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Creating a Geologic Play Book for Trenton-Black River Appalachian Basin Exploration

Semi-Annual Report

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ABSTRACT

The Trenton-Black River Appalachian Basin Research Consortium has made significant progress toward their goal of producing a geologic play book for the Trenton-Black River gas play. The final product will include a resource assessment model of Trenton-Black River reservoirs; possible fairways within which to concentrate further studies and seismic programs; and a model for the origin of Trenton-Black River hydrothermal dolomite reservoirs.

All seismic data available to the consortium have been examined. Synthetic seismograms constructed for specific wells have enabled researchers to correlate the tops of 15 stratigraphic units determined from well logs to seismic profiles in New York, Pennsylvania, Ohio, West Virginia and Kentucky. In addition, three surfaces for the area have been depth converted, gridded and mapped. A 16-layer velocity model has been developed to help constrain time-to-depth conversions. Considerable progress was made in fault trend delineation and seismic-stratigraphic correlation within the project area.

Isopach maps and a network of gamma-ray cross sections supplemented with core descriptions allowed researchers to more clearly define the architecture of the basin during Middle and Late Ordovician time, the control of basin architecture on carbonate and shale deposition and eventually, the location of reservoirs in Trenton Limestone and Black River Group carbonates. The basin architecture itself may be structurally controlled, and this fault-related structural control along platform margins influenced the formation of hydrothermal dolomite reservoirs in original limestone facies deposited in high energy environments. This resulted in productive trends along the northwest margin of the Trenton platform in Ohio. The continuation of this platform margin into New York should provide further areas with good exploration potential.

The focus of the petrographic study shifted from cataloging a broad spectrum of carbonate rocks that occur in the Trenton-Black River interval to delineation of regional limestone diagenesis in the basin. A consistent basin-wide pattern of marine and burial diagenesis that resulted in relatively low porosity and permeability in the subtidal facies of these rocks has been documented across the study area. Six diagenetic stages have been recognized: four marine diagenesis stages and two burial diagenesis stages. This dominance of extensive marine and burial diagenesis yielded rocks with low reservoir potential, with the exception of fractured limestone and dolostone reservoirs. Commercial amounts of porosity, permeability and petroleum accumulation appear to be restricted to areas where secondary porosity developed in association with hydrothermal fluid flow along faults and fractures related to basement tectonics.

A broad range of geochemical and fluid inclusion analyses have aided in a better understanding of the origin of the dolomites in the Trenton and Black River Groups over the study area. The results of these analyses support a hydrothermal origin for all of the various dolomite types found to date. The fluid inclusion data suggest that all of the dolomite types analyzed formed from hot saline brines. The dolomite is enriched in iron and manganese, which supports a subsurface origin for the dolomitizing brine. Strontium

isotope data suggest that the fluids passed through basement rocks or immature siliciclastic rocks prior to forming the dolomites. All of these data suggest a hot, subsurface origin for the dolomites.

The project database continued to be redesigned, developed and deployed. Production data are being reformatted for standard relational database management system requirements. Use of the project intranet by industry partners essentially doubled during the reporting period.

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EXECUTIVE SUMMARY

This report documents further progress of the Appalachian Oil and Natural Gas Research Consortium (AONGRC) to create a geologic play book for Trenton-Black River exploration in the Appalachian basin. The AONGRC organized a Trenton-Black River Research Team, consisting of recognized experts currently employed by the state geological surveys in Kentucky, Ohio, Pennsylvania and West Virginia, and the New York State Museum Institute, and then recruited seventeen gas exploration companies to form an industry-government-academic partnership. This "Trenton-Black River Appalachian Basin Exploration Consortium" (the Consortium), agreed to co-fund and conduct the research effort.

This project has three main objectives:

1) to develop an integrated, multi-faceted, resource assessment model of Trenton-Black River reservoirs in New York, Ohio, Pennsylvania, Kentucky and West Virginia;
2) to define possible fairways within which to conduct more detailed studies leading to further development of the gas resource in these reservoirs; and
3) to develop an integrated structural-stratigraphic-diagenetic model for the origin of Trenton-Black River hydrothermal dolomite reservoirs.

