deposited in the Cambrian slowly migrated northward over a period of about 10 million years. There is a fairly well-documented unconformity at the Cambro-Ordovician boundary that is not honored with the time-transgressive facies distribution. The truth is that there are probably several unconformities present in the interval between the Galway and the Theresa (Landing, 2007) and the two formations could not be correlated in any way. It is not the intention of this study to change the name from Theresa to Galway, but to correctly relate the subsurface to the outcrop stratigraphy. The authors of this paper have little interest in what people call the formations. For the purposes of this work, the formation of interest will now be called the Galway.

PLAY CONCEPT

The "Theresa Sandstone" play in New York appears to be an extension of the Rose Run Sandstone play in Ohio which has produced more than 200 BCF and 12 million barrels of oil (Figure 7). In Ohio, most production comes from the Rose Run Sandstone, but there has also been production from the interbedded sandstones and dolomites below the Rose Run in places where they are directly beneath the unconformity. Most of the porosity is of a secondary origin (Riley et al., 2002).

Most of the production in Ohio comes from erosional remnants directly beneath the Knox Unconformity. This is also known as a subcrop play. Erosional remnants are highs surrounded by areas where there was deeper erosion (Figure 8). These structures can form 4-way closures where gas was trapped. The majority of the production comes from the area where the Rose Run and underlying sands subcrop under the Knox Unconformity. Some of the Ohio fields may also occur in structural anticlines or fault bounded structural highs (Ron Riley, pers.comm.). There does appear to be a close association between mapped basement faults and the occurrence of the larger Rose Run Fields. The Cambridge Cross Strike Structural Discontinuity (CCSD) appears to border the Baltic Field on the southwestern edge and the South Randolph Field also seems to be bounded by a fault (Figure 7). In New York, it appears that both erosional remnants and structural anticlines/fault-bounded structural highs are gas-bearing and productive.

PRODUCTION AND FIELD DISCOVERIES IN NEW YORK

To date, there are eight named fields in the Galway/Rose Run trend in New York, seven of which have some production (Table 1). The Bockhahn Field has the highest production to date and is expected to produce 6-9 BCF. The Northwoods and Cascade Brook Fields are the next largest with the others producing little or no gas through December 2006.

Most of the fields in New York were found by drilling 4-way closures visible on seismic. Not every well is porous, so it is not always enough to find a structural closure. There appears to be more porosity in the Rose Run and underlying sandstones toward the west where they either onlap the basement or lie directly below the Knox Unconformity. This may be related to dissolution under the unconformity, or burial fluids being focused onto the arch. This diagenetic aspect adds a further degree of complexity to the play.

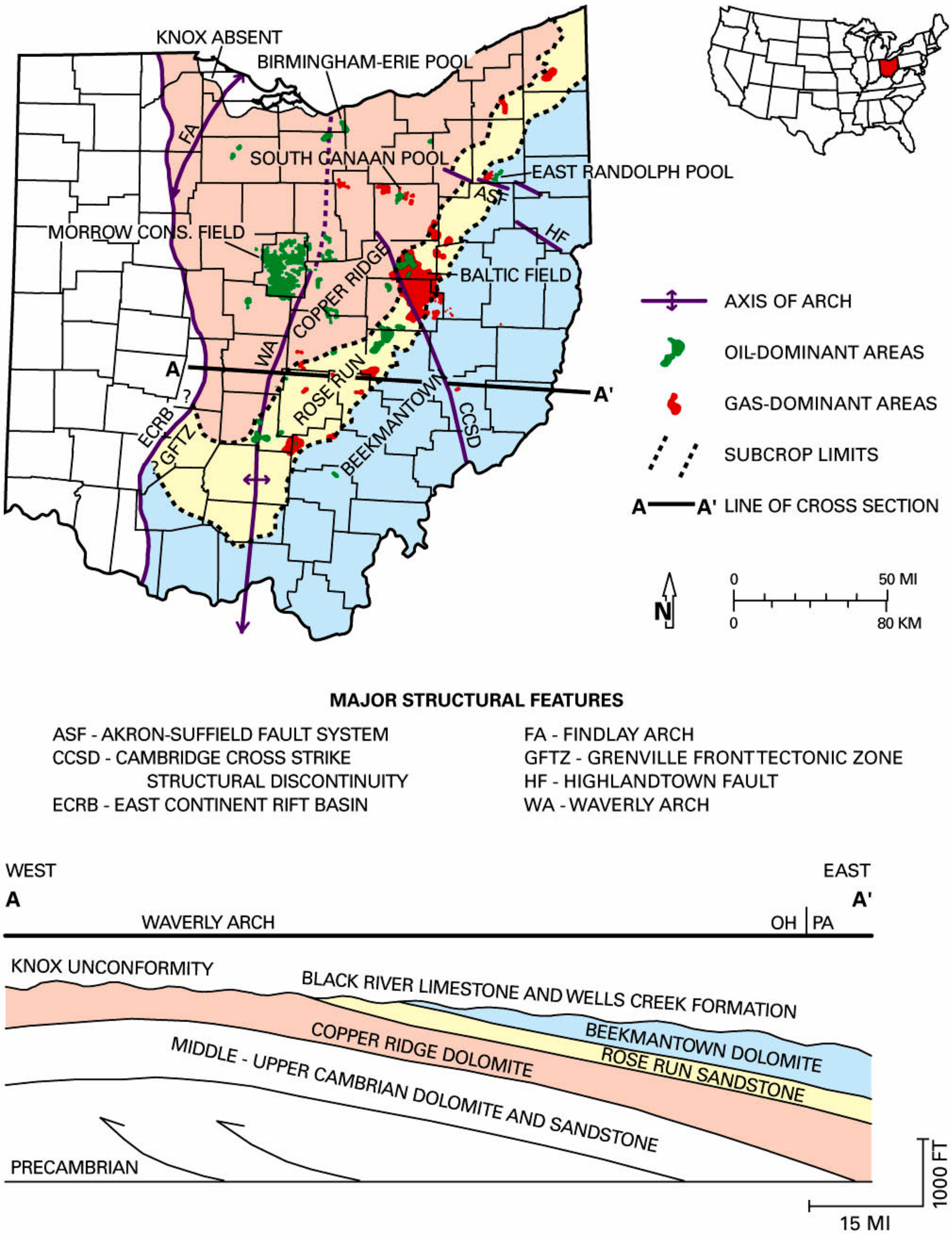


Figure 7. Ohio map and cross section view showing progressively deeper erosion to the northwest (same as New York). Most production comes from the Rose Run and deeper formations where they are directly beneath the unconformity. (From Ron Riley, Ohio Geological Survey)

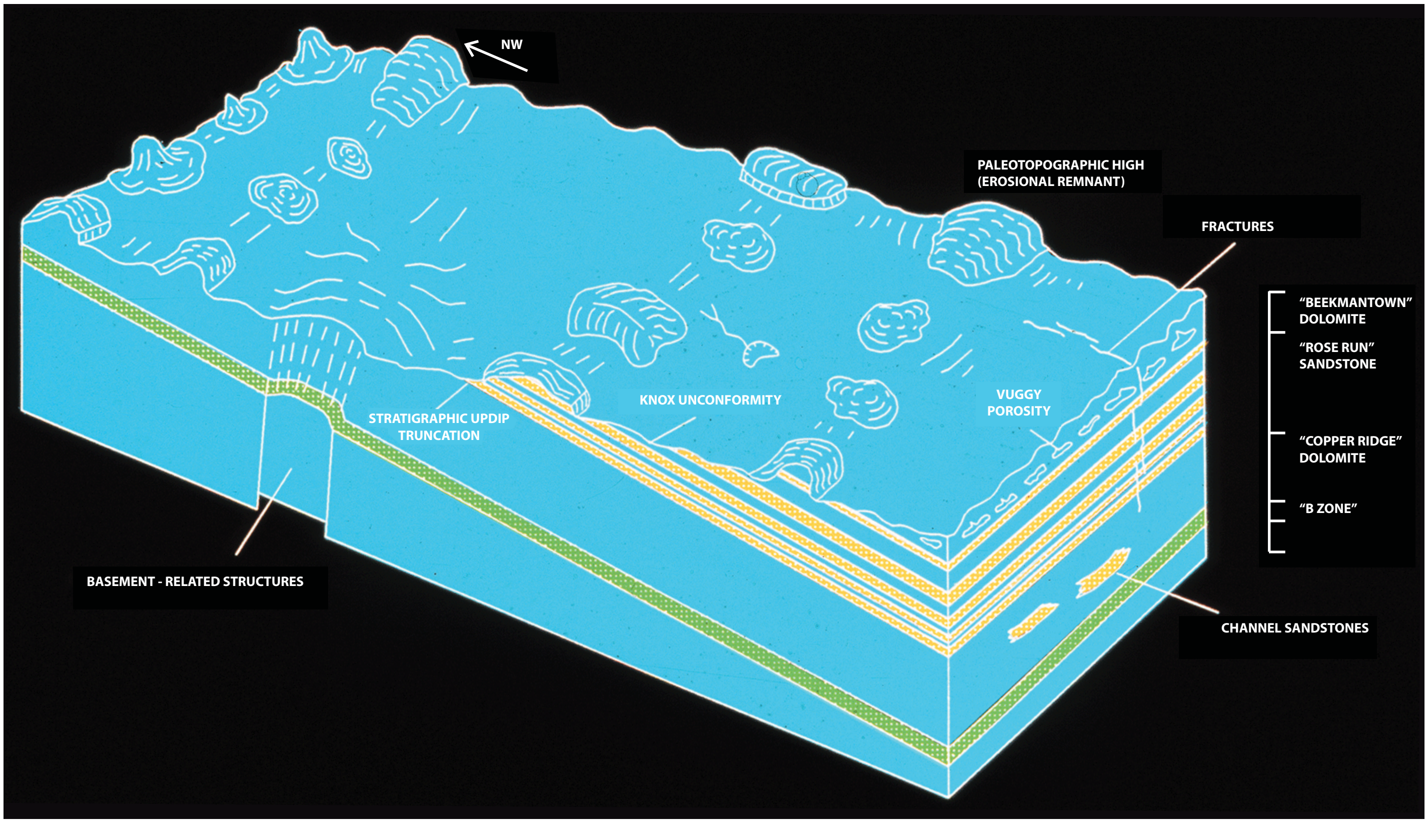


Figure 8. Image shows different play types in Ohio Rose Run and associated Copper Ridge Dolomite and "B Zone" sandstones. Most fields are thought to be erosional remnants under the Knox Unconformity, but some others are thought to be related to basement faults (From Ron Riley, Ohio Geological Survey).

Field	Total Gas Production (mcf)	Years Active	Number of Wells
Bockhahn	1,366,848	2004-2007	3
Cascade Brook	482,036	1991-1993, 2005-2007	10
Northwoods	422,285	1997-2007	2
Hannon	68,871	2007	1
Bixby Hill	29,144	2004-2007	1
Burr Bear	6,744	1996-1998	1
Cagwin	2,711	2005-2007	1
Connoisarauley Creek	0		1

Table 1. Named gas fields in the "Theresa" Sandstone of New York with production through 2006.

Section 2
DATA

Cores, cuttings and thin sections have been described for this study. These analyses were then linked to the wire-line logs to better understand log responses and make cross sections and maps.

CUTTINGS

Drill cuttings, collected in ten foot increments, were examined for three wells in New York. These samples were used to make thin sections from above the Knox Unconformity to the base of the well. Relative abundances of different minerals and rock types were estimated including quartz, dolomite, limestone, clay and chert. Results of these analyses are presented in Figures 9, 10 and 11. These quantitative values help interpret the logs in these and nearby wells. No porosity is visible in the cuttings which are generally very small. In some sandstone intervals, only individual quartz grains are preserved and cements are rarely seen.

The cuttings work has helped to refine log interpretation techniques. In each of the wells, dolomite is picked where the density is greater than 2.8 g/cc, sandstone was picked when the density in low porosity rocks is <2.65 g/cc. Pure quartz has a density of 2.65 g/cc while pure dolomite has a density of 2.86 g/cc. Everything with a density between those values was interpreted to be a mixture of dolomite and sandstone with the values closer to 2.65 g/cc being sandier and those closer to 2.8 g/cc being more dolomitic. PEF logs also help with values between 2.5 and 3 generally being sandstones and those closer to 3.5 being dolomites. Clay-rich intervals generally have leftward shifts in the neutron porosity log but not the density. Limestones have densities around 2.71 and the density and neutron curves overlay each other.

Figure 9 is from the Hannon #1 well in the Hannon Field, Erie County. It shows the relative abundance of various cuttings types, the logs and an interpretation of the rock type. Figure 9 shows that above the interpreted Knox Unconformity, the basal Black River Pamelia Member is composed of clay, dolomite and fine grained sandstone. Below the unconformity, the Rose Run Sandstone is a fine- to medium-grained sandstone that has porosity values between 0 and 8% with higher values toward the base according to the logs. The underlying Rose Run Interbedded and A Dolomite units are mainly composed of sandy dolomite with thin beds of cleaner dolomite and sandstone.

Figure 10 is from the Degolier Unit #1 well in the Bockhahn Field, Erie County. It shows a very similar stratigraphy to that of the Hannon #1 well from the base of the Black River through the Rose Run Sandstone interval. Figure 11 is from the Bockhahn G1 well, also in the Bockhahn Field. Here again the basal Black River is composed mainly of dolomite with some sand and clay. Below the Knox Unconformity, the upper Rose Run Interbedded member is a fine- to medium-grained sandstone with some beds of sandy dolomite. These beds disappear as the upper

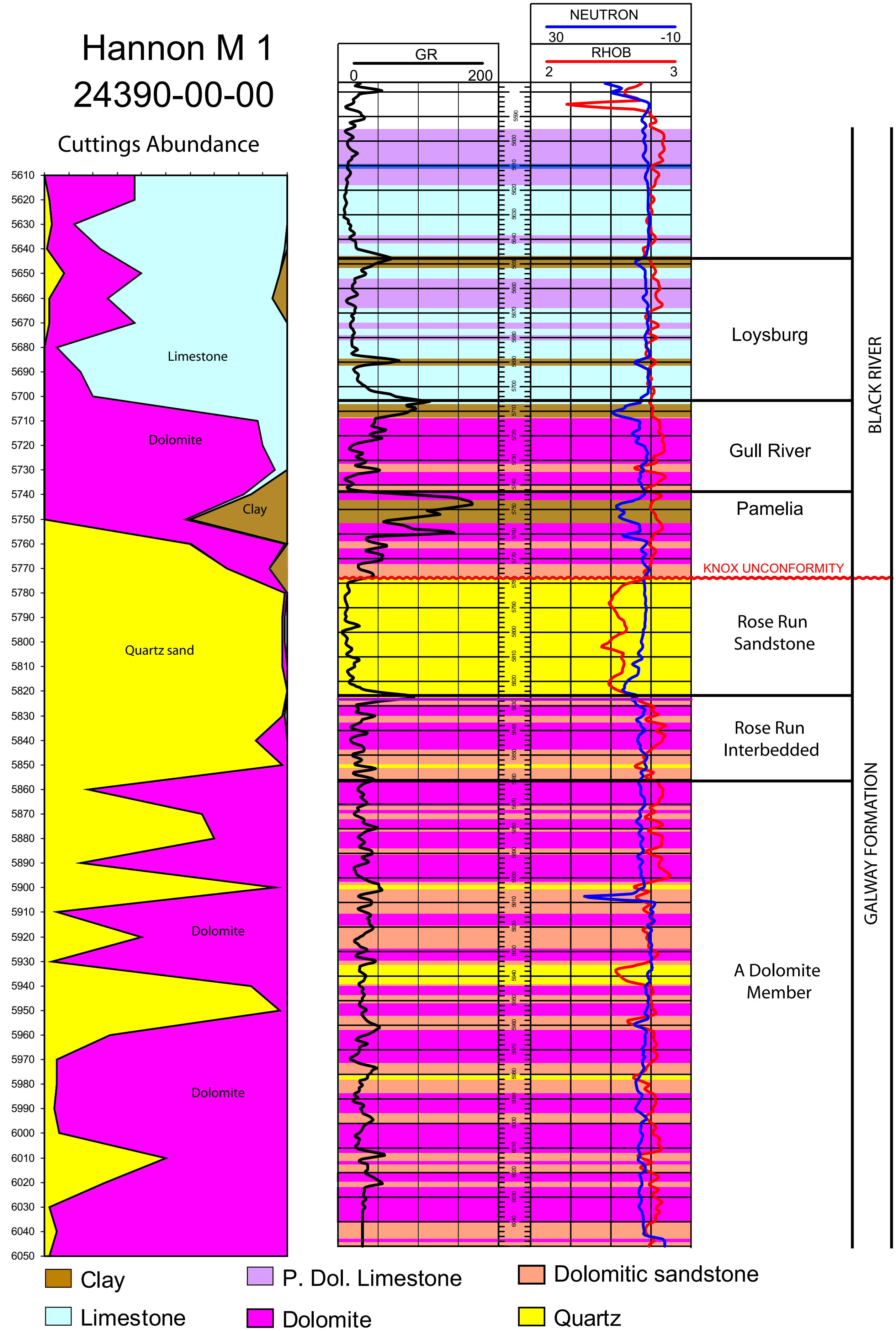


Figure 9. Cuttings and log analysis from the Hannon #1 well in the Hannon Field. The cuttings extend from the lower Black River, across the Knox Unconformity, through the Rose Run Sandstone and into the A Dolomite Member.

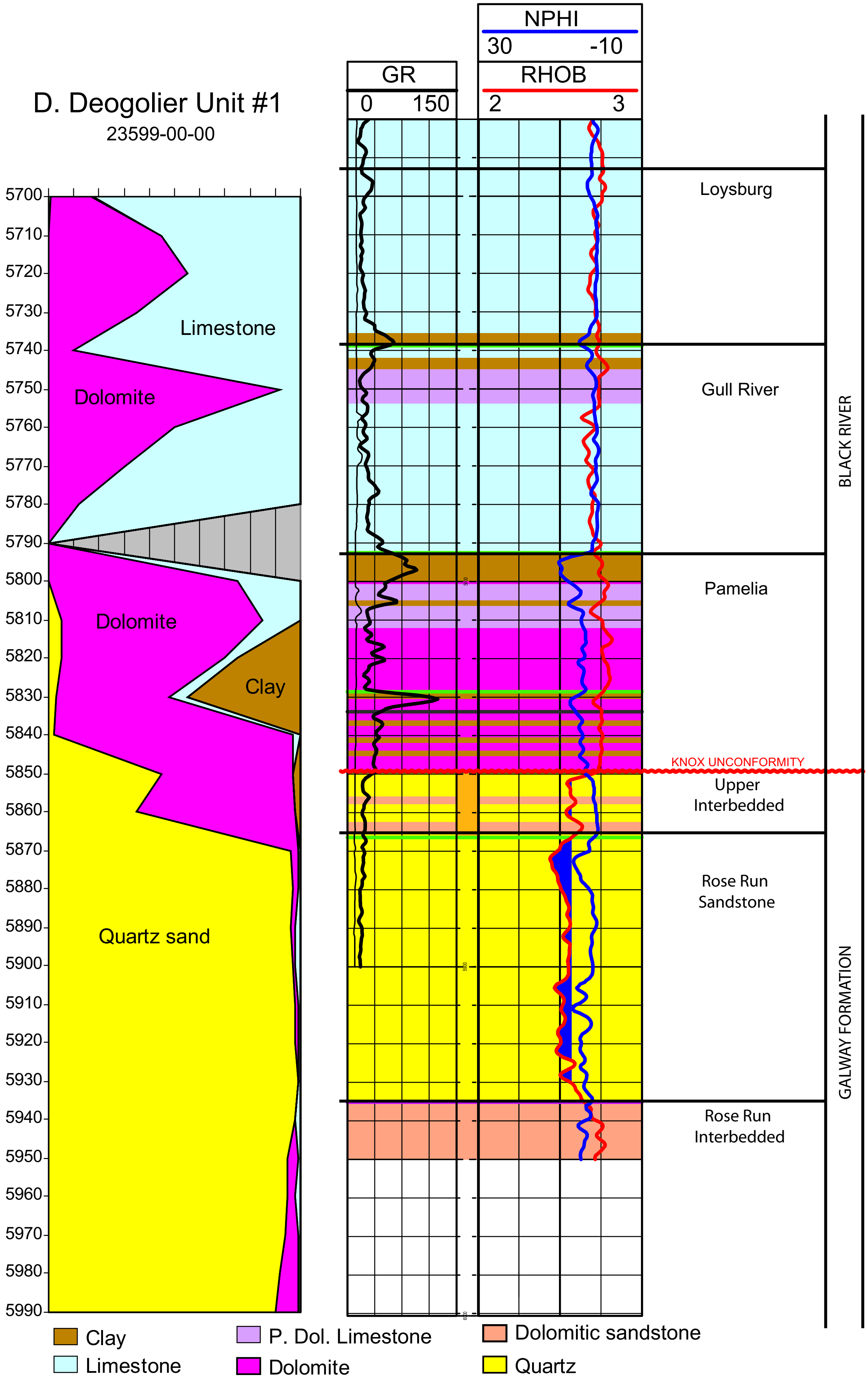


Figure 10. Cuttings and log analysis from the Degolier #1 well in the Bockhahn Field. This figure shows stratigraphy from the Lower Black River and Rose Run Sandstone Member of the Galway Formation.