Researchers have examined and interpreted all of the seismic data that are currently available to the consortium. To aid in the correlation between well logs and seismic profiles, synthetic seismograms were made for key wells, providing an intermediate correlation step between geophysical logs and seismic data. These seismograms, together with the revised 3-D velocity models, have enabled researchers to identify formations tops on seismic, and to begin the process of mapping these tops and stratigraphic intervals throughout the basin. A database has been created for the seismic and well log data. This collection of seismic, geophysical well log and well stratigraphic top data has continued to increase in size over the past 6 months.

Stratigraphers have examined and scanned approximately 1,800 geophysical logs and measured and described 16 cores from across the basin. Approximately 500 of the scanned logs have been converted to vector (LAS) format for use in regional cross sections. A network of 18 cross sections has been generated, along with a series of preliminary isopach maps that are based on formation tops interpreted from approximately 1,000 well logs, plus core and sample descriptions. A better understanding of the basin architecture during deposition of the Trenton Formation has emerged from this effort, and production can be seen to be related to this basin architecture, which itself could be structurally controlled. A preliminary depositional model for Trenton rocks consisting of two platforms with an intervening sub-basin has been developed and placed within this architectural framework. Cross sections, isopach maps, core descriptions and the presence of hydrocarbon reservoirs all support the validity of this model.

To date, 605 thin sections have been analyzed by conventional petrographic microscopy, and 130 core samples have been examined with scanning electron microscopy and energy dispersive x-ray spectroscopy. A pattern of basin-wide marine and burial diagenesis of original limestone facies has emerged from this effort. Six diagenetic stages have been recognized, four of which are marine diagenesis and two of burial diagenesis. This dominance of marine and burial diagenesis resulted in rocks of low porosity and permeability and poor reservoir potential. Commercial amounts of porosity, permeability and petroleum accumulation appear to be restricted to areas of the basin where secondary porosity developed in association with hydrothermal fluid flow upward from the basement along faults and associated fractures.

To better understand the origin of the four different dolomite types that have been observed, researchers are conducting stable isotope, strontium isotope, trace element and fluid inclusion analyses. More than 1,200 samples have been analyzed for stable isotopes of oxygen and carbon. Oxygen isotope values for samples from New York wells clearly indicate that the fluids from which the rocks formed was not sea water. Data from Ohio suggest a similar origin. Strontium isotope data suggest that the fluids that made the dolomite passed through continental basement rocks or immature feldspar-rich siliciclastics prior to making the dolomite. Trace elements are being analyzed for Fe and Mn, which are essentially absent in sea water but are common in subsurface brines. The Fe and Mn concentrations that were observed support a burial origin for the dolomites. Fluid inclusions trapped in dolomite crystals represent the original fluid from which the crystals formed. Therefore, fluid inclusions can be analyzed to determine the temperature and salinity of the original fluid and to gain information on the environment of formation. All of the fluid inclusion and geochemistry results to date support a hydrothermal origin for all of the various dolomite types that occur in the Trenton Limestone and Black River Group across the study area.

The project database and intranet continue to be developed and expanded; data from all project tasks are posted on the website, as are all presentations made at consortium meetings. Approximately two thirds of the company partners were represented at a recent meeting of the entire consortium. Presentations made by research team members at this day-long meeting serve as the basis for this technical report.

During the recent consortium meeting, several company partners expressed an interest in providing more data to the research teams. The general consensus of the entire consortium was that incorporating these new data into the effort would result in a final product that would be more beneficial to industry and to the funding agencies. However, everyone present also agreed that to fully analyze and integrate results from these additional data would require additional time beyond the original scope of the project. Following the consortium meeting, the Project Director made a lengthy presentation to NETL staff members, after which the advantages of a no-cost extension were discussed.