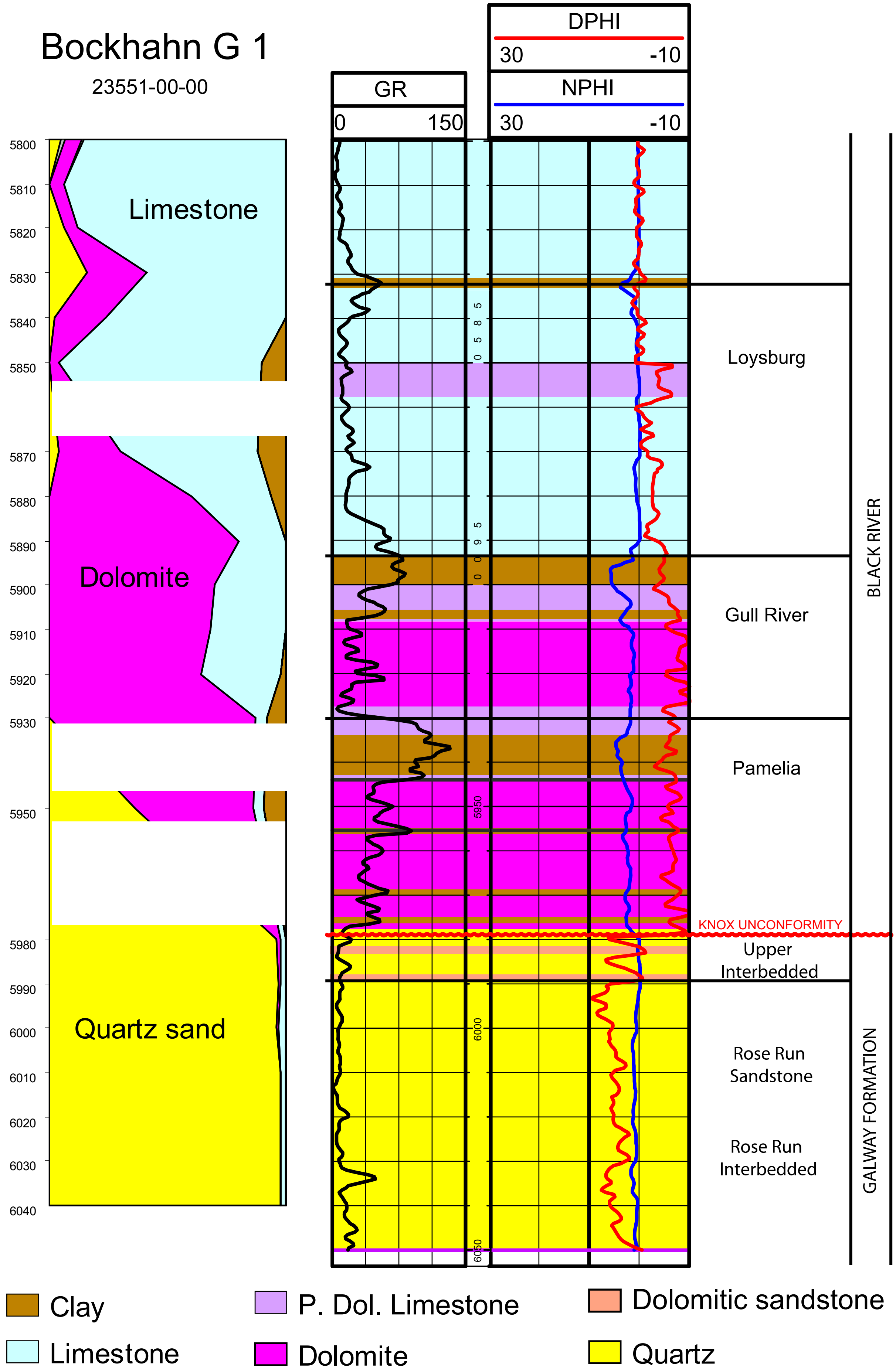


Figure 11. Cuttings and log analysis from the G Bockhahn #1 well in the Bockhahn Field. The interval begins in the lower Black River and extends into the Rose Run Sandstone Member of the Galway Formation

interbedded member grades into the clean sandstone that makes up the bulk of the Rose Run unit. This well did not reach the lower interbedded member of the Rose Run.

Several cuttings descriptions of older wells were also used. These descriptions were prepared by Geological Sample Log Co. in the 1960's. They are an excellent tool for correlating wells with poor logs or no logs at all. More than 50 of these descriptions were imported into a Petra project on the Galway. A sample of one of these logs is presented in Figure 12.

CONVENTIONAL CORE AND CORE THIN SECTIONS

The New York State Museum has two cores and associated thin sections from the Galway Formation both of which are described for this report. One is the Kennedy #1 well from Livingston County and the other is the Hooker #1 from Erie County. A report on the analysis of sidewall cores from the Stahl #1 well, which produces from the Rose Run Sandstone in Wyoming County, was also obtained.

Kennedy #1 (04630-00-00)

The core from the Kennedy #1 well is in the Rose Run Sandstone, which is a cross-bedded shallow marine sandstone (Figure 13). This is the only core in the clean sandstone interval of the Rose Run. The core is in poor shape with some intervals missing and is about 23 feet long. It is almost entirely composed of fine to coarse-sized quartz sand and quartz overgrowth cement (Figures 14 and 15). The porosity is almost all of a secondary nature and can be as high as 12%, although most of it is lower (Table 2). The average porosity for the core is about 6%. The main pore types appear to be secondary from leached quartz sand and quartz overgrowth cement (Figure 15). Leaching of quartz is generally considered rare and will be discussed in a later section.

According to the logs for this well there are two lobes of porosity in the Rose Run below the cored interval. These intervals spike to porosities greater than 30%. These values are easily the highest values found in the Rose Run in New York. They are so high that they may reflect a problem with the density log. The measured core porosities agree with the log values from the cored interval, which suggests that the log response below the core may be real and not just a problem with the wireline tool. Perhaps these high porosity zones exist, but do not have values as high as the logs suggest.

Hooker Chemical #1 (06669-00-00)

The Hooker Chemical #1 well was originally drilled as a disposal well near the city of Buffalo. The core from this well consists of B Sand and B Dolomite which directly overlie the basement in that part of the state. The core is composed of mixed dolomite and siliciclastics. There are very few samples that are either pure dolomite or pure sandstone. The interbedded carbonates mainly look to be of a very shallow origin with common ooids and peritidal

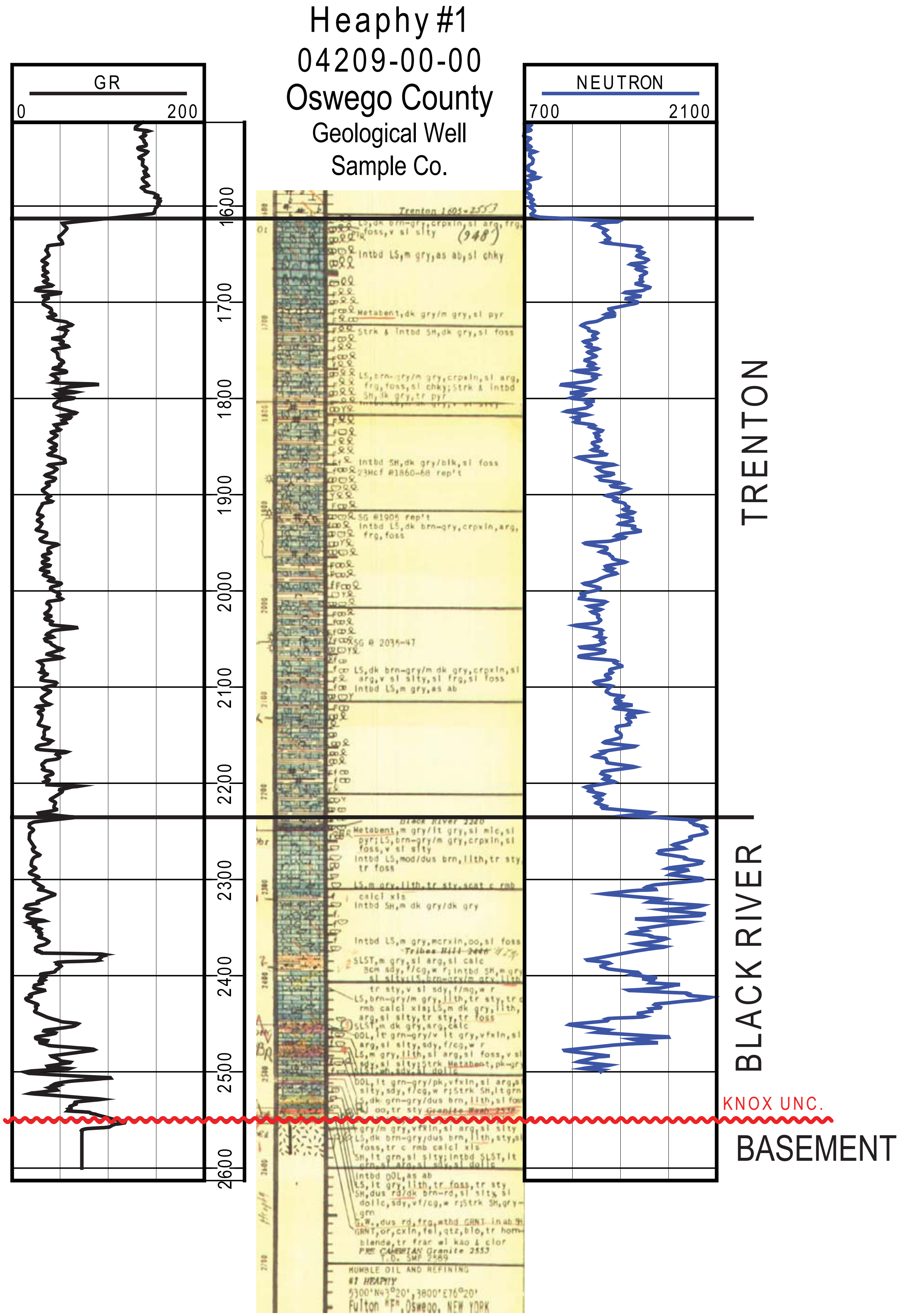


Figure 12. In addition to wireline logs the Heaphy #1 well from Oswego County east of Lake Ontario has a cuttings sample description produced by the Geological Well Sample Co. The cutting descriptions were colored with sandstone as yellow, limestone colored blue, dolomite colored pink, shale colored gray, and silstone colored orange. Note that the Knox Unconfomirty immediately overlies the basement in this well.

Figure 13. Core slab photo of cross-bedded Rose Run Sandstone from Kennedy #1 well.

Depth (ft.)	Visible Porosity	Depth (ft.)	Visible Porosity
5660	12.63	5672	9.66
5661	7.29	5673	3.21
5662	10.28	5674	11.13
5663	12.36	5675	1.78
5664	2.45	5676	6.53
5665	3.64	5677	3.68
5666	3.64	5678	6.08
5667	3.37	5679	2.94
5668	5.18	5680	12.15
5669	8.93	5681	4.4
5670	11.11	5682	1.55
5671	5.52	average	7.20

Table 2. Kennedy #1 porosity estimates made from core thinsections.

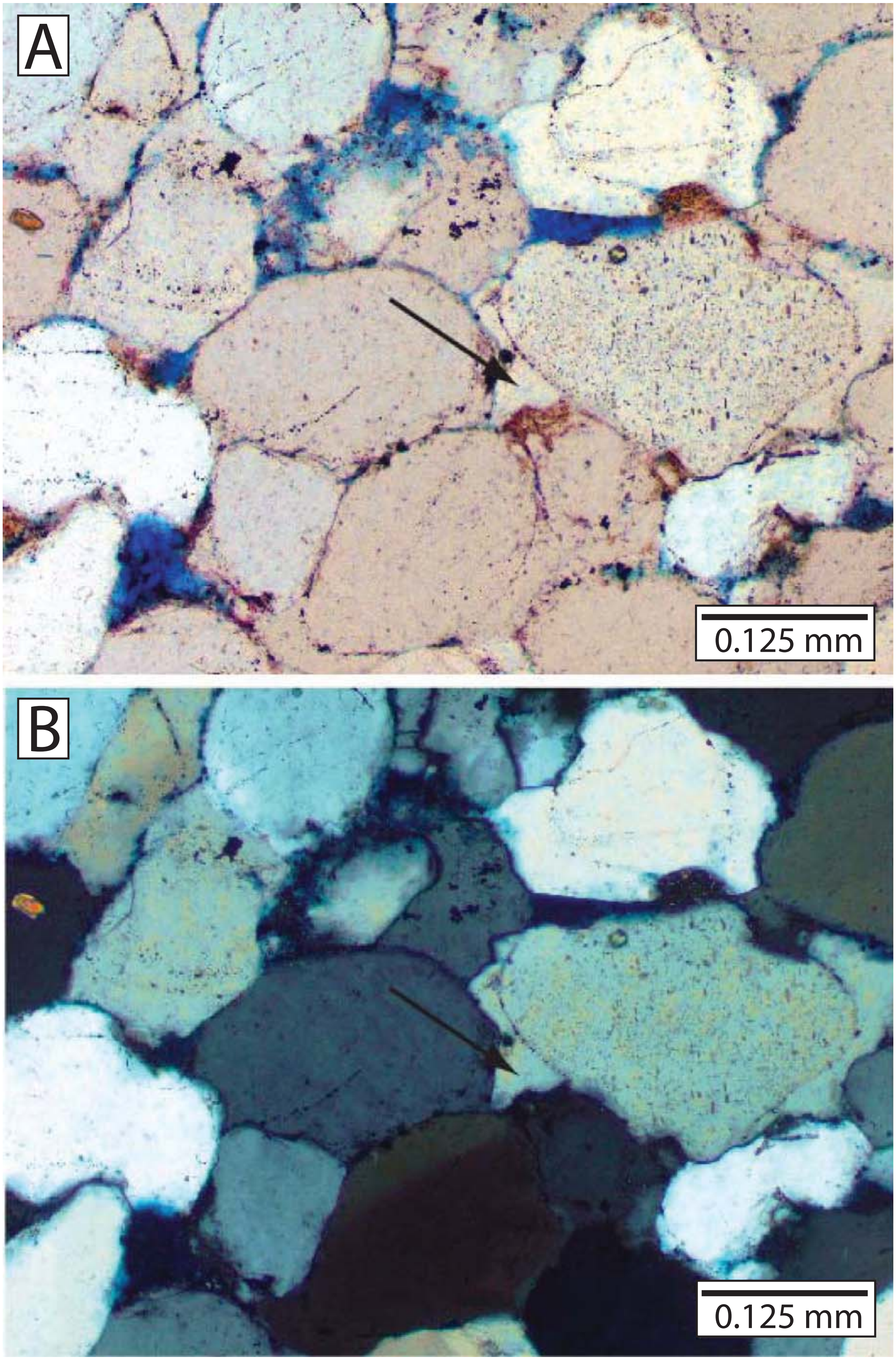


Figure 14. Quartz overgrowth cements from sample at 5665 ft. A) Plane light B) Cross polarized light show that cement cros in optical continuity with grain.

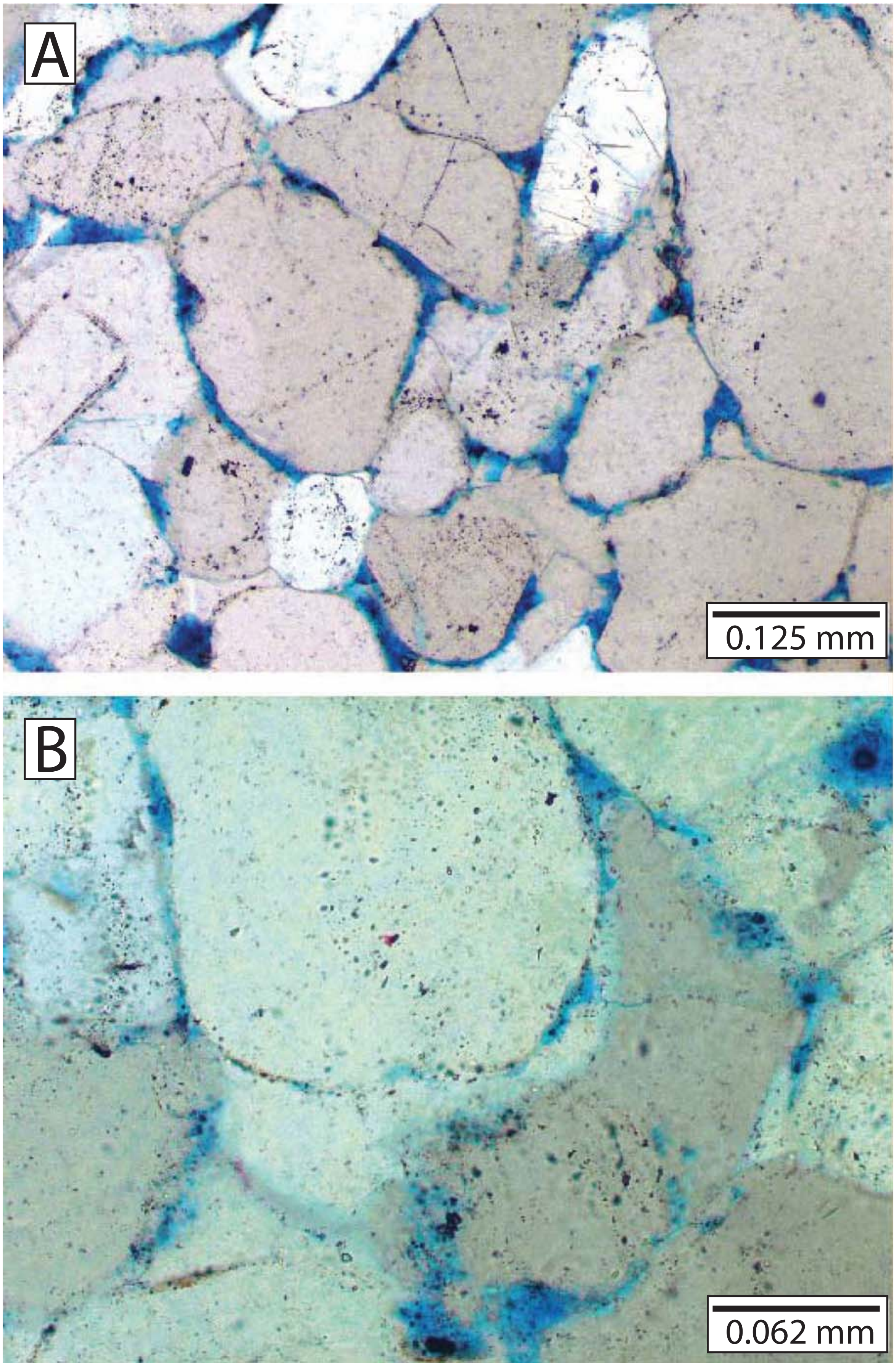


Figure 15. Leached quartz sandstone from Kennedy #1 well. A) Sample from 5679 feet shows leaching concentrated in zone between sand grains and quartz overgrowth cement. B) Closeup of same sample show that quartz grains and cement are leached.

laminates which both form in intertidal to supratidal settings. There is one interval from 2940-2965 ft. that is rich in glauconite and may be of a slightly deeper lagoonal origin.

The B Dolomite and B Sand consist of thin beds of dolomite, sandstone, sandy dolomite and dolomite-cemented sandstone (Figure 16). The B Sand is very feldspathic in this area. The graph on the left side of the figure shows the relative abundance of siliciclastics in yellow, dolomite in pink, glauconite in green and a few other constituents in other colors.

Porosity and permeability measurements from core samples are presented in Table 3. The core plug porosity values can be as high as 10% and have permeabilities up to 7 mD. Some sections have porosities as high as 9%, but little or no permeability. Other samples have porosities as low as 2% with a millidarcy of permeability. Fractures are likely to have enhanced permeability in samples with low porosity but higher permeability. A linear trend placed over the porosity vs. permeability cross plot indicates a 5% cutoff for effective porosity (Figure 17).

Figures 18A and 18B show that while the dolomites can be porous, the siliciclastic-rich strata have slightly higher porosity on average. To put this into perspective, the samples composed of 75-100% quartz and feldspar have an average porosity of 5.85%. Those with 25-75% quartz and feldspar have an average of 4.4% and those with 0-25% quartz and feldspar have an average porosity of 3.5%. Feldspathic sandstones are likely to have higher porosity than those with little feldspar because feldspar is easily dissolved. In most cases, feldspar cannot be transported as far as quartz in most cases because it breaks apart easily. Therefore the abundance of feldspar is likely to increase as you get closer to the source area which would be exposed basement rocks. It may be that sandstones closer to the basement and closer to the source area are more porous because they had higher feldspar content.

Table 4 shows the relative abundance of each of six pore types found in the thin sections. The most abundant pore type is leached feldspar (48%) followed by leached dolomite (19%), moldic (18%) and interparticle (11%) with minor amounts of leached quartz and intercrystalline. The moldic porosity probably occurs where entire feldspar or carbonate grains were dissolved.

Figure 19 shows some of the only primary porosity found in dolomite. Figure 19A shows primary interparticle porosity in a dolomitized ooid grainstone and Figure 19B shows intercrystalline porosity in a dolomite.

Figures 20 and 21 show examples of leached dolomite which is common in these cores. Close examination of the leaching shows that the cores of the rhombs are most commonly dissolved (Figures 20A and B and 21A) sometimes to the point where the rhombs collapse (Figure 21B). The later ferroan dolomite which stains a dark blue color is rarely if ever leached. The earlier non-ferroan dolomite is much more likely to experience dissolution.

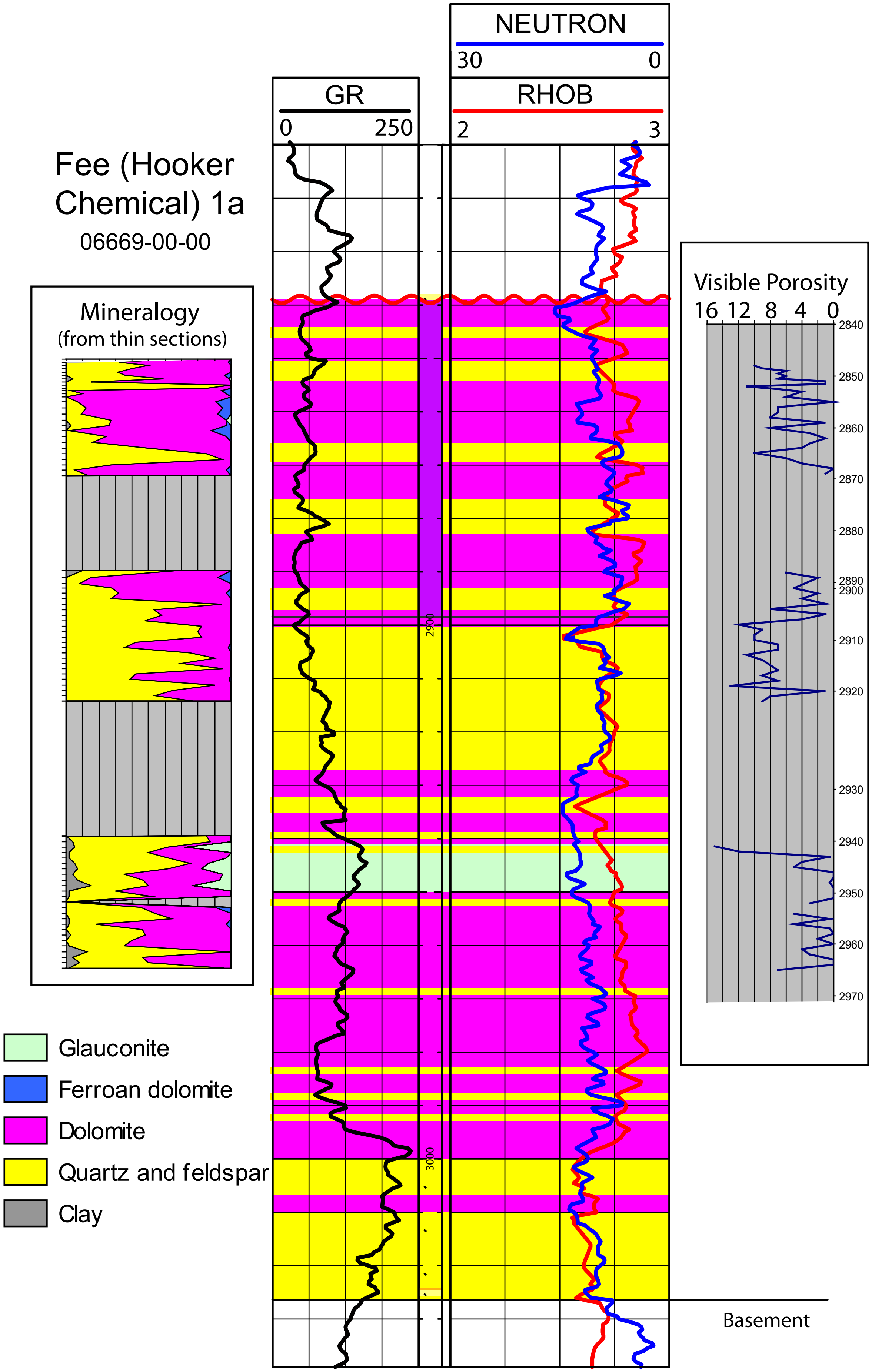


Figure 16. Semi-quantitative analysis of thin sections from Hooker Chemical #1 well. Left column is the minerology abundances from thin section, middle is interpreted logs and the right column is th eestimated porosity from thin sections.

Hooker Chemical #1 Porosity and Permeability		
Depth	Porosity	Permeability (air)
2906.1	10.1	6.8
3011	9.2	0.8
3012	9.2	0.01
2906.5	8.9	4.8
2849.4	8.5	3.2
3014.2	8.1	0.01
2848.7	8	2.3
2849	7.8	7.7
2896	7.2	1.9
2898.2	7.2	0.01
2901.3	7.1	3.1
2940	6.9	0.01
3018.8	6.9	0.01
3011.6	6.2	0.01
3002.5	6.1	1.4
2992.9	5.1	1.2
2869.5	5	0.01
2870.5	4.9	0.01
3013.2	4.9	0.01
3010.2	4.7	0.6
3009.1	4.5	1.1
2940.6	4.3	0.01
3019.6	3.9	0.01
2898.5	3.3	0.01
2901.7	3.3	1
2992.4	3.1	0.7
2870.3	3	0.01
2995.4	2.9	0.6
2897.8	2.8	0.01
2968.9	2.4	0.01
3008.8	2.4	0.01
2896.5	2.3	0.01
2988.1	2	1.1
3031.5	1.6	0.01
2849.8	1.5	0.01
2897.3	1.5	0.01
2896.8	1.2	0.01
Average	5.08	1.04
Median	4.9	0.01

Table 3. Porosity and permeability values for the Hooker Chemical #1 well in Niagara County.

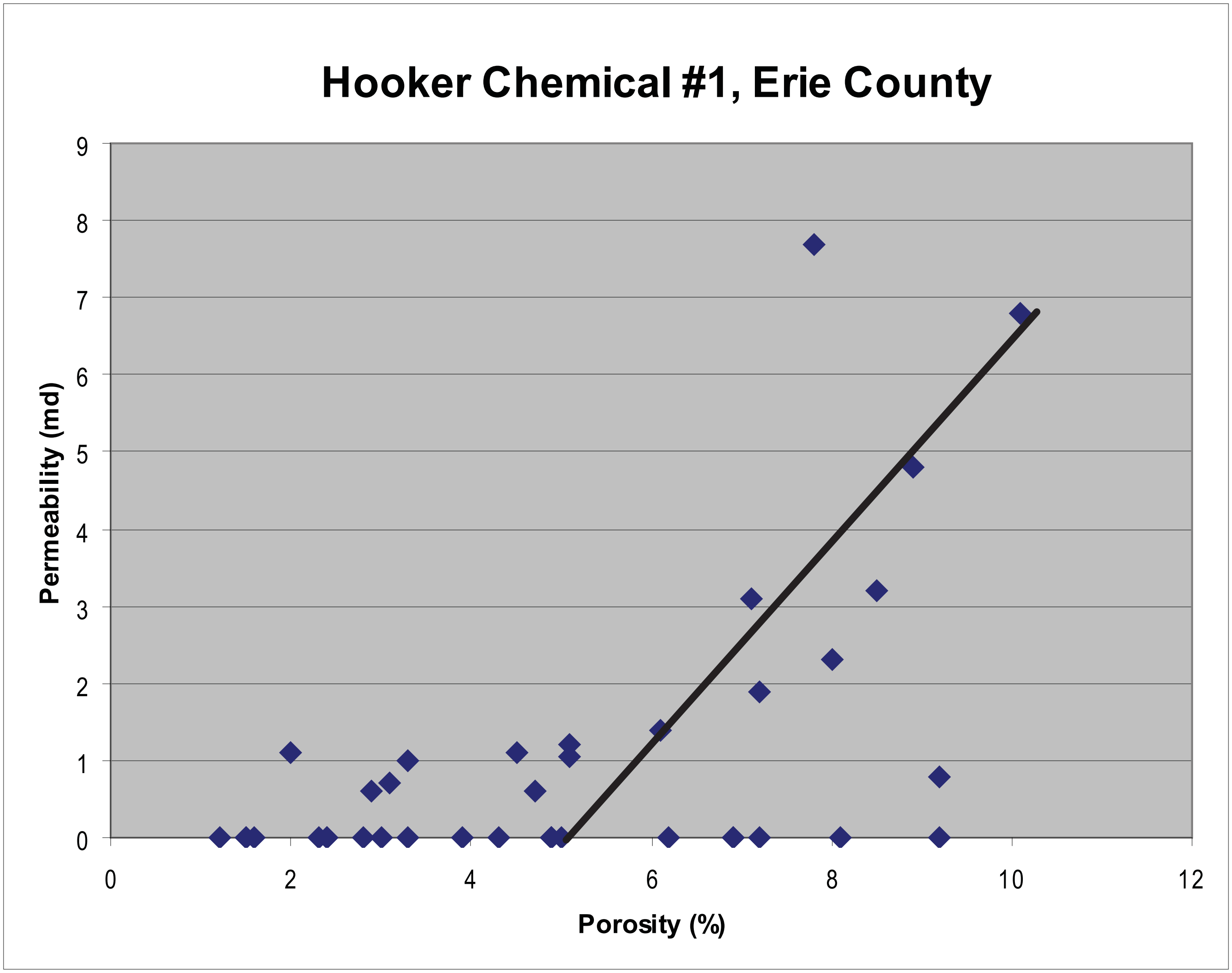
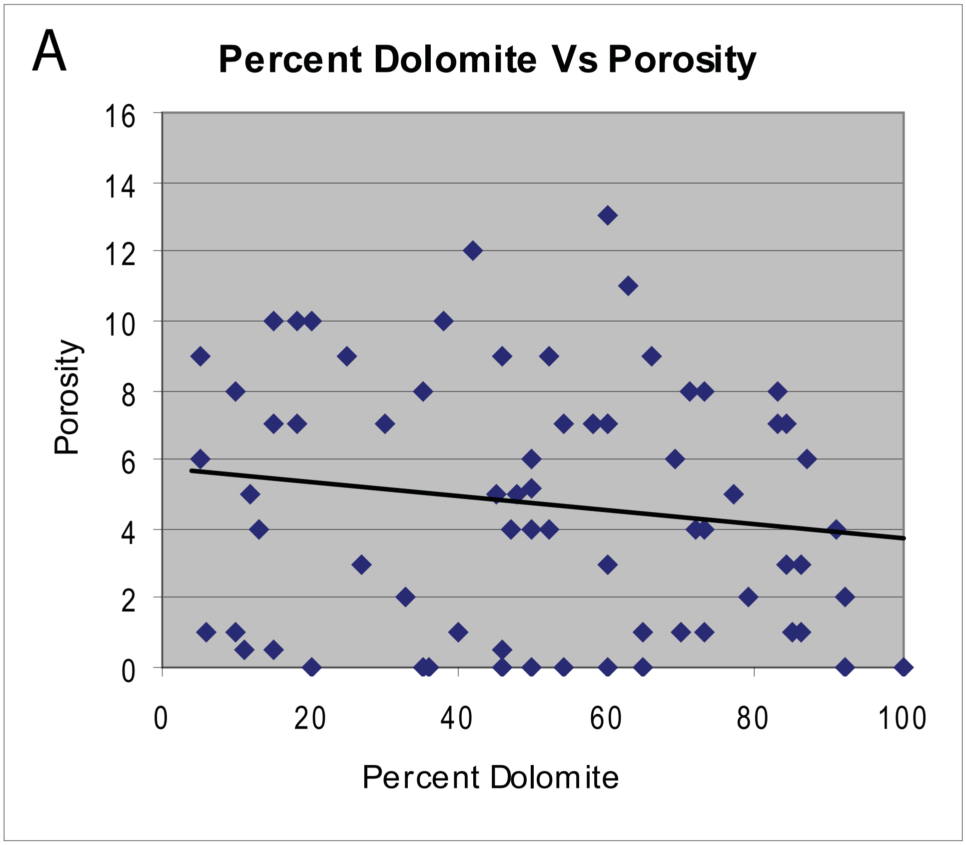


Figure 17. Porosity and permeability from Hooker Chemical #1 well in Erie County. Sampled interval consists of A Dolomite and B Dolomite .

Pore Type Abundance Hooker Chemcial #1A					
Interparticle	intercrystalline	Leached Dolomite	Leached Feldspar	Leached Quartz	Moldic
0.11	0.01	0.19	0.48	0.03	0.18

Table 4. Pore type abundances from the Hooker Chemcal #1A well in Niagara County.



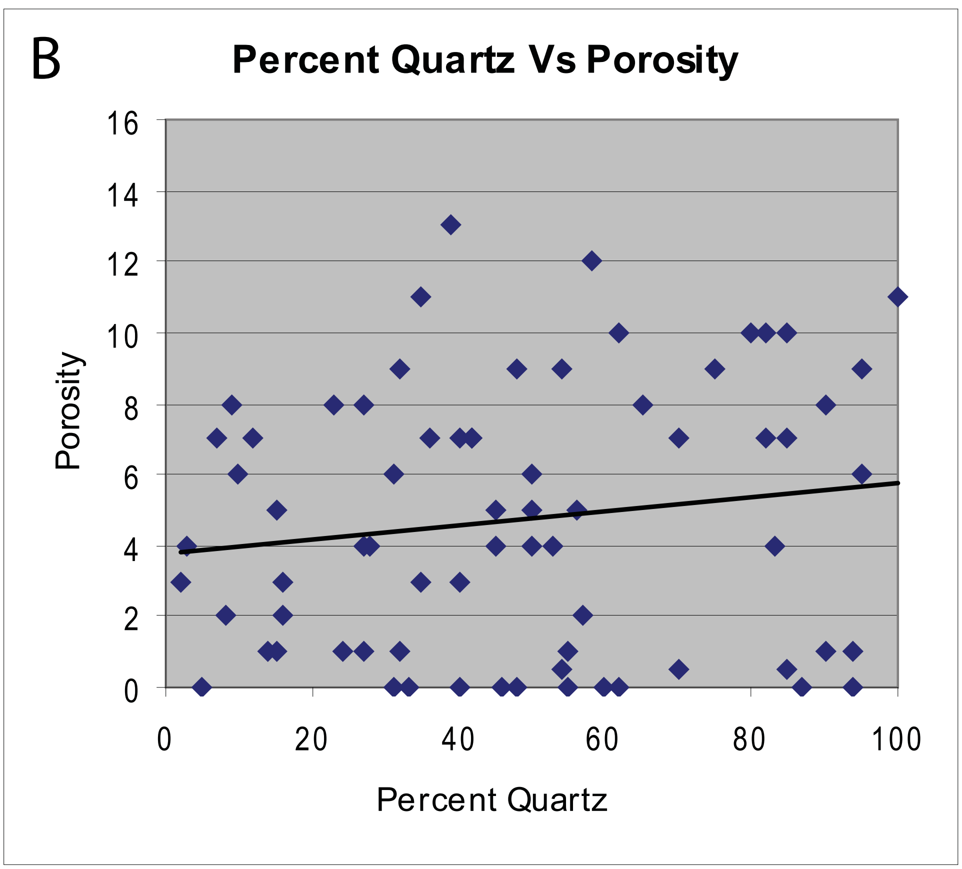


Figure 18. A) Graph of percent dolomite versus estimated visible porosity and B) percent siliciclastics (quartz and feldspar) versus estimated visible porosity. There is a slight increase in averate porosity with incrreasing siliclastics and a slight decreas in porosity with increasing dolomite.

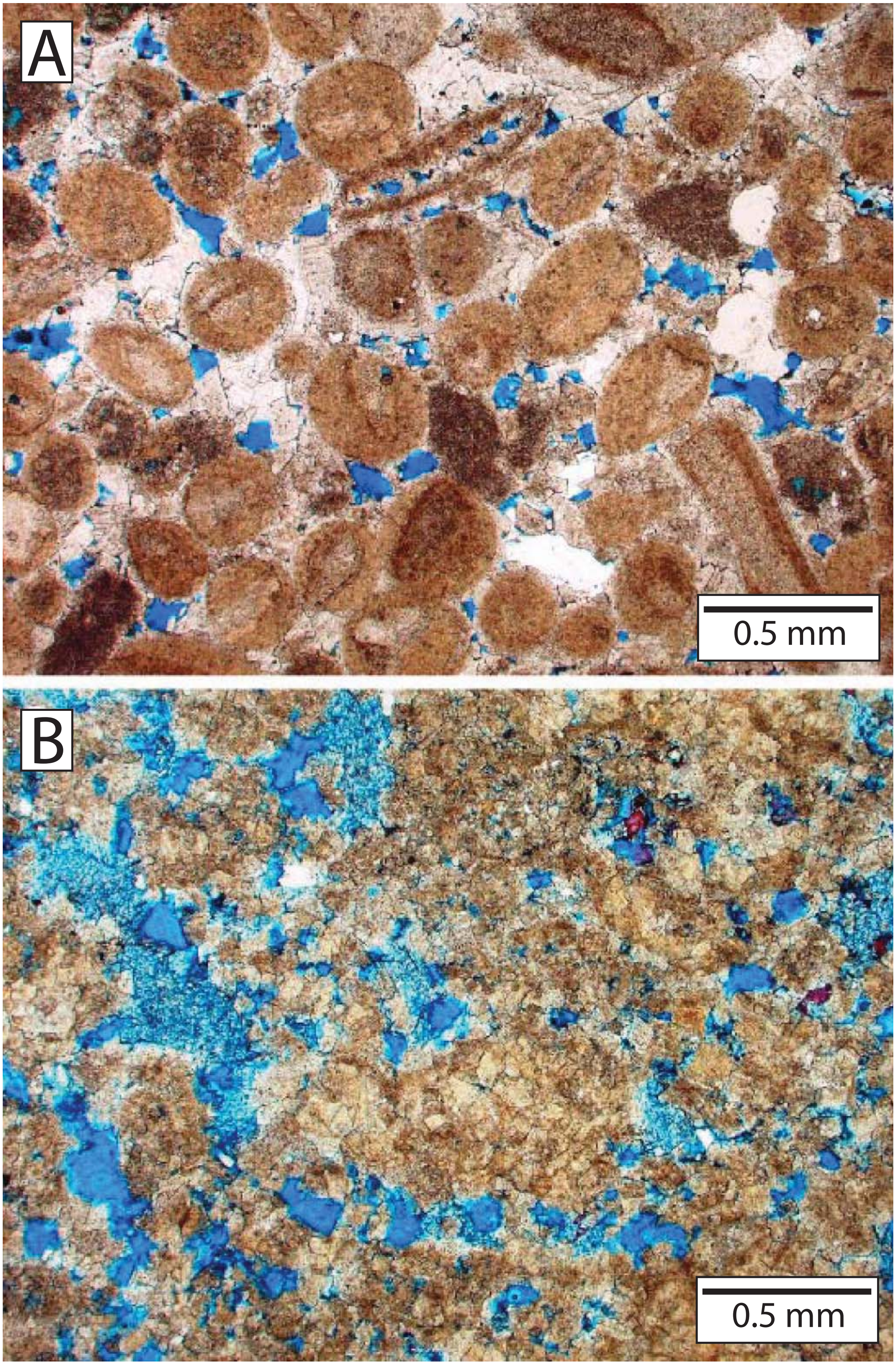


Figure 19. Porous dolomite from Hooker Chemical #1 core. A) Interparticle porosit in dolomitized ooid grainstone (2857').
B) Intercrystalline porosity partially filled with later ferroan dolomite which is stained blue (2858').

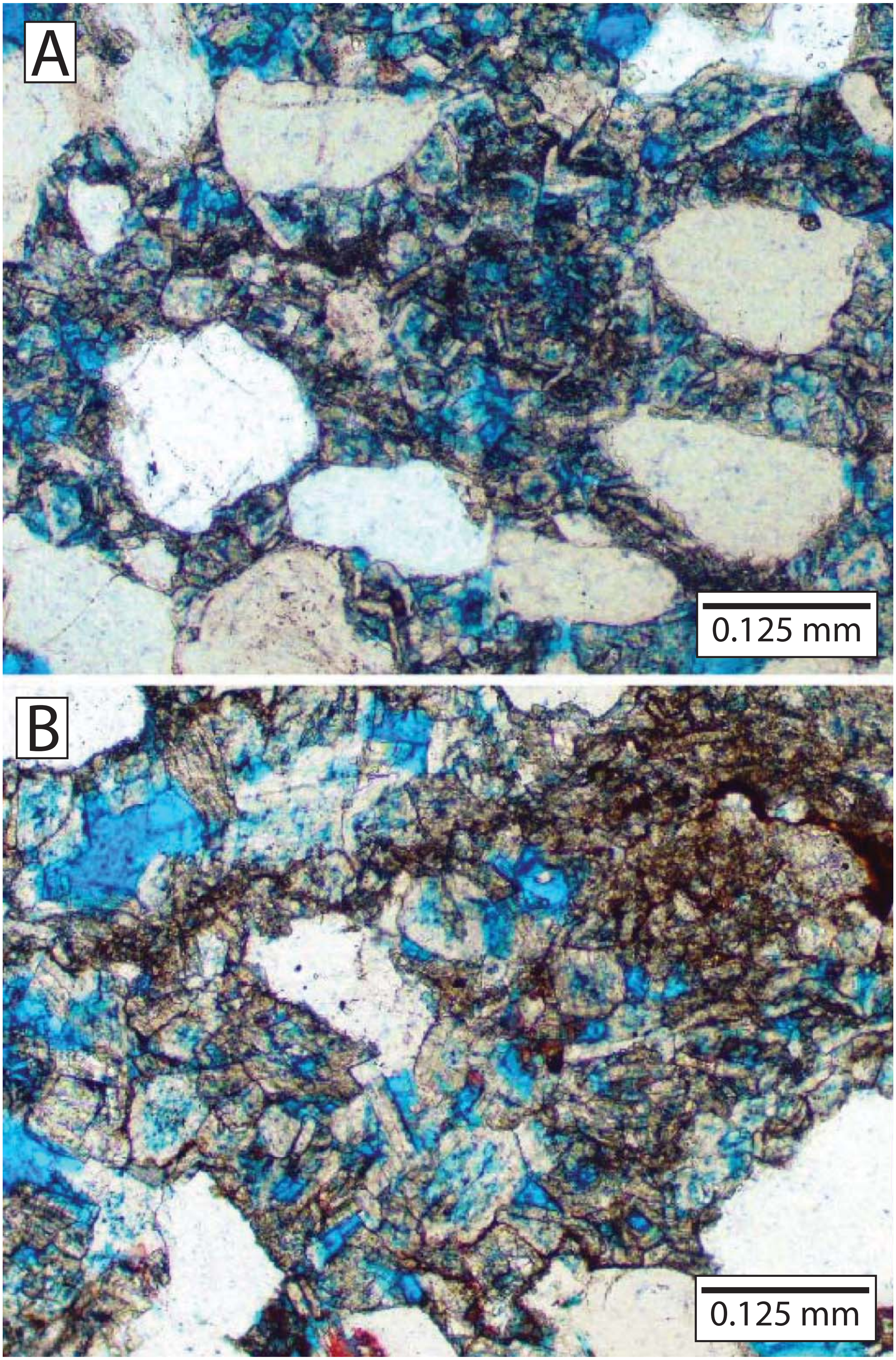


Figure 19. Leached dolomite from Hooker Chemical #1 core. A) Dolomite cement between quartz grains has been dissolved, especially in the middle of the rhombs (2911'). B) Again, cores of dolomite rhombs are leached (2841').

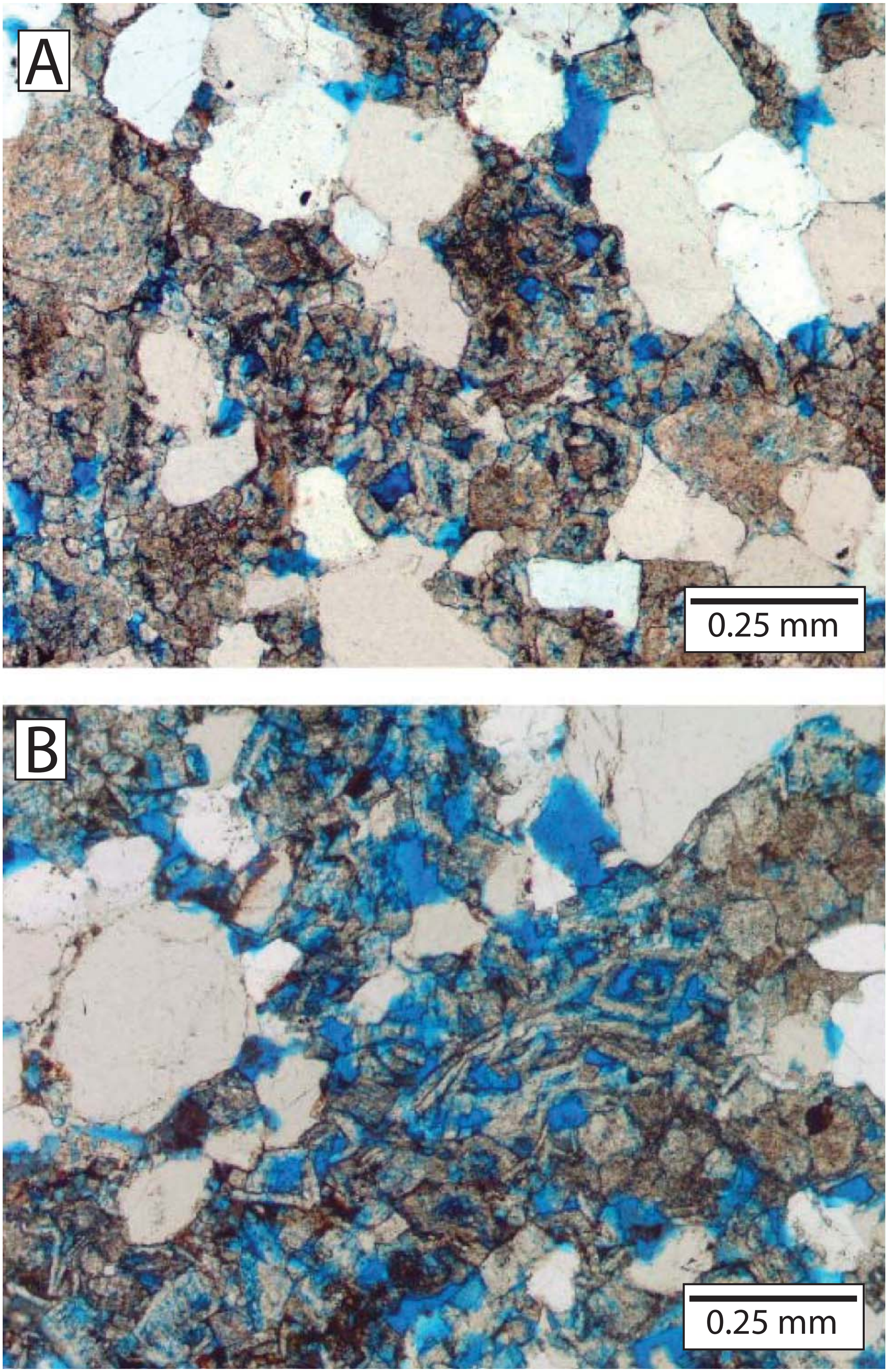


Figure 21. More leached dolomite from Hooker Chemical #1 core. A) Dolomite cement between quartz grains has been dissolved, especially in the middle of rhombs (2912'). B) Dolomite leached to the point where rhombs collapsed (2941').

Figure 22 shows leached feldspar, which is the most common pore type found in this core. It makes up approximately 48% of the porosity (plus some percentage of the moldic porosity). In some cases feldspar overgrowth cement also gets leached (Figure 23) suggesting that at least some dissolution occurred after feldspar cementation.

Figure 24 shows leached quartz and feldspar. Quartz leaching was also responsible for most of the porosity in the Kennedy #1 core (Figure 15).

Stahl #1 (22655-00-00)

The Stahl #1 well, located in the Northwoods Field of Wyoming County, has produced more than 300 MMCF from the basal Little Falls and upper Rose Run. Twenty sidewall cores were taken from the producing interval for analysis. Point counting of various constituents was done by Omni Labs and graphed in Figure 25. The areas shaded green represent visible porosity which is clearly higher in the sand-rich intervals than it is in the dolomite-rich intervals. The logs for this well do not go as deep as the sidewall cores and are not displayed here. Visible porosity ranged from 0-10% with most values in the sandstones around 7%. Pore types found in the report include primary interparticle, moldic and leached quartz and feldspar (Jacobi et al., 1999).

STRATIGRAPHY

The subject interval of this report includes the Little Falls, Galway and Potsdam Formations, with most of the efforts focused on the Galway. Figure 26 is a type log from the Hilts #1 well that shows all of the formations and informal members in the study interval. The Galway and underlying Potsdam formations thicken from north to south (Figure27). However, the Little Falls and Tribes Hill Formations thicken in a more southeasterly direction (Figure 28) This implies that there must have been a major change in subsidence patterns between the deposition of the Galway and the deposition and erosion of the Little Falls and Tribes Hill Formations. This may be related to uplift of a NE-SW trending arch and/or increased subsidence to the southeast.

Knox Unconformity

Picking the Knox Unconformity is not always easy and there is a good chance that it has not always been picked correctly in this report. There are two ways to approach the pick – from the top down and from the bottom up. Coming from the top down, the strata overlying the unconformity are fairly flat lying and consistent but there are slight variations in different areas. Areas that were eroded more deeply may have a thicker Pamelia section. The Pamelia has an interval that is hot on the gamma ray that consists of shaly dolomite and sandstone but does not always immediately overly the unconformity. From the bottom up, different strata underlie the unconformity in different areas. Log character can be traced in from neighboring wells and when it can no longer be correlated one may have crossed the unconformity.

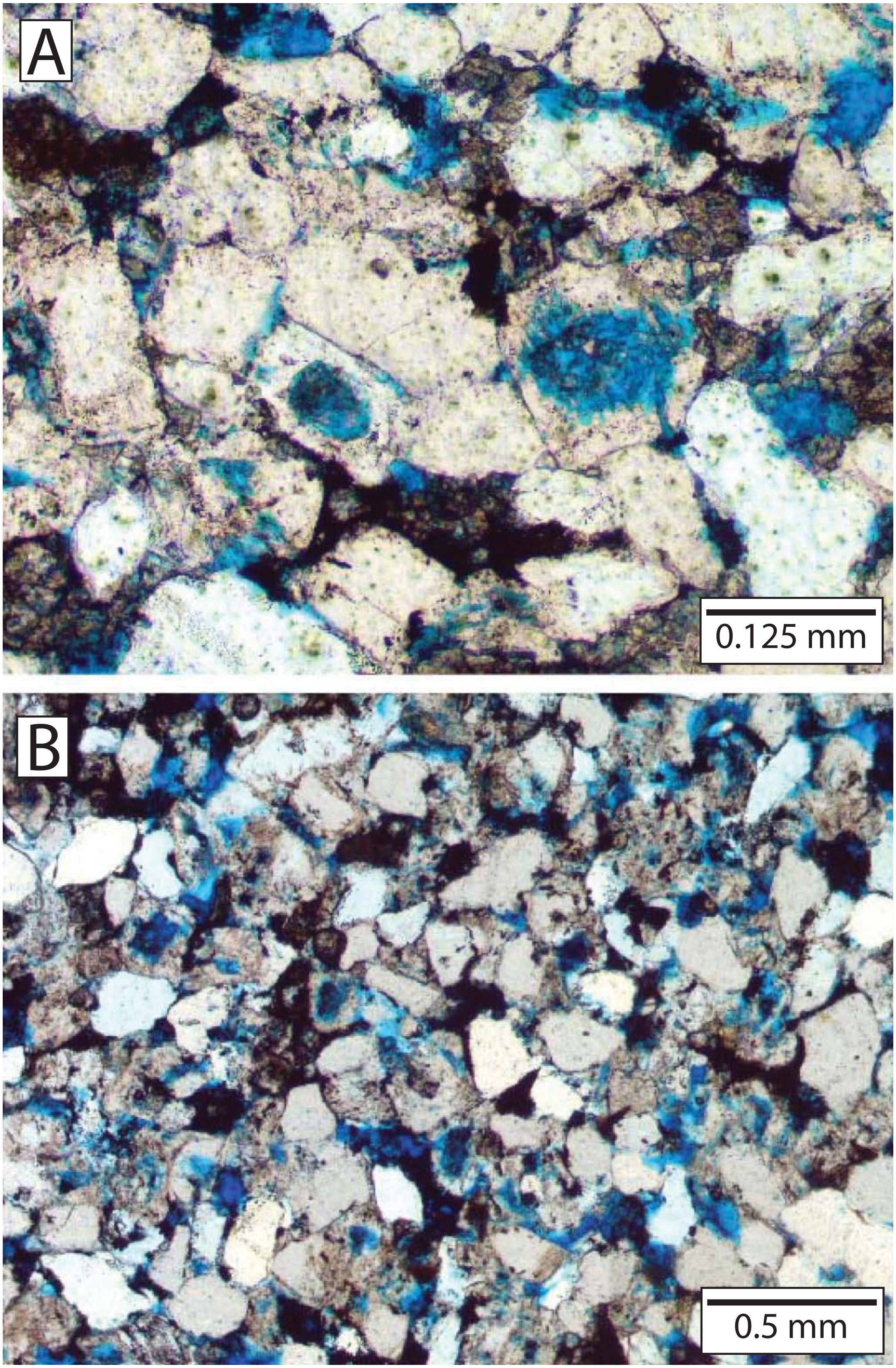


Figure 22. Leached feldspar from Hooker Chemical #1 core. A) Feldspar leached from inside and outsides of grains (2909').
B) Most of the porosity in this slide is from leached feldspar (2910').

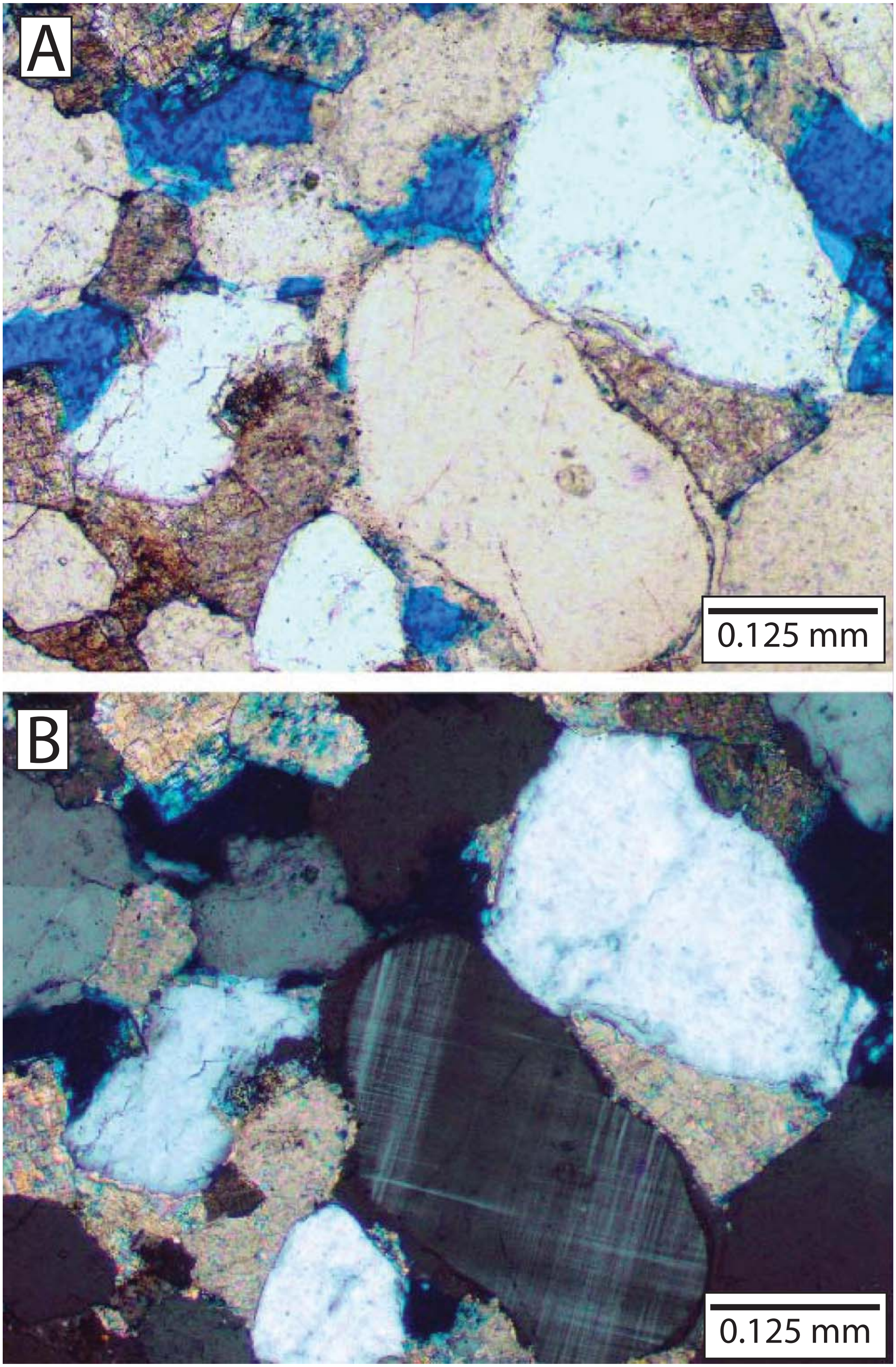


Figure 23. Feldspar cement from Hooker Chemical #1 core. A) Overgrowth on microcline fedspar is partially leached (plane light - 2911'). B) Same as A in cross ploarized light.

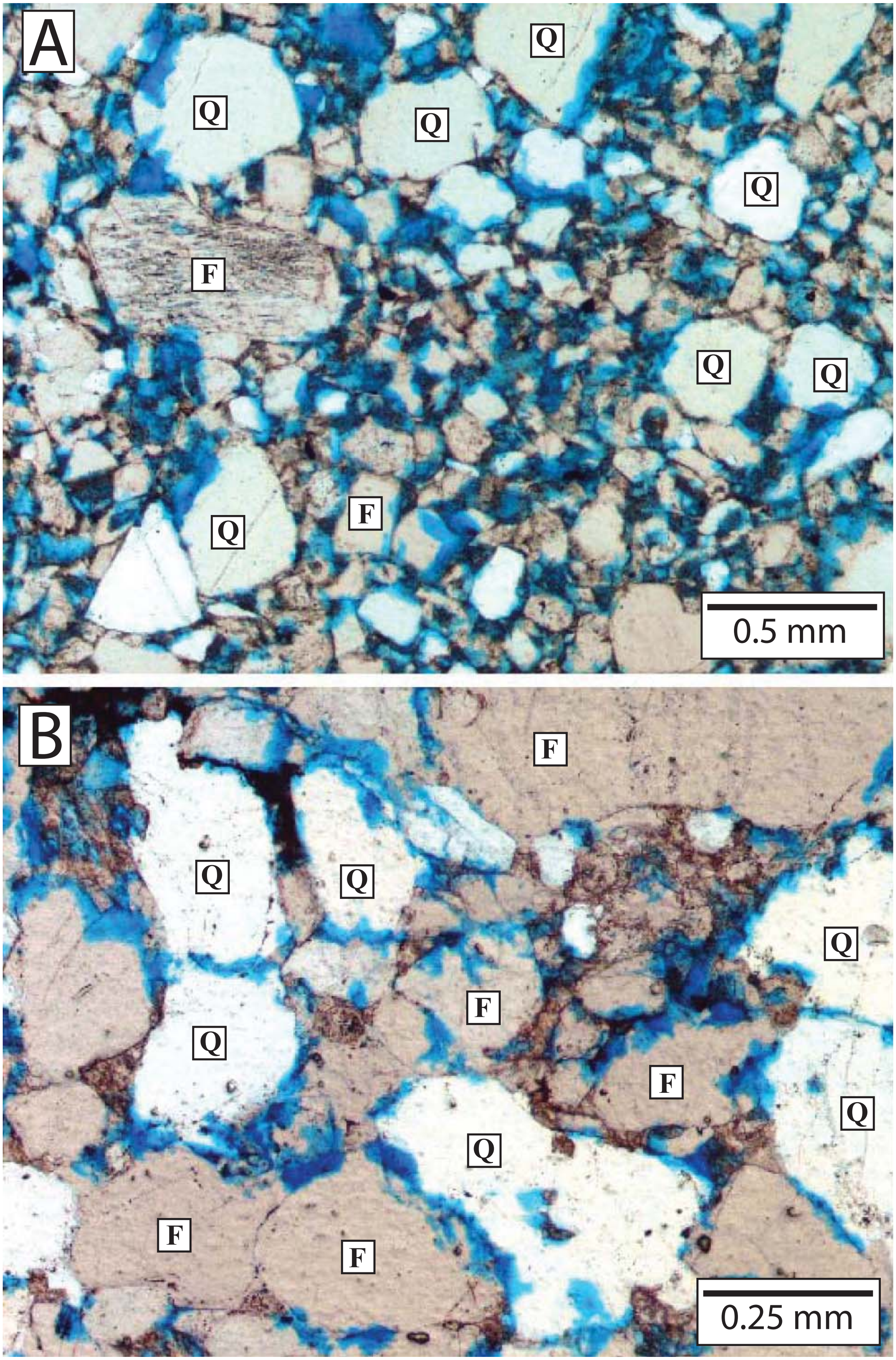


Figure 24. Leached quartz and feldspar from Hooker Chemical #1 core. Lighter colored grains are quartz (Q) and darker grains are feldspar (F). A) Quartz grains have clearly been dissolved (2852'). B) Quartz and feldspar dissolution (2866').

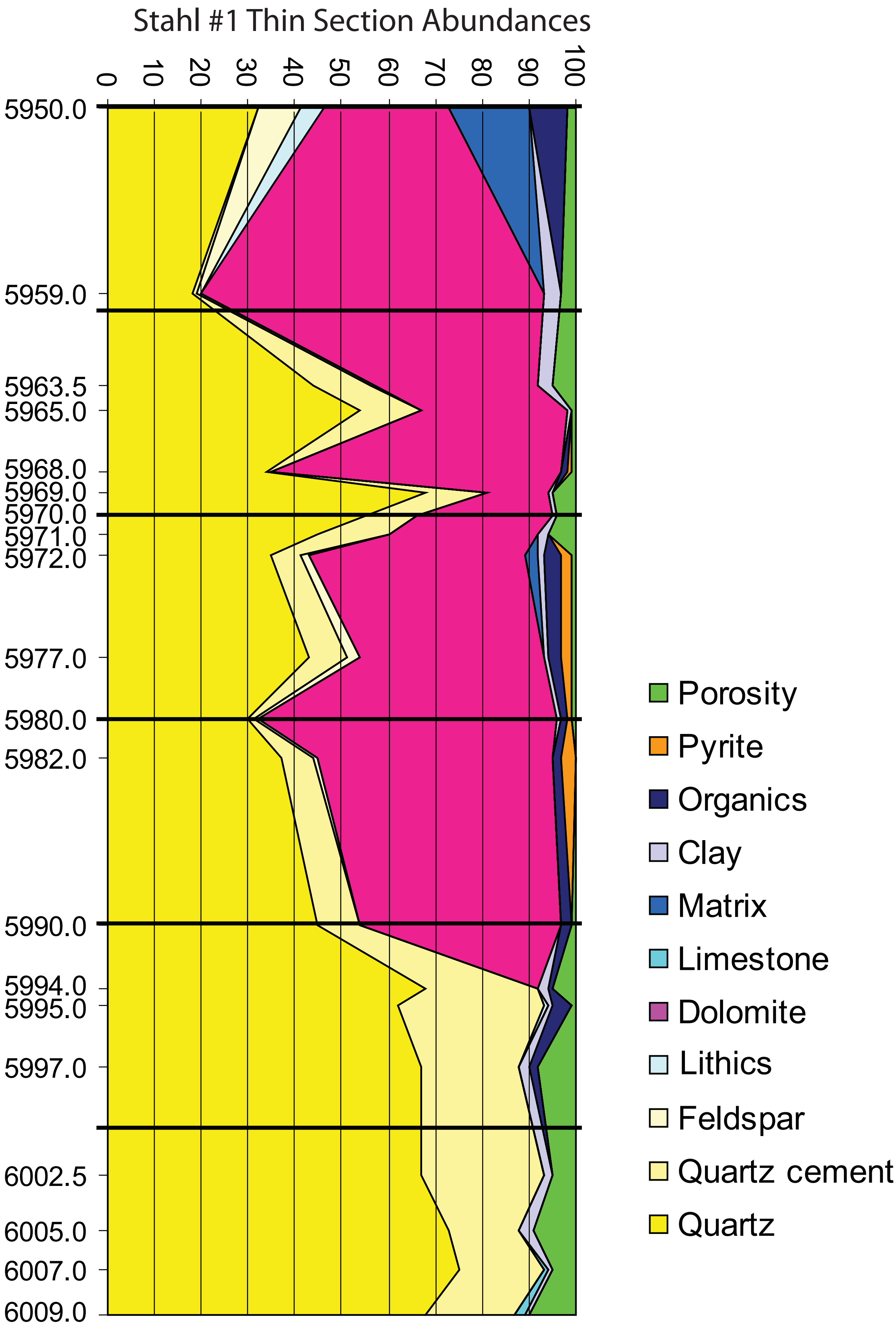


Figure 25. Thin section abundances from Stahl #1 well.

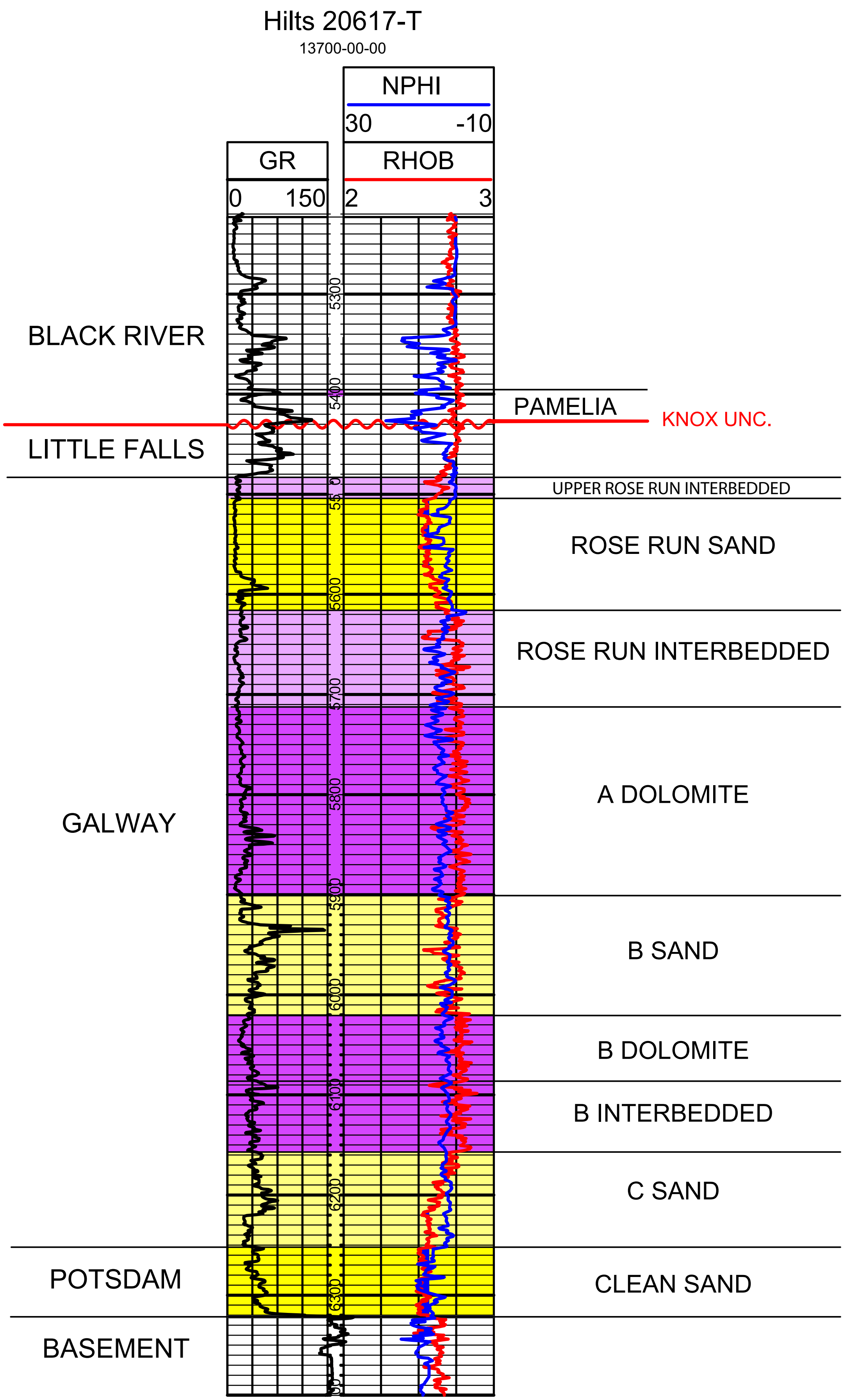


Figure 26. Type log for the interval from Knox Unconformity to Basement in western New York with informal member names and formation names.

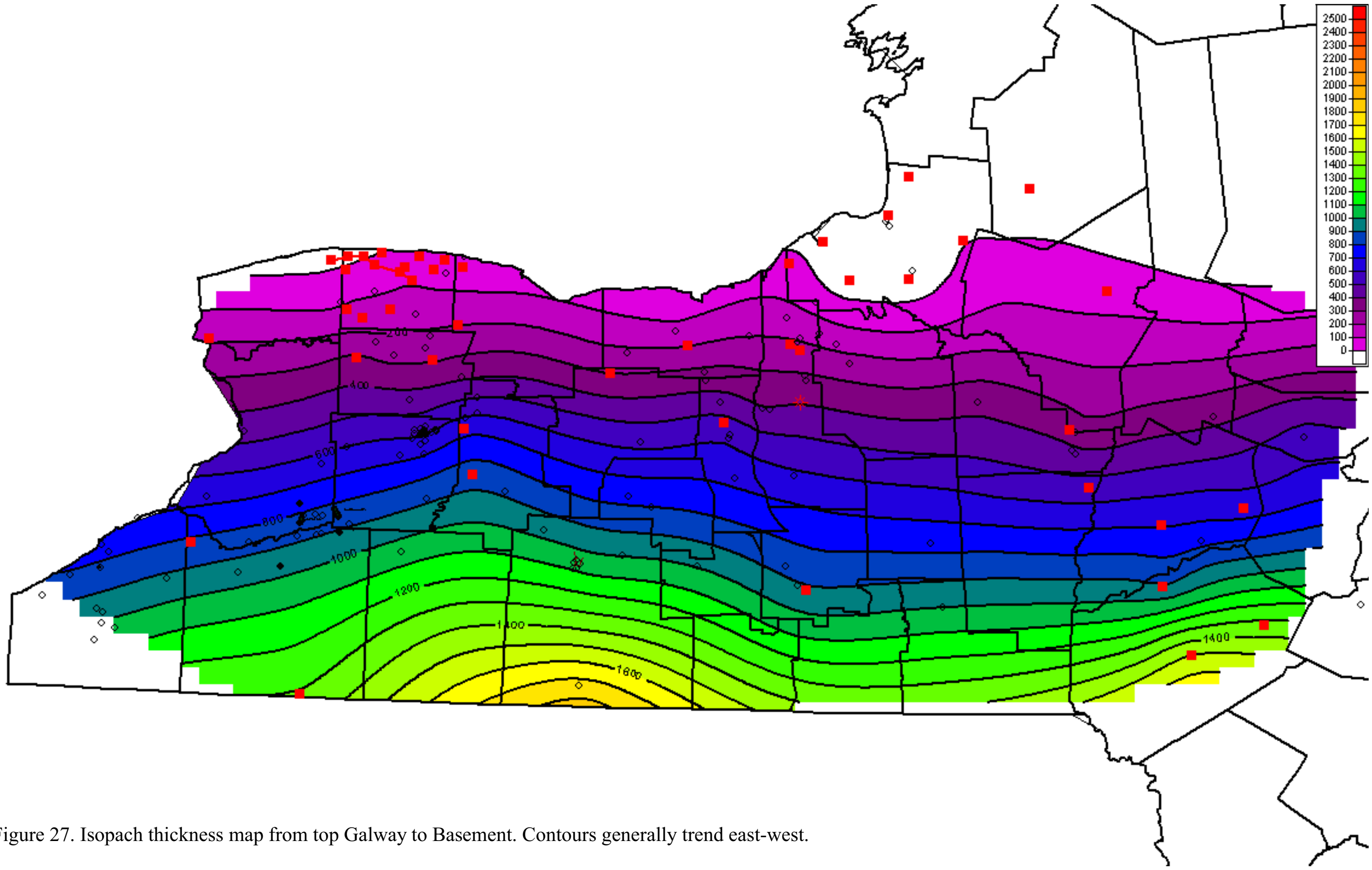


Figure 27. Isopach thickness map from top Galway to Basement. Contours generally trend east-west.

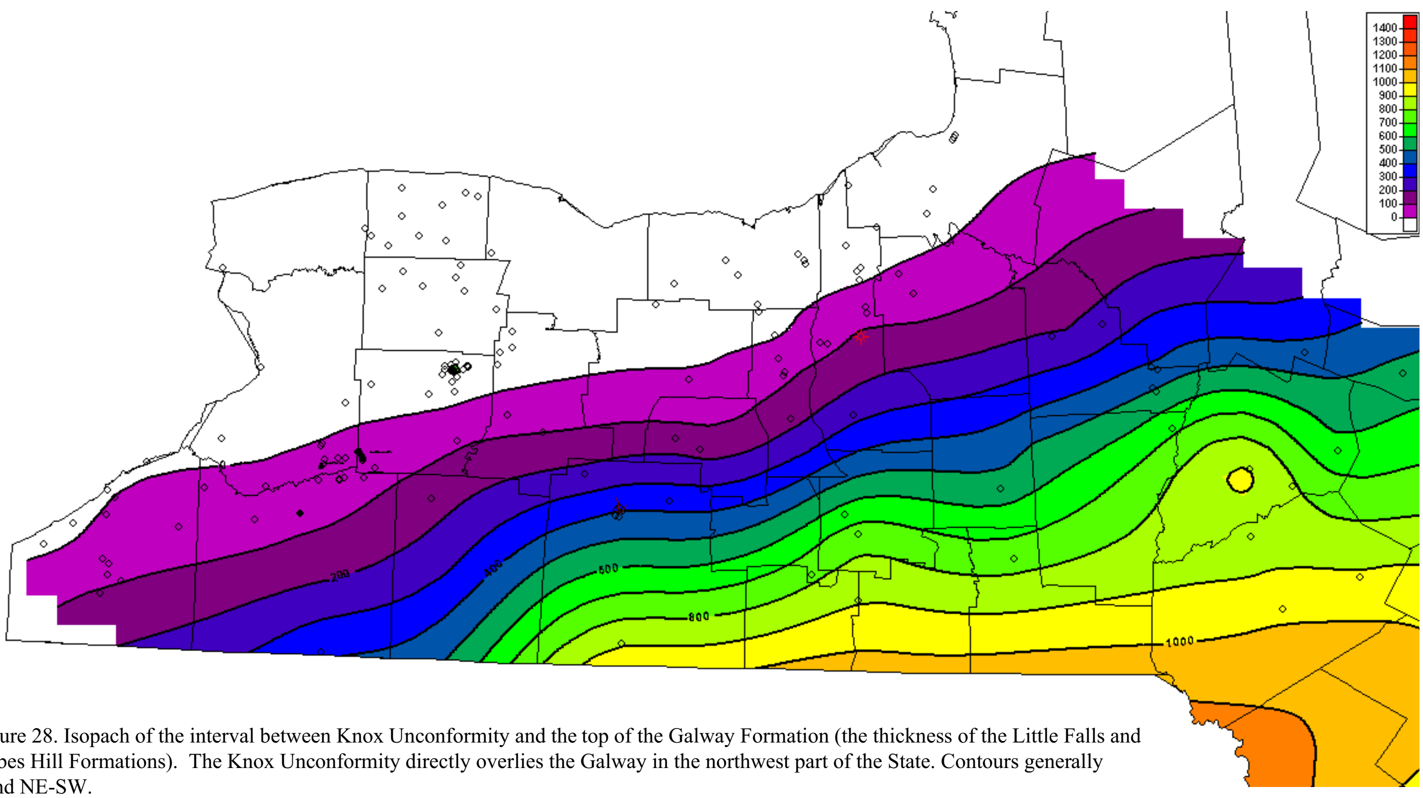


Figure 28. Isopach of the interval between Knox Unconformity and the top of the Galway Formation (the thickness of the Little Falls and Tribes Hill Formations). The Knox Unconformity directly overlies the Galway in the northwest part of the State. Contours generally trend NE-SW.

Little Falls Formation

Previous work on the Little Falls Formation has been done by Donald Zenger of the NY State Museum (Zenger, 1981 & 1989).

The Little Falls is primarily composed of dolomite, but has several sandstone or dolomitic sandstone beds near the base. These represent a transition into the underlying Galway Formation. The base of the Little Falls is not always easy to pick. One way to pick the contact is to use the gamma ray log and make the pick at the top of a distinctive clean gamma ray marker (Figure 26). Another is to use the PEF and density-neutron logs to pick the top of the clean sandstone or the base of the last dolomite. These picks line up in some cases but not in others.

There are commonly a few dolomite beds below the top of the clean gamma ray marker. The presence of these sandstone beds makes picking the top of the Galway more difficult, but the Galway is here picked at the top of the distinctive clean gamma ray signature. This puts some thin dolomite beds in the upper most Galway and some thin sandstone beds in the basal Little Falls. The sandstones at the base of the Little Falls can have some porosity, but at this point they are not thought to contribute significantly to production.

The Little Falls (and overlying Tribes Hill Formation) are completely eroded beneath the Knox Unconformity in the northwestern part of the state. In areas where the Little Falls is eroded the Knox Unconformity overlies the Galway or in some cases the Precambrian Basement such as in the Heaphy #1 well in Oswego County (Figure 12).

Galway Formation (also known as the Theresa Formation in the subsurface)

Previous work on the stratigraphy and sedimentology of the Galway/Theresa Formation has been done by Charles Flagler and Bruce Selleck (Flagler, 1966; Selleck, 1984).

We have broken the Galway Formation into seven members based on the abundance of sand and dolomite in each. The upper Galway consists of the Rose Run Upper Interbedded, Rose Run Clean Sandstone, and Rose Run Lower Interbedded. These units consist primarily of pure sandstone beds with some sandy dolomite. The lower Galway has been broken into the A Dolomite, B Sand, B Dolomite, B Interbedded and C Sand. These units contain more dolomite and dolomitic sandstone. There are few beds that do not contain any dolomite, therefore units are called sands where they are predominantly sandstone and dolomites where they are predominantly dolomite.

Rose Run Sandstone Upper Interbedded

There are one or two cycles of interbedded sandstone and dolomite at the very top of the Galway where it has not been eroded by the Knox Unconformity. The sandstone beds can be porous. These sandstones were captured by the sidewall cores in the Stahl #1 well and may have produced some of the gas in that well. This section may be a key part of the play.

Rose Run Clean Sandstone

This name is borrowed from Ohio where the Rose Run Sandstone produces gas and occurs in the same stratigraphic position. It is here divided into the Upper and Lower Rose Run Sandstone units. The Upper Rose Run sandstone is a clean blocky sandstone that usually has a very low gamma ray response. It is variably cemented with quartz overgrowth cement. Porosity ranges from near zero to as high as 12-15% and maybe higher in a few wells such as the Kennedy #1. Along with the overlying dolomitic sandstone unit, this interval produces the gas in the Northwoods and Bockhahn Fields. It has also had oil and gas shows in other parts of the state, particularly in the north central area.

The lower part of the Rose Run Sandstone may have some shaly interbeds based on the gamma ray, but it can also have what appears to be the highest porosity in the Galway. Because there are some shaly beds, the gamma ray is a little hotter than it is in the overlying Upper Rose Run. The Lower Rose Run Sandstone is the producing member in the Cascade Brook Field where the upper part of the Rose Run Sandstone has been eroded under the Knox Unconformity.

The sand throughout the Rose Run is typically fine to medium and rounded to subrounded and has been the primary target for gas exploration to in this play. The map in Figure 29 shows that the Rose Run Clean Sandstone ranges in thickness from 0-200 feet in New York. It is eroded under the Knox Unconformity to the northwest and grades laterally into dolomite to the east where it is virtually absent. The thickest accumulation of Rose Run occurs near the Avoca wells in Steuben County.

Porosity in the Rose Run Sandstone in the Kennedy #1 well is almost entirely due to leached quartz and leached quartz cement (Figures 14 and 15). In the Stahl #1 well, some porosity may be of a leached origin while some of it appears to be preserved primary porosity.

Rose Run Lower Interbedded

The Interbedded Member consists of interbedded dolomites and dolomite-cemented sandstones. This unit is picked at the top of the first dolomite bed where the density log shifts to values greater than 2.75 g/cc (Figure 26). The sandstone beds in the interbedded unit are most commonly cemented tight with dolomite cement and were not found to be porous in any of the wells encountered except in rare cases where they immediately underlie the unconformity. The contact between the Rose Run Lower Interbedded Member and the underlying A Dolomite Member is picked where the density log first crosses the 2.75 g/cc line suggesting more than 50% dolomite. In the east, the sandy layers get much thinner and are unlikely to have reservoir potential.

A Dolomite

The top of the A Dolomite is picked where the density log stays steadily to the right of the 2.75 g/cc line suggesting far fewer sandstone beds. The dolomite itself is typically not porous, however there are a few sandy beds in the

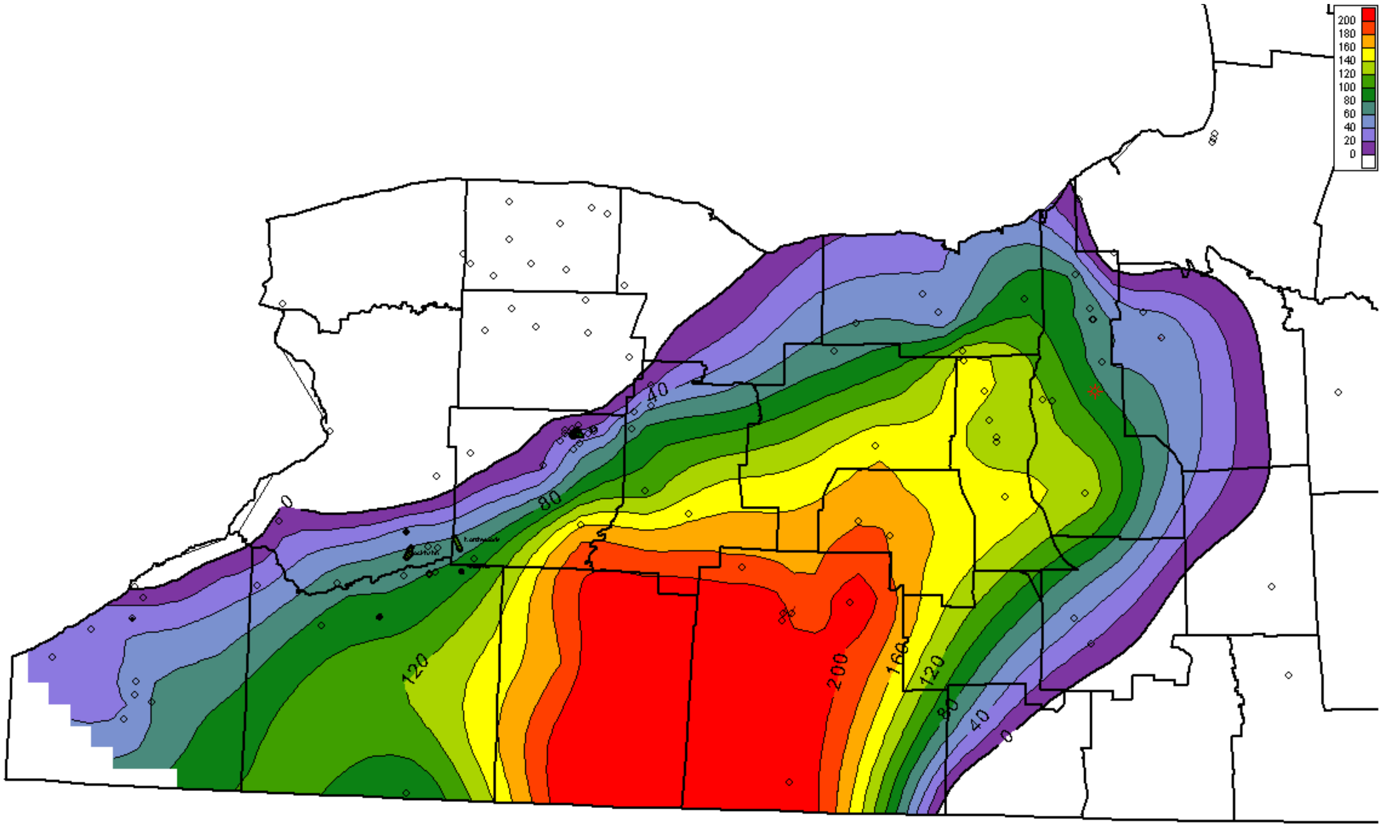


Figure 29. Isopach thickness map of Rose Run Sandstone (contour intervals are 20 feet). In the northwest corner of the State it has been eroded, in the eastern part of the State it grades laterally into dolomite. Rose Run thickens to center of basin which is likely trend of northern Rome Trough

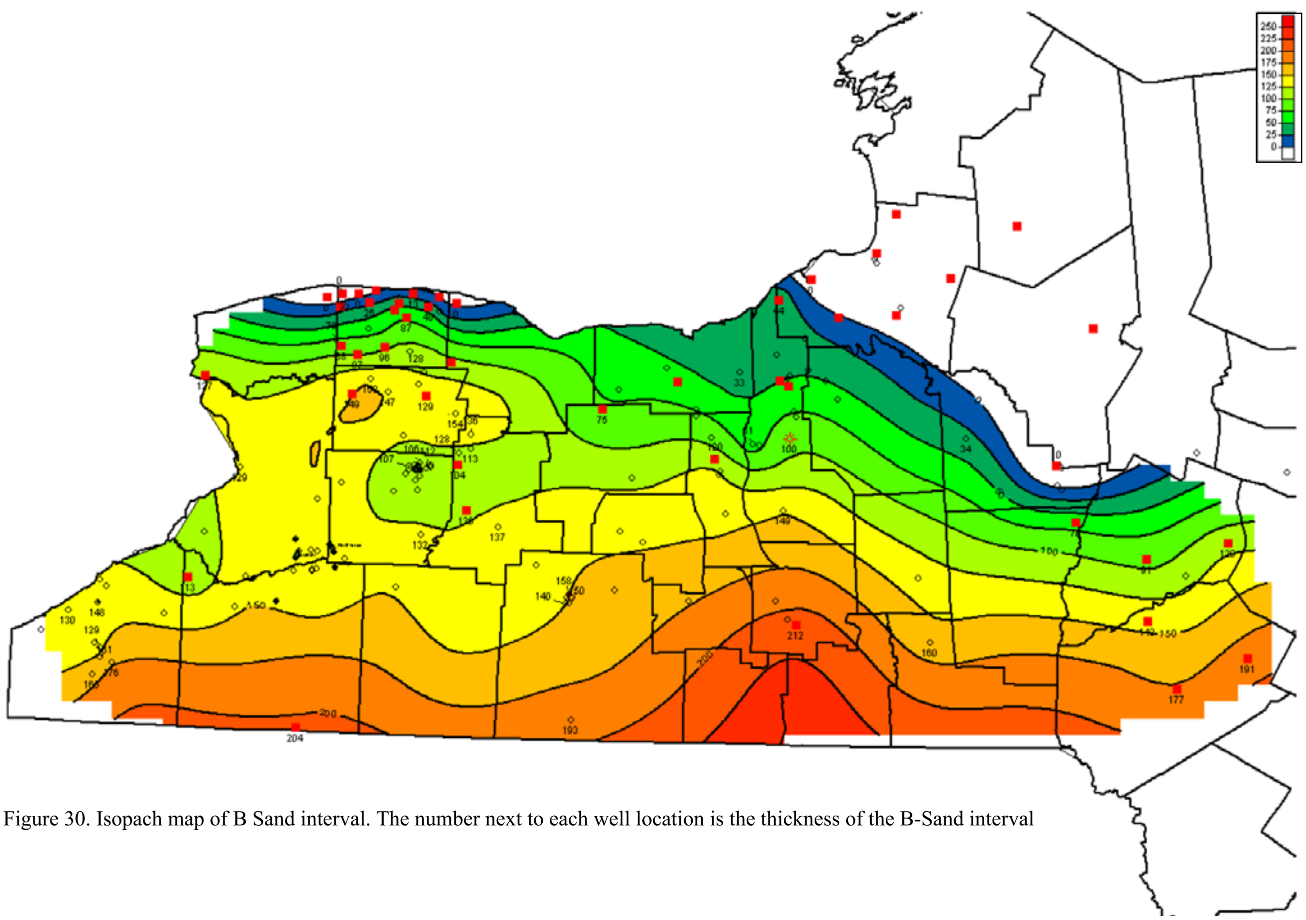


Figure 30. Isopach map of B Sand interval. The number next to each well location is the thickness of the B-Sand interval

middle and basal parts of the unit which may be porous in the far western part of the State. The Hooker Chemical #1A core contained some porous thin sandy beds in this interval. The A Dolomite has fewer sandy beds to the east and south and more sandy beds to the north and west.

B Sand

The B Sand is composed of sandstone, dolomitic sandstone and sandy dolomite with a few pure dolomite beds in some places. Beds are commonly very thin, changing every few inches or feet from sandstone to sandy dolomite and back to sandstone again. All of the facies appear to be shallow marine. There B Sand appears to be porous in the wells of Erie County where it overlies the basement and is either directly beneath or very close to the Knox Unconformity. The B Sand is commonly feldspathic and the gamma ray logs are generally hotter where it is near or immediately overlying the basement. The amount of feldspar decreases from west to east and it has a fairly clean gamma ray signature in the central and eastern parts of the basin.

The porosity of this unit in the Hooker Chemical #1A well is almost all of a secondary nature and consists of leached dolomite, leached feldspar and leached quartz. Porosity can be over 10% and the higher measured permeabilities are greater than a millidarcy (Table 3). The B Sand has an upper sandy and lower sandy interval with a more dolomitic interval in the middle.

The B Sand gets more sand-rich to the north and west and more dolomite rich to the east and south. The B Sand interval has the greatest lateral extent of all of the Galway sandstone intervals (Figure 30).

B Dolomite

The B Dolomite is picked at the top of an interval where the density log stays below 2.75 g/cc. This contact lies below a particularly sandy part of the B Sand. The B Dolomite has little sand in it in the east and south but gets more sandy beds to the north and west. The B Dolomite has very low porosity in most wells.

B Interbedded Dolomite and Sandstone

There is an interval at the base of the B Dolomite where discreet sandstone beds become more common. Some of these beds can be correlated across the western part of the State. There is commonly a high gamma ray spike at the top and then the density log shows several lower density sandstone beds below that point. In some cases, this interval is lumped in with the B Dolomite. There may be some porosity in the more sand-rich beds of this interval. There is more sand to the north and west and more dolomite to the east and south.

C Sand

The C Sand is a predominantly sandstone interval at the base of the Galway Formation that still has some interbedded dolomites and dolomite cement in sandstone beds. This is in contrast to the Potsdam which is here not thought to have any interbedded dolomite beds. The C Sand appears to have some porosity near where it overlies the basement, but is generally tight where it overlies significant thicknesses of Potsdam. The C Sand can be feldspathic and is very difficult to discriminate from the Potsdam where it immediately overlies the basement it.

The C Sand has a limited lateral extent relative to the B Sand because it onlaps the basement and pinches out to the north (Figure 31). There appears to be some porosity in the C Sand in Chatauqua County but it is generally in the 3 to 5% range.

Potsdam Sandstone

The Potsdam Sandstone in western New York has a basal feldspathic member and an upper clean sandstone member. It is picked at the base of the last density excursion above 2.75 g/cc which marks the base of the last dolomite in the C sand. The Potsdam has porosity in some wells, but appears to be tight in others. It is several hundred feet thick in the middle of the basin but thins to zero where it onlaps basement highs to the west, north and east (Figure 32).

WELL CROSS SECTIONS

This section includes several cross sections that show the stratigraphic relationships of the Cambrian Potsdam, Galway and Little Falls Formations. Figure 33 is a west-east cross section from Chautaqua County to the basin center in Steuben County. The wells in Chautaqua County don't quite reach the basement. The lowermost formation encountered in those wells is the C Sand, but there may be Potsdam below it. The Tribes Hill and most of the Little Falls have been eroded to the west, but the Rose Run Sandstone does not subcrop below the Knox Unconformity on this cross section. The Rose Run Sandstone drastically changes in character from a thick blocky sandstone in the Olin and Enterprise wells to a more interbedded sandstone and dolomite in the Chautaqua County wells. The sandier beds of the Rose Run in Chautaqua County may have just as much or more porosity but they are also much thinner and more likely to have a percentage of dolomite.

Figure 34 is a N-S cross section from Orleans County just, south of Lake Ontario, to Steuben County, along the Pennsylvania boarder. This section shows the radical thinning of the entire Pre-Knox Unconformity section. In Steuben County, the Olin well has a Pre Knox section from Ordovician Tribes Hill to basement that is more than 2600 feet thick. This entire section thins to zero in the northernmost well where the Black River sits directly on the basement. Some of this thinning is due to onlap of the basement in the Potsdam and Lower Galway Formations and some is due to erosion or non-deposition of the younger Upper Galway, Little Falls and Tribes Hill Formations.

Figure 35 is a cross section that extends from the Enterprise #1 well in Cattaraugus County eastward to the Paul Lum #1 well in Otsego County. The B Sand correlates close to the basement in the eastern wells as the Potsdam and C Sand onlap the basement. The Rose Run Clean Sandstone pinches out between the Olin Well in Steuben County

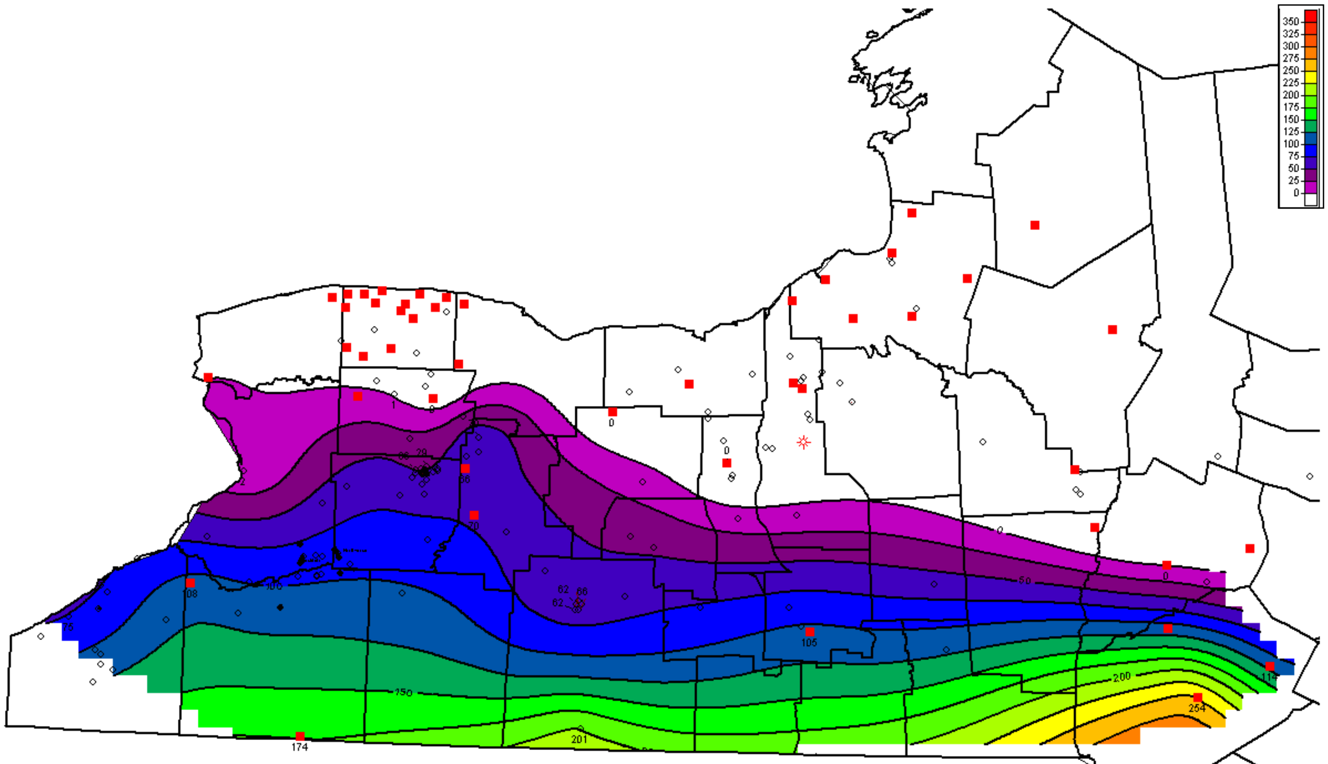


Figure 31. Isopach thickness map of C Sand interval. It thins and pinches out to the north where it onlaps the basement and thickens to the south.

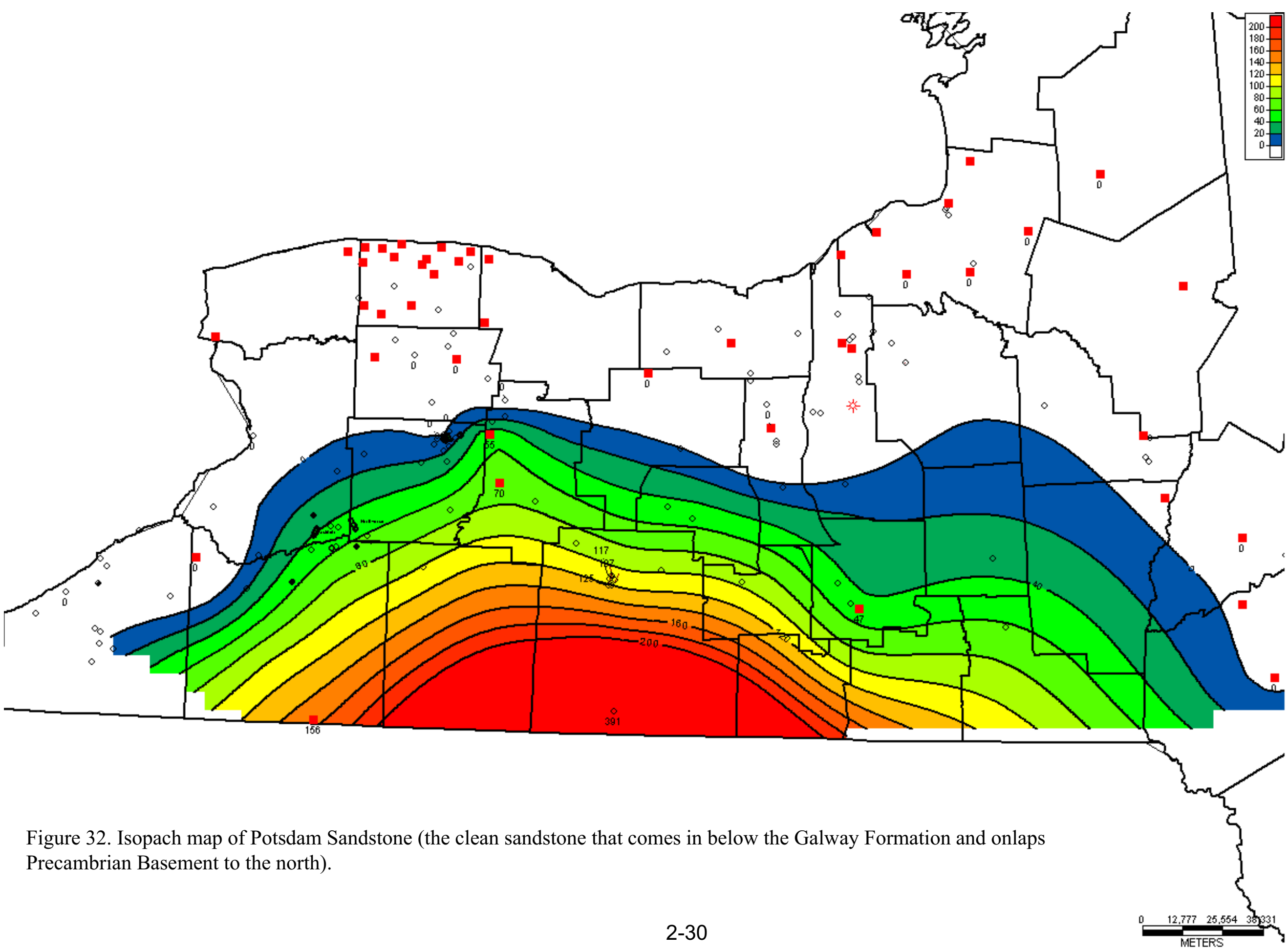


Figure 32. Isopach map of Potsdam Sandstone (the clean sandstone that comes in below the Galway Formation and onlaps Precambrian Basement to the north).

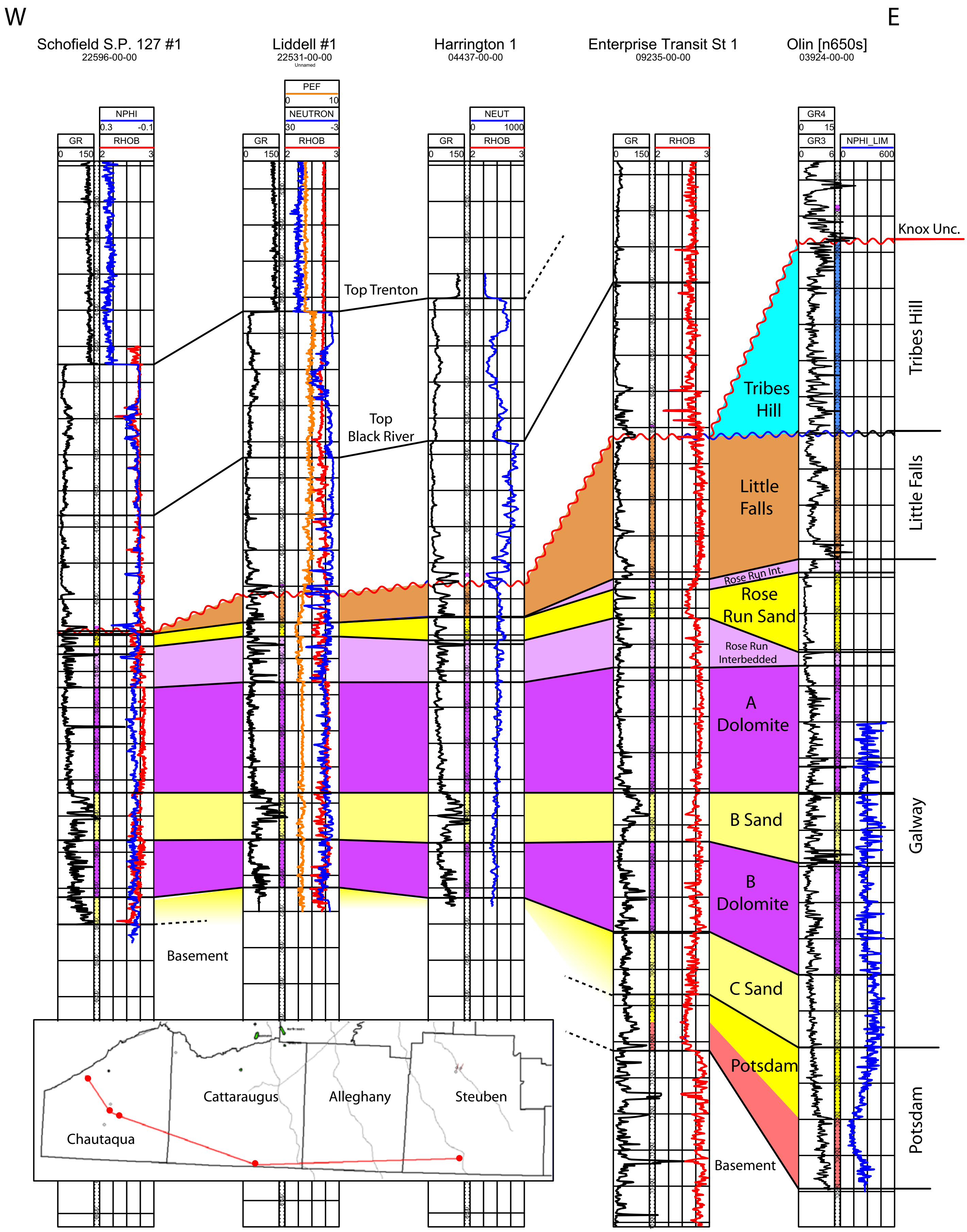


Figure 33. West to East cross section from Chautauqua to Steuben County. The Potsdam appears to onlap the basement to the west with the C Sand at the base of each of the wells in Chautauqua Co.

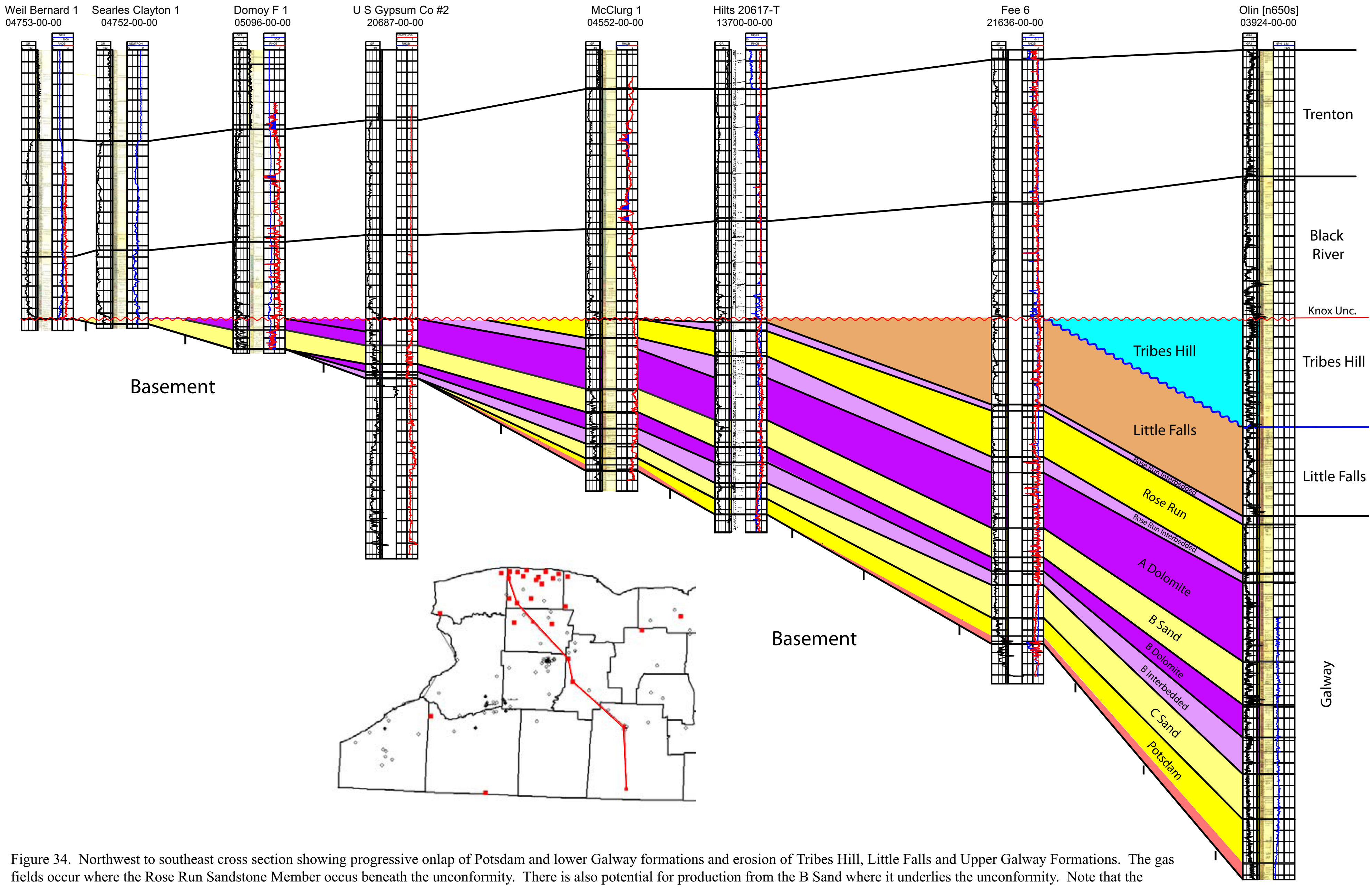


Figure 34. Northwest to southeast cross section showing progressive onlap of Potsdam and lower Galway formations and erosion of Tribes Hill, Little Falls and Upper Galway Formations. The gas fields occur where the Rose Run Sandstone Member occus beneath the unconformity. There is also potential for production from the B Sand where it underlies the unconformity. Note that the flat0lying Black River Formation immediately overlies the basement in the northernmost well.

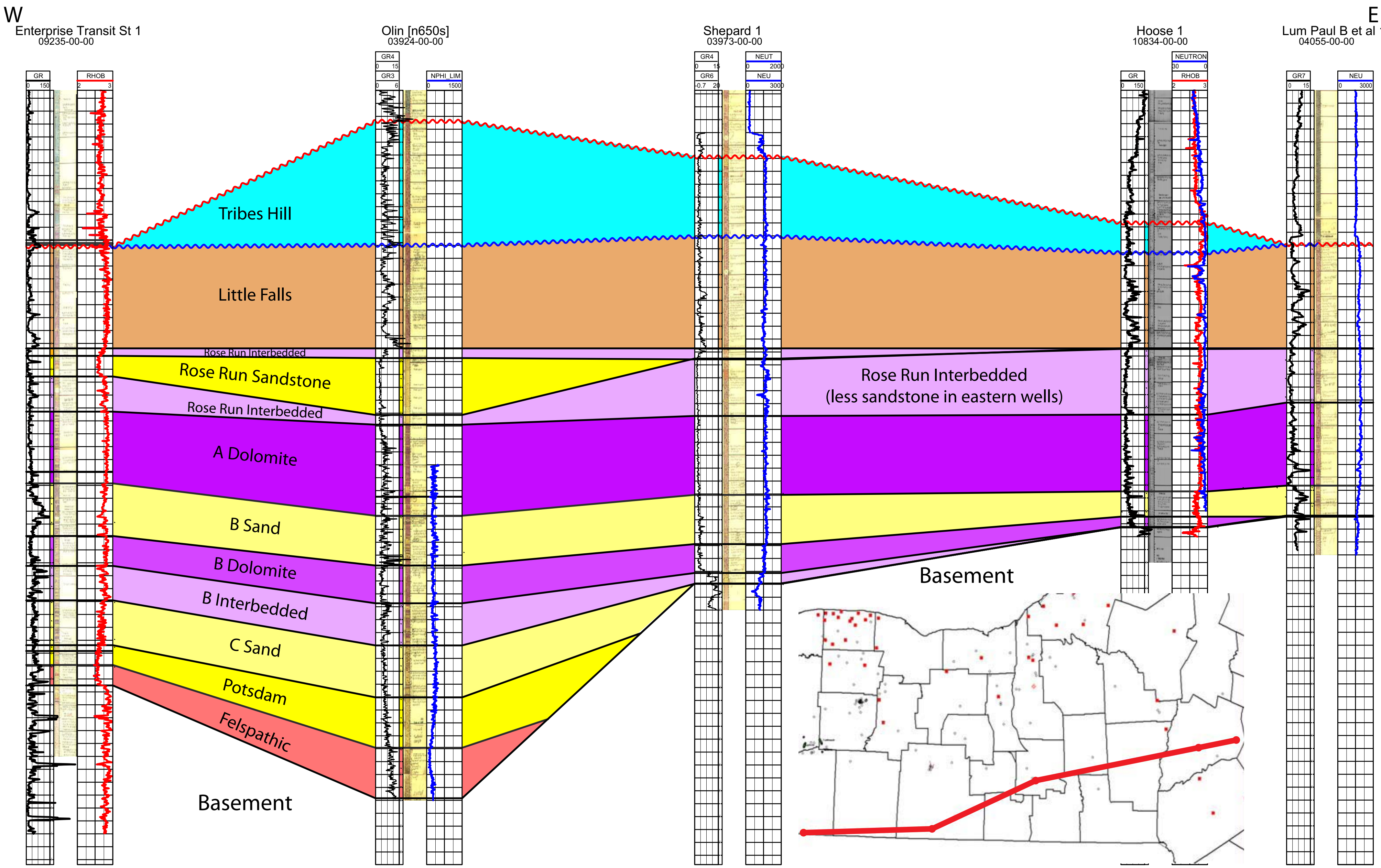


Figure 35. West to East cross section from its center to the east side of the basin. Rose Run Clean Sandstone piches out to the east and there is very little quartz sand on the east side of the basin. The Potsdam and C Sand onlap and pinch out to the northeast. In the east, the B Sand is the main sandstone of the seaquence.

and the Shepard well in Tompkins County. There it grades into thin interbeds of sandstone or sandy dolomite as seen in the eastern wells. None appear to have any effective porosity.

FIELD CROSS SECTIONS

The three major fields discovered to date in the Rose Run Sandstone of New York all occur where the Rose Run is partially eroded under the Knox Unconformity. Two of the fields are presented in Figures 36 and 37.

Figure 36 is a cross section through the one-well Hannon and three-well Bockhahn Fields and shows the Rose Run Sandstone immediately underlying the Knox Unconformity. These wells have been the most prolific of the play. Each has a thick section of blocky Rose Run Sandstone. The porous intervals generally have between 5 and 10% porosity, but the rest of the unit appears to have little, if any, porosity. The well with the highest cumulative production, the Degolier #1. also has the most porosity over 5%.

Figure 37 shows the Cascade Brook Field in Wyoming County. The producing interval appears to be in the lower half of the Rose Run Sandstone in many of these wells because the upper portion has been eroded under the Knox Unconformity.

The Northwoods Field has poor logs that do not record much data over the producing interval in the Rose Run Sandstone.

Figure 38 shows a subcrop map beneath the Knox Unconformity. The Formation depicted on the map is the formation that occurs directly beneath the unconformity. The three main producing fields (Northwoods, Bockhahn and Cascade Brook) are marked in red and other wells that penetrate the top of the Galway are marked in black. There are vast areas where the Rose Run subcrops beneath the Knox Unconformity that have not been explored.

POROSITY MAPS

Most or all of the production in from the Galway (Theresa) has been from the sandstone at the top of the formation, here called the Rose Run Sandstone. Three maps were made using *Petra* software to try to understand where porosity in this sandstone might occur and to develop ideas for the origin of that porosity. Maps of the net feet of sandstone with >5%, >7.5% and >10% sandstone porosity were constructed for all wells with density logs (RHOB) (Figures 39, 40 and 41). Density logs were chosen because it was the most common log type among wells that penetrate the Rose Run. Neutron porosity logs were not used because many of these wells have older neutron logs that have not been converted to neutron porosity and therefore have different scales. The interval examined for each map began at the top of the Galway and ended at the top of the A Dolomite. This interval includes the relatively

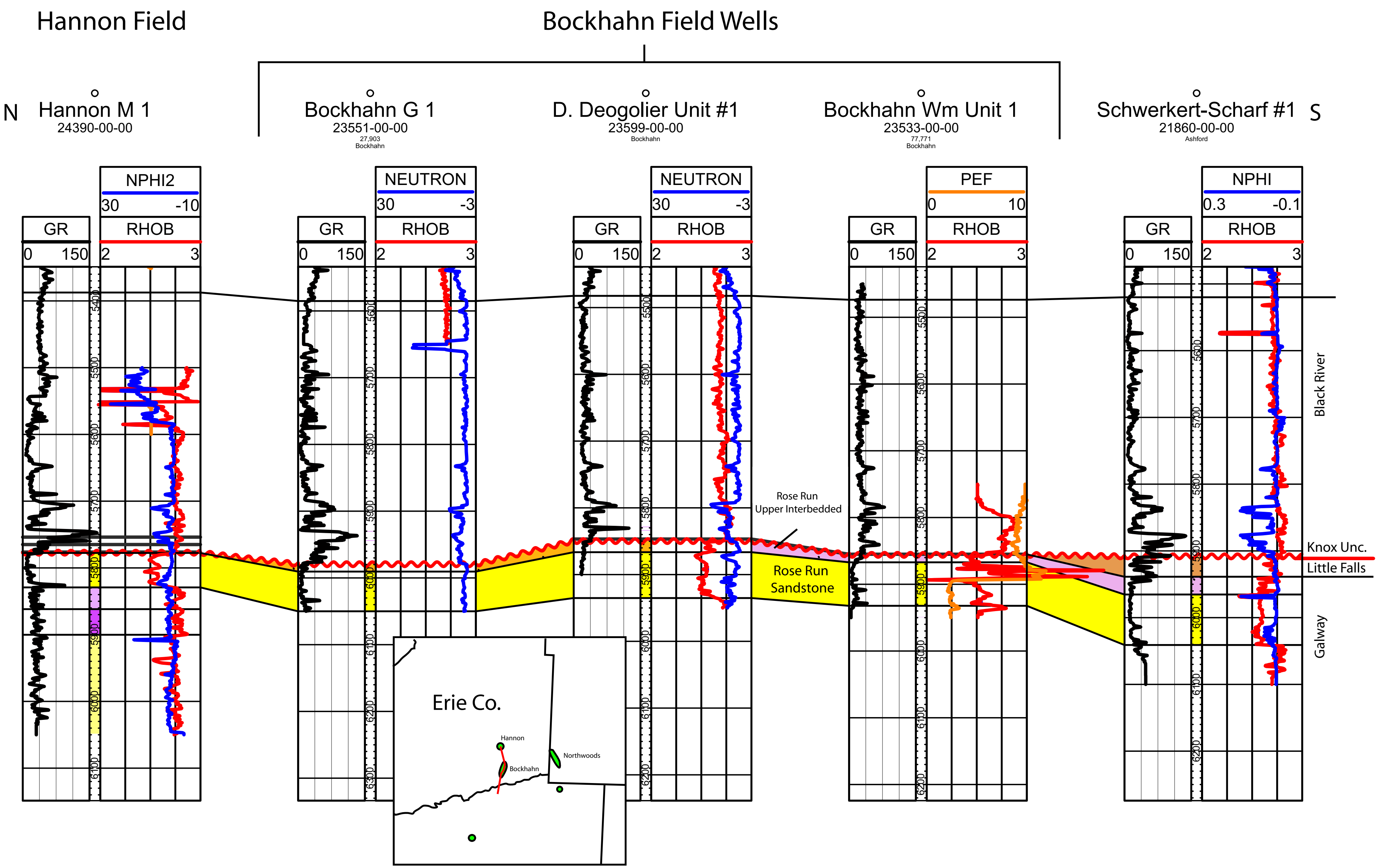


Figure 36. Cross section through the Hannon and Bockhahn Fields. In most of these wells the Knox Unconformity is interpreted to immediately overlie the top of the Rose Run Sandstone Memeber. The Hannon and Bockhahn Fields have been the most prolific producers for this play in NY. Intervals showing both neutron and density porosity are likely to have the best reservoir characteristics.

Cascade Brook Field

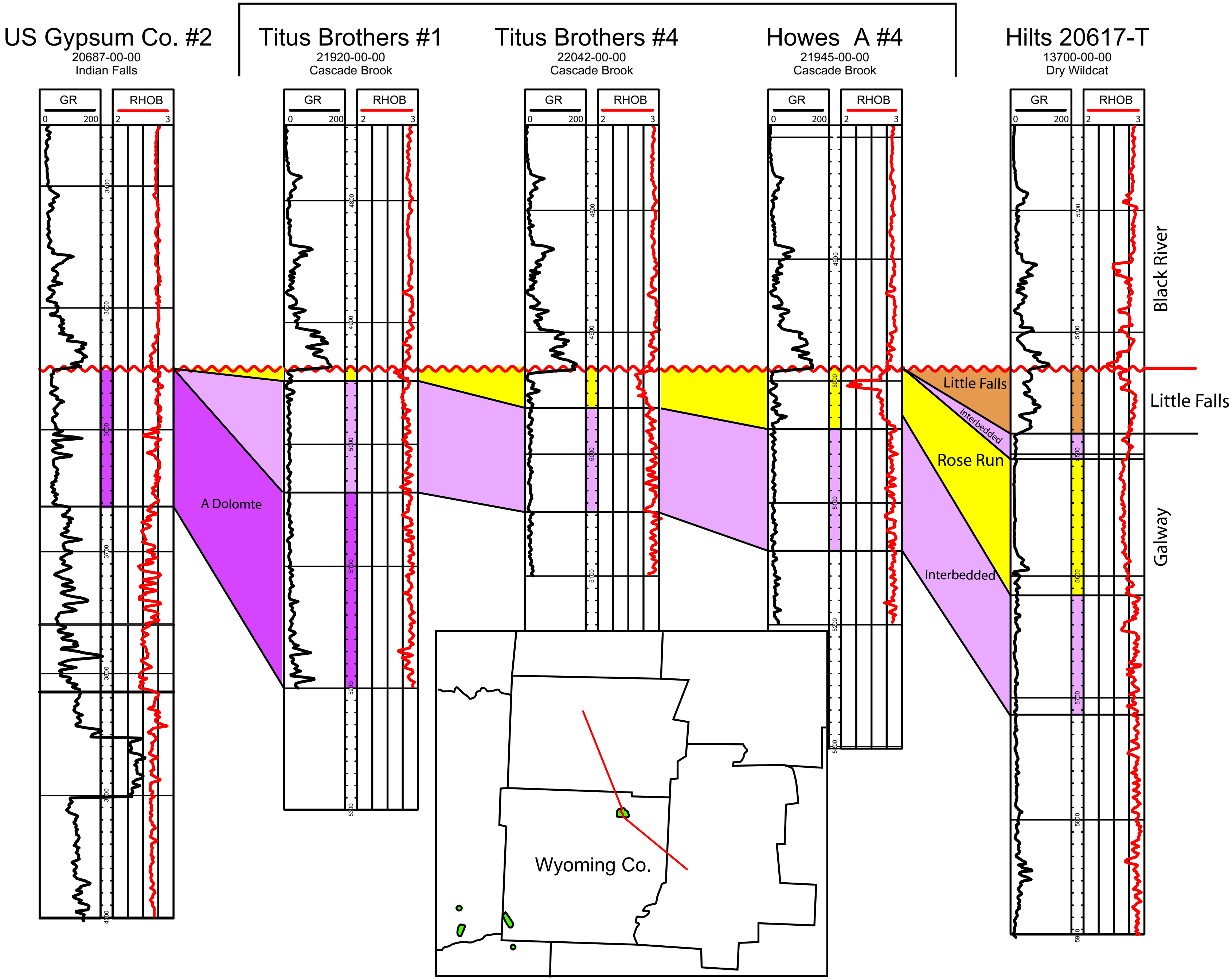


Figure 37. Cascade Brook Field occurs where the Rose Run is partially eroded under the Knox Unconformity. The wells in the northwestern part of the field have a very thin section of Rose Run Sandstone remaining. The field has produced a total of 482 MMCF which is half of what the Hockhahn Field has produced.

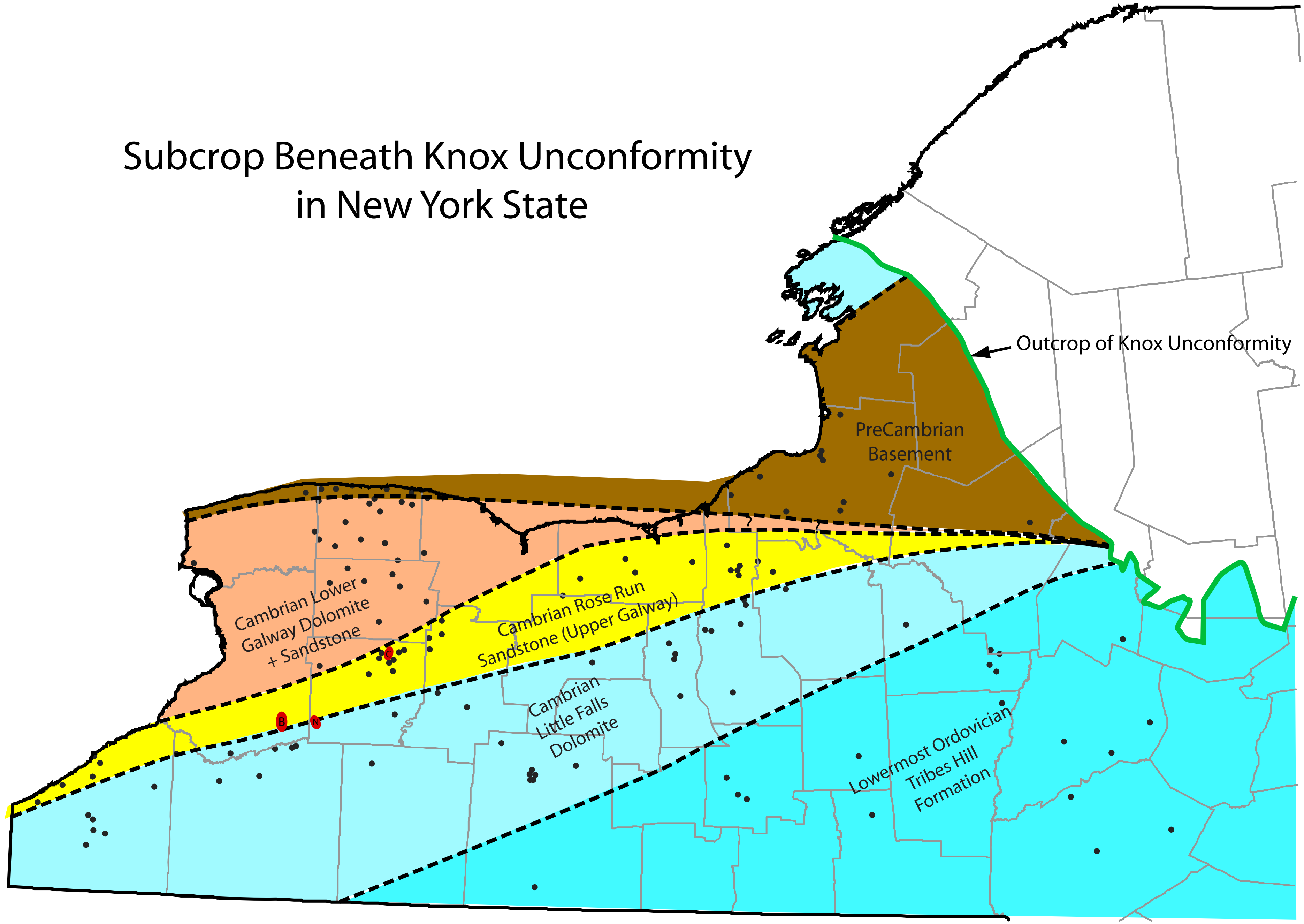


Figure 38. Map of Formation directly beneath Knox Unconformity (aka subcrop). There is no reservoir potential in the Rose Run Sandstone northwest of the green line where it is completely eroded. The pinchout of the Tribes Hill Limestone is poorly constrained. Gas fields in red (B=Bockhahn, N=Northwoods, C=Cascade Brook). Black dots are location of wells that have penetrated the top of the Galway. Boundaries are dashed because their exact position is not known.

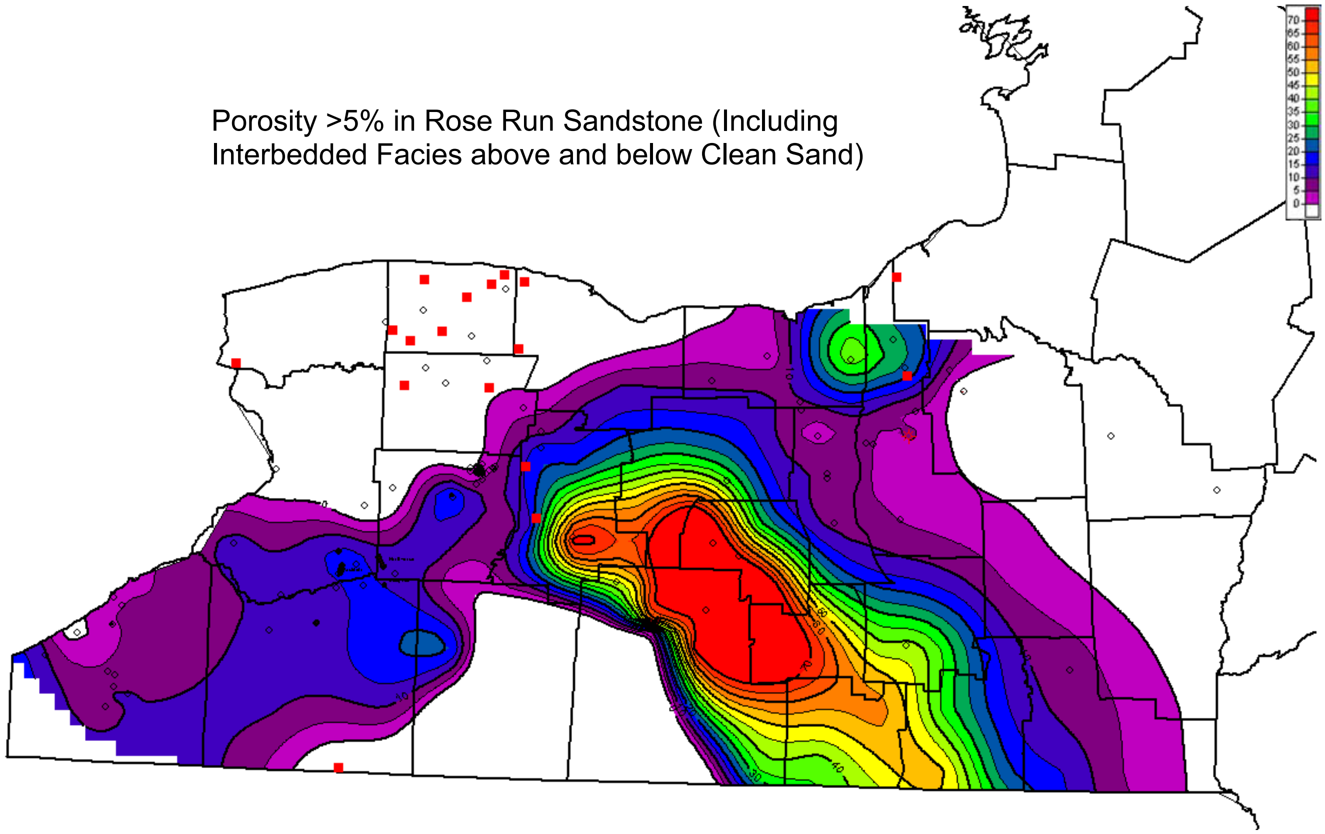


Figure 39. Contour map for feet with >5% porosity in the Rose run Sandstone (feet of RHOB <2.53 g/cc). Interval from top Galway to top A Dolomite includes top of Galway to top of A Dolomite which includes the upper interbedded, the Rose Run Clean Sand and the underlying Rose Run Interbedded sandstone and dolomite. There are two wells with low density that make the porosity thick in thecentral part of the State. Other than that, most areas are in the 0-20 ft range. There are some artifacts of the contouring program but it captures the trends.

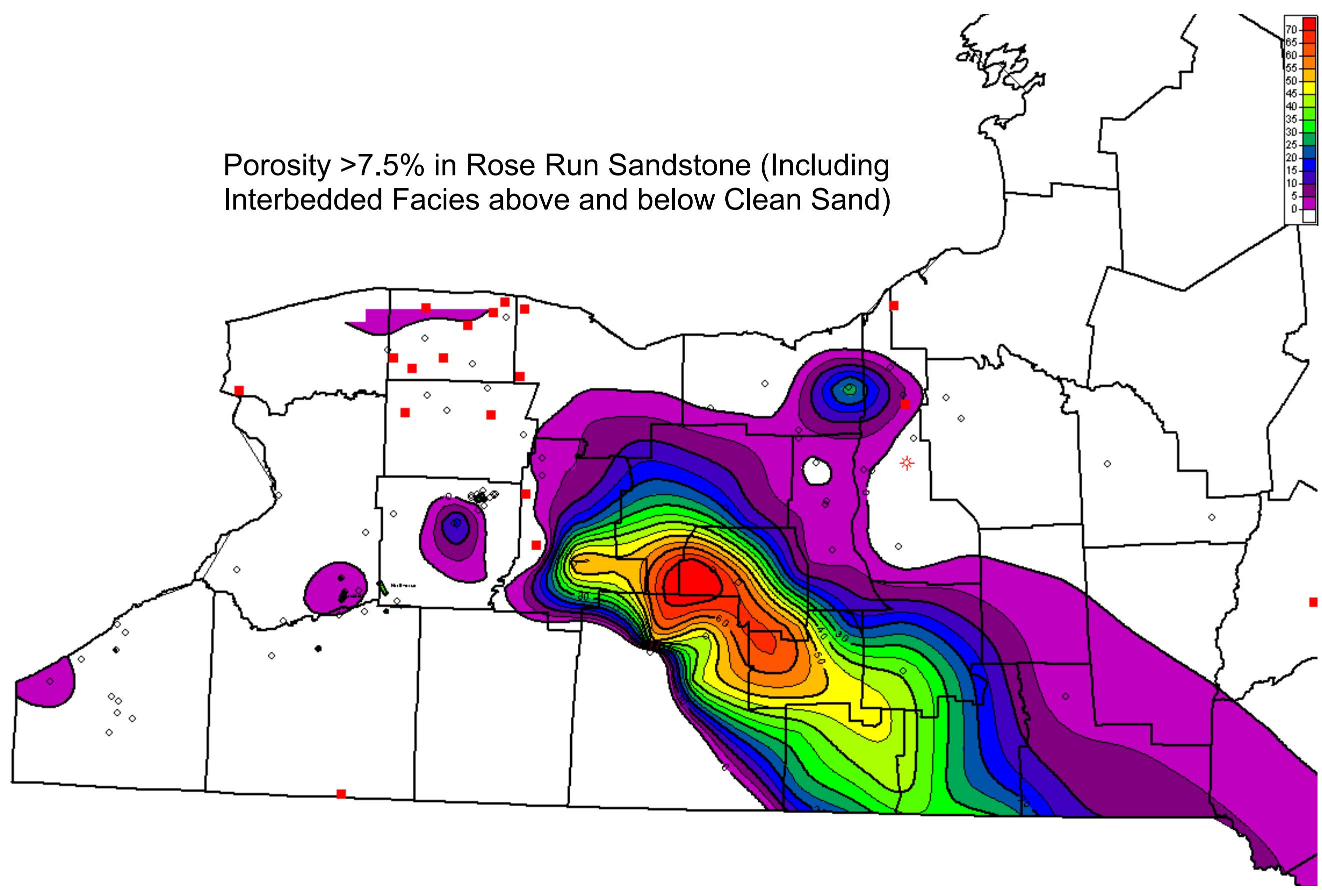


Figure 40. Contour map for feet with >7.5% porosity in the Rose Run Sandstone and interbedded intervals (top Galway to top A Dolomite). This map was made by summing the number of feet with density <2.47 g/cc.

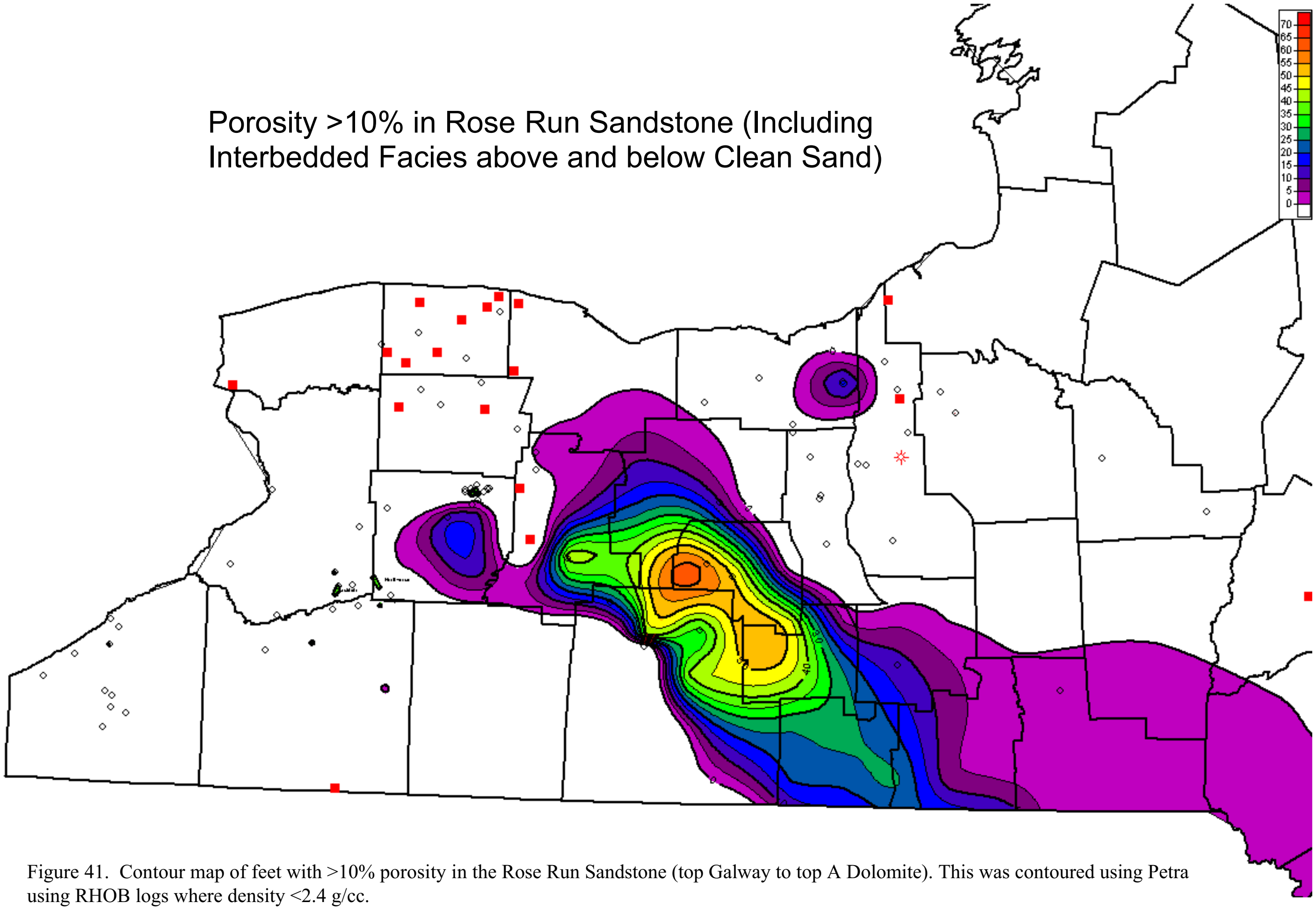


Figure 41. Contour map of feet with >10% porosity in the Rose Run Sandstone (top Galway to top A Dolomite). This was contoured using Petra using RHOB logs where density <2.4 g/cc.

thin Rose Run Upper Interbedded Member, the Rose Run Clean Sandstone Member, and the Rose Run Lower Interbedded Member.

These maps were designed for porosity in quartz sandstone with a small amount of dolomite cement. Pure quartz sandstone has a grain density of 2.65 g/cc. A pure quartz sandstone with 5% porosity should have a density value around 2.517 g/cc. For the map in Figure 39, this was rounded up to 2.53 g/cc to account for a small percentage of dolomite in the rock, which many of these samples contain. Dolomite has a grain density of 2.85 g/cc therefore its presence will cause the average grain density of the rock to be higher. The bulk density of a pure quartz sandstone with 7.5% porosity is around 2.45 g/cc which was rounded up to 2.47 g/cc to account for a small percentage of dolomite in Figure 40. The bulk density of a clean quartz sandstone with 10% porosity is approximately 2.38 g/cc and this was rounded up to 2.4 g/cc to account for dolomite in Figure 41.

It should be reemphasized that these maps are for porosity in sandstones, not dolomites or sandstones with high dolomite content. In a pure dolomite, which has a density of 2.85 g/cc when it has 0% porosity, 5% porosity would have a bulk density value around 2.65 g/cc and 10% porosity would have a bulk density value of around 2.5 g/cc. Most or all of the production in the Galway is thought to come from sandstone so these maps should be a good proxy for actual porosity distribution.

Other potential problems with these maps are that only wells that have the entire interval of interest are included. If only the top of the Rose Run was logged, the well is not included in the maps.

POROSITY DISTRIBUTION

The maps in Figures 39 to 41 show two interesting trends. The most obvious trend is the high porosity zone that trends from NW to SE. It should be pointed out that this is largely driven by the porosity in two or three wells, which have questionable density logs. Figure 42 shows that the density log goes off the scale in some of these wells but is not matched by porosity in the neutron logs. This NW-SE trend would disappear if these questionable logs were dropped. Support for using these logs is that the low density (high porosity) seems to occur in the same stratigraphic interval in each well. The second, less noticeable, trend is the SW-NE band of porosity that runs from Northern Cattaraugus and Chemung Counties through Wyoming and Livingston Counties, and into Ontario and Wayne Counties. This trend is most noticeable in Figure 39. This band of porosity appears to correlate with the area where the Rose Run lies directly beneath the Knox Unconformity (see subcrop map in Figure 38). This relationship is discussed in further detail later in this report.

Section 3
DISCUSSION

ORIGIN OF POROSITY

The hypothesis going into this study was that porosity is best developed in the Rose Run Sandstone where it directly underlies the Knox Unconformity. The idea is that meteoric leaching occurred during the Ordovician when the unit was exposed to surface conditions and that this enhanced porosity was preserved throughout the burial history. This may be the case in some areas, but analysis of some wells indicate that meteoric leaching may not be the only source of dissolution. Hydrothermal or some sort of burial leaching may also play a significant role.

The porosity in the Rose Run core from the Kennedy #1well is almost all of a secondary nature. There appears to have been an episode of quartz overgrowth cementation followed by an episode during which that quartz cement and even some of the quartz grains were leached (Figures 14 and 15). This dissolution is focused on the boundary between the cement and the grains which may have had more impurities and been easier to dissolve.

There has not been much published on leached quartz overgrowth porosity but it has also been observed in the Medina Sandstone and other Appalachian Basin Sandstone reservoirs (Laughrey, PA Survey, pers.comm.). Quartz overgrowth cements typically form at temperatures of at least 60-80°C and are not thought to form at near surface conditions. If this is the case here, then the leaching must have occurred after these sandstones were exposed to temperatures normally associated with ~2 km of burial or possibly exposed to hydrothermal fluids while at shallower depths. If the leaching is due to meteoric diagenesis, then there must have been fairly significant uplift prior to the dissolution. It does appear that the northwestern part of the State was uplifted during Knox Unconformity time as is evidenced from the erosion and/or non-deposition of the Tribes Hill, Little Falls and upper Galway Formations.

In the Kennedy #1 well there is a relatively thick section of Little Falls and the Rose Run lies well below the Knox Unconformity. It is unlikely that the Galway was shallow enough to be affected by meteoric diagenesis during Knox Unconformity time. The porosity development in this well may have been entirely due to some sort of subsurface leaching. This is odd, because almost all subsurface fluids are saturated with quartz. Figure 42 shows the solubility of different phases of quartz versus temperature. Warmer fluids can hold more quartz in solution than cooler fluids therefore warming fluids should dissolve quartz and cooling fluids such as those associated with meteoric diagenesis should precipitate quartz. There are a few types of very strong acids that will dissolve quartz, most notably hydrofluoric acid (HF). Fluorine occurs in the basement rocks in NY and there is a small possibility that warm hydrofluoric acid-rich fluids flowed up faults and dissolved the quartz.

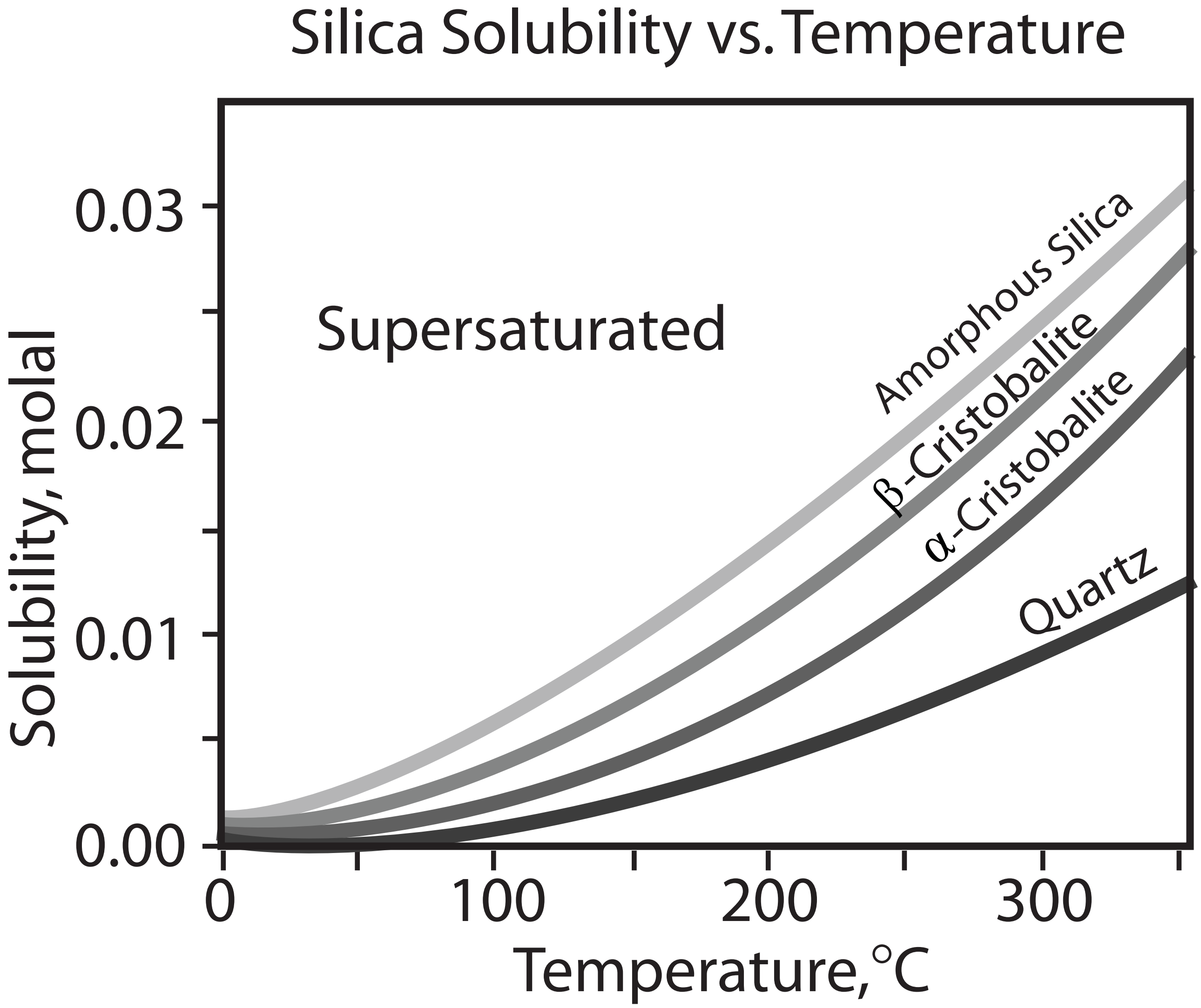


Figure 42. Solubility of quartz versus Temperature. Note that the solubility of quartz increases with temperature, therefore warmer fluids should dissolve quartz while cooling fluids precipitate quartz.

It may be that the pores preserved in the Kennedy #1 well are not representative of the porosity found in the producing fields. Most wells away from the subcrop of the Rose Run do not have good porosity preserved in them and the Kennedy #1 is an outlier.

The porosity in the Hooker Chemical #1 well, which is in the A Dolomite and B Sand, is also of a secondary nature consisting of leached dolomite, feldspar and quartz overgrowths. These units do directly underlie the unconformity, but there are low porosity beds interbedded with the higher porosity beds. Feldspar overgrowths also only form at elevated temperatures and the feldspar overgrowth leaching would also have to have occurred either in a burial environment or after significant uplift.

The origin of the porosity is important because if porosity can form anywhere, the trend could be expanded significantly. There are vast areas where the Rose Run subcrops beneath the Knox Unconformity that have not been drilled, and if there is porosity away from the subcrop (as it appears there is) then prospects could be developed anywhere the Rose Run Sandstone occurs.

EROSIONAL REMNANTS VERSUS 4-WAY STRUCTURAL CLOSURES

The three major fields found to date occur at or near the subcrop of the Rose Run Sandstone (Figure 38). The Cascade Brook Field has had significant erosion of the Rose Run sandstone and produces from the very base of the unit. The Bockhahn Field has had some erosion of the Rose Run in one well while erosion may have occurred down to the very top of the Rose Run in the others. The Northwoods field appears to have some wells where the Galway lies directly beneath the erosion surface and one that clearly has some Little Falls remaining. The Bockhahn and Northwoods Fields were also drilled into structural highs that are visible on seismic and the gas accumulation may have to do with those structural closures and nothing to do with erosion. There have also been discoveries in the area to the southeast of the subcrop that cannot be related to erosion and must be structural closures.

The fact that some fields clearly occur in structural closures is a very important point because it opens up the play for exploration across a much wider area. There is now potential anywhere that porous Rose Run Sandstone occurs and not just in the subcrop area. Any four-way structural closure has potential to be a gas reservoir.

POTENTIAL

There is great remaining potential in the Rose Run Sandstone Member of the Galway Formation (aka Theresa Sandstone). There are vast areas where the Rose Run subcrops beneath the Knox Unconformity that have not been tested. New fields are almost certain to be found through identification of 4-way structural or erosional closures. There is also potential away from the subcrop as some of the most porous wells occur where there is a significant section of Little Falls overlying the Rose Run.

There is also some potential in the sandstones and perhaps in the dolomites that underlie the Rose Run within the Galway Formation. In the Hooker Chemical #1 core examined for this study there is common porosity in sandstones, dolomites and mixed strata (although sandstones appear to be the best). These units produce oil and gas in Ohio and there is no reason that they shouldn't also produce in New York.

Section 4

CONCLUSIONS

A number of new wells targeting Late Cambrian strata of western New York have been drilled, some establishing new field designations and all available data from them was used in this report.

The wells and/or fields include:

Upper Cambrian Galway Fields

Field Name	Location		Wells	API	Operator	TD	Year of First production	Cumulative Production (through 2009)
	Twp	County						MCF
Bockhahn	Sardinia	Erie	Wm Bockhahn Unit #1	31-029-23533	Ardent Resources, Inc	5971	2004	1956798
			G. Bockhahn #1	31-029-23551		6063		
			D. DeGolier Unit #1	31-029-23599		5994		
Northwoods	Arcade	Wyoming	Stahl	31-121-22655	Ardent Resources, Inc.	6021	1998	292279
Hannon	Sardinia	Erie	M. Hannon #1	31-029-24390	Ardent Resources, Inc.	6068	2006	162117
Krohn	Sardinia	Erie	Krohn Unit #1	31-029-24935	Ardent Resources, Inc.	6037	2008	83919
New Field Un-named	Sardinia	Erie	Spencer	31-029-29565	Ardent Resources, Inc.		2009	0
Wildcat	Sardinia	Erie	R. Baker Unit #1	31-029-23600	Ardent Resources, Inc.	6074	Dry	0
New Field Un-named	Sardinia	Erie	Pilkington #1	31-029-24924	Ardent Resources, Inc.	6216	2008	21057
New Field Un-named	Sardinia	Erie	Porter #1	31-029-25005	Ardent Resources, Inc.	6307	2008	4006
Connoisarauley Creek	Ashford	Cattaraugus	Hebdon #1	31-009-21809	Ardent Resources, Inc.	7502	Awaiting Pipeline	0
Bixby Hill	Freedom	Cattaraugus	Bixby Hill #1	31-009-23534	Stedman Energy, Inc.	6859	2004	48088
Wildcat	Sardinia	Erie	Kuntz #1	31-029-24789	Stedman Energy, Inc.	6130	Dry	0
New Field Un-named	Yorkshire	Cattaraugus	Weaver #1	31-009-24790	Stedman Energy, Inc.	6334	2008	123638
Gagwin	Yorkshire	Cattaraugus	Gagwin # 1	31-009-23545	Stedman Energy, Inc.	6412	2005	6007
Dale	Middlebury	Wyoming	L. Wellman #1	31-121-04436	Transamerican Petroleum Corp.	5616	Not in Production	0
Cascade Brook	Middlebury	Wyoming	A. Howes #1	31-121-21840	Miller Gas Corp.	5320	1991	548367
			A. Howes #4	31-121-21945		5272		
			G. Leaton #1	31-121-21900	Lenape Resources, Inc.	5079		
			A. Howes #3	31-121-21908		5148		
			A. Howes #2	31-121-21909		5350		
			Titus Brothers #1	31-121-21920		5260		
			B. Chamberlain #1	31-121-21946		5201		
			Titus Brothers #4	31-121-22042		5211		
			Titus Brothers #3	31-121-22046		5050		
			E. Johannes #1	31-121-21964	GFS Energy, Inc.	5300		
New Field Un-named	Yorkshire	Cattaraugus	Berger #1	31-009-25100	Somerset Production Company LLC	6580	Awaiting Pipeline	0
New Field Un-named	Yorkshire	Cattaraugus	Ashford Properties 1-A	31-009-25133	Somerset Production Company LLC	5900	Awaiting Pipeline	0
Burr Bear Pool	Pomfret	Chautauqua	Crowe #3	31-013-22616	New York Gas & Oil, Inc.	6174	1996	6744

Although it has long been called the Theresa Sandstone Play, paleontological and stratigraphic research indicates that the producing formation in western NY is actually the Rose Run Sandstone Member of the Late Cambrian Galway formation.

The Galway Formation has been subdivided into 7 members: the Rose Run Upper Interbedded, Rose Run Clean Sandstone, Rose Run Lower Interbedded, A Dolomite, B Sand, B Dolomite, B Interbedded and C Sand.

Analysis of 3 cores taken from the Galway formation reveals that the majority of the porosity is secondary in nature consisting of leached dolomite, feldspar and quartz.

Meteoric diagenesis may be responsible for the enhancing porosity where the Rose Run subcrops under the Knox Unconformity, however there are porous wells away from the subcrop belt with a significant thickness of Little Falls between the Galway and exposure surface.

Leaching of both quartz grains and quartz overgrowth cement is difficult to explain through meteoric diagenesis and may imply some sort of subsurface leaching or the involvement of hydrothermal fluids.

Erosional remnants are believed to be the main trapping mechanism where the Rose Run lies just below the Knox Unconformity, but discoveries in the area to the southeast of the subcrop cannot be related to erosion and must be structural closures.

There are large unexplored areas both where the Rose Run lies immediately beneath the Knox Unconformity and away form the subcrop belt.

As a direct result of this report four new prospects have been identified along the subcrop edge and will be drilled in 2010.

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