RESULTS AND DISCUSSION

Structural and Seismic Analysis and Mapping

Structural and seismic analyses are being carried out to characterize the major geologic structures of the study area and to determine as closely as possible their timing relative to the fracturing, dolomitization and hydrocarbon charging of reservoirs in the Trenton-Black River interval**.** To accomplish this, members of the Structural and Seismic Analysis and Mapping research team developed and implemented the following work plan:

- Data Acquisition
    - -- Seismic, well logs and stratigraphic well tops
- Load Seismic data
    - – Digital SEGY files into Kingdom Suite
    - – Raster images into PetraSeis
- Load Well Data
    - – Digital LAS files into Kingdom Suite & Petra
    - – Raster images into Petra
- Load preliminary (i.e. any available) well tops
- Use sonic logs for synthetic seismogram creation and creation of velocity model
- Correlate log tops to reflecting seismic horizons
- Interpret stratigraphy and structure from seismic
- Use velocity model to transform depths in time to depths in feet subsea
- Create 3D surfaces from seismic horizon and well-based stratigraphic tops elevations
- Merge products with those of the other consortium members

Traditional subsurface data derived from well logs have been integrated with seismic data to map the Precambrian surface, including fault locations and major structural axes, which may be indicators of potential Trenton-Black River dolomitized and/or fractured target areas. In addition, contour maps are being constructed using the two combined data sets to develop the following:

- Base of Devonian Shale
- Top of Ordovician
- Kope Formation
- Utica Shale
- Trenton Formation
- Black River Limestone
- Knox Unconformity
- Pre-Knox sediments (Conasauga Group, Rome Formation, etc.)

- Basal sandstones
- Major structural features (especially those affecting dolomitization)

In developing these maps, well-data tops agreed to by the five research agencies are being used together with two-way–travel times from available seismic data. The two-way-travel times are being converted to elevations in feet (relative to mean sea level) based on sonic data and formation tops data from the well logs.

Seismic Data

Existing seismic data already available for this study at the five research agencies form a general data base for the project. Each of the sponsoring companies, however, has been and is being solicited for contributions of additional data. The additional data are considered critical to meet the objectives of this part of the study. A summary of the collected seismic data and potential seismic data contributions are illustrated in Table 1 below.

As a result of the seismic data contributed by the five research agencies and industry, the following datasets were made available and loaded into the Kentucky Geological Survey's (KGS's) seismic interpretation workstations:

- Digital and paper data made available by the KGS, covering eastern Kentucky, West Virginia, and parts of Pennsylvania and New York
- Digital data made available by the New York State Museum, covering parts of western New York
- Paper data made available by the Pennsylvania Geological Survey, covering part of western Pennsylvania
- Digital data made available by North Coast Energy, covering small parts of West Virginia
- Digital and paper data made available by the Ohio Division of Geologic Survey within Ohio
- Digital data from Abarta Oil and Gas for data in eastern Kentucky
- Digital 3-D data made available by Talisman Energy in southwestern Ontario.

The map in Figure 1 shows the extent of the data that are currently available for seismic interpretation in the project.

Table 1.

Company	Results
Abarta	**DATA:** 2 lines in central KY
Belden and Blake*	Waiting to see who will contribute, concerned, confidentiality; data now Talisman's
Cabot	No data available
Ceja	Don't know; checking with attorneys again; originally committed; no shot point map
Compton	No U.S. data
Enervest (CGAS)	Checking with new owners and partners on Saybrook 3-D data
EOG	possible work in EOG office with some NY data
Equitable	Seisco owns former Equitable data; Checking with Seisco on requested PA, OH data
EXXON**	Will allow for 3rd party data
GeoData*	Will give permission of 3rd party data; checking with Exxon on joint CNG data
Great Lakes	Checking contracts with partners; skeptical; no shot point map
NY State Museum	**DATA:** western NY
PA Geological Survey	**DATA:** western PA
North Coast	**DATA:** several lines in WV
Petro Evaluation	Sending DATA for Musking. Co. OH thru John Foreman; possibly more
Pioneer	SEI data; difficult to obtain; no shot point map
Seisco**	**DATA:** covers much of KY, WV; some in PA, NY; KGS has rights
Seismic Exchange**	Visited in ¾; concerned; issues: rights and sharing; want +$; shot point maps
Seneca	Visited in ¾; data in PA; issues: confidentiality, rights, access; shot point map
Schlumberger	Not contacted for seismic data
Talisman	**DATA:** 3-D part Rochester Field, Ont.; 2-D data on NY/PA border being sent
Texas Keystone	Talked with John Taylor; will send stick maps of available data; WV data likely
Ultra	SEI data; may allow consortium work at their Denver office only; PA CGG map rec'd
Vintage	Unable to provide licensed data to consortium

* Now owned by Capitol C Energy Operations

** Not a sponsor

*** Robert Gaston, Consultant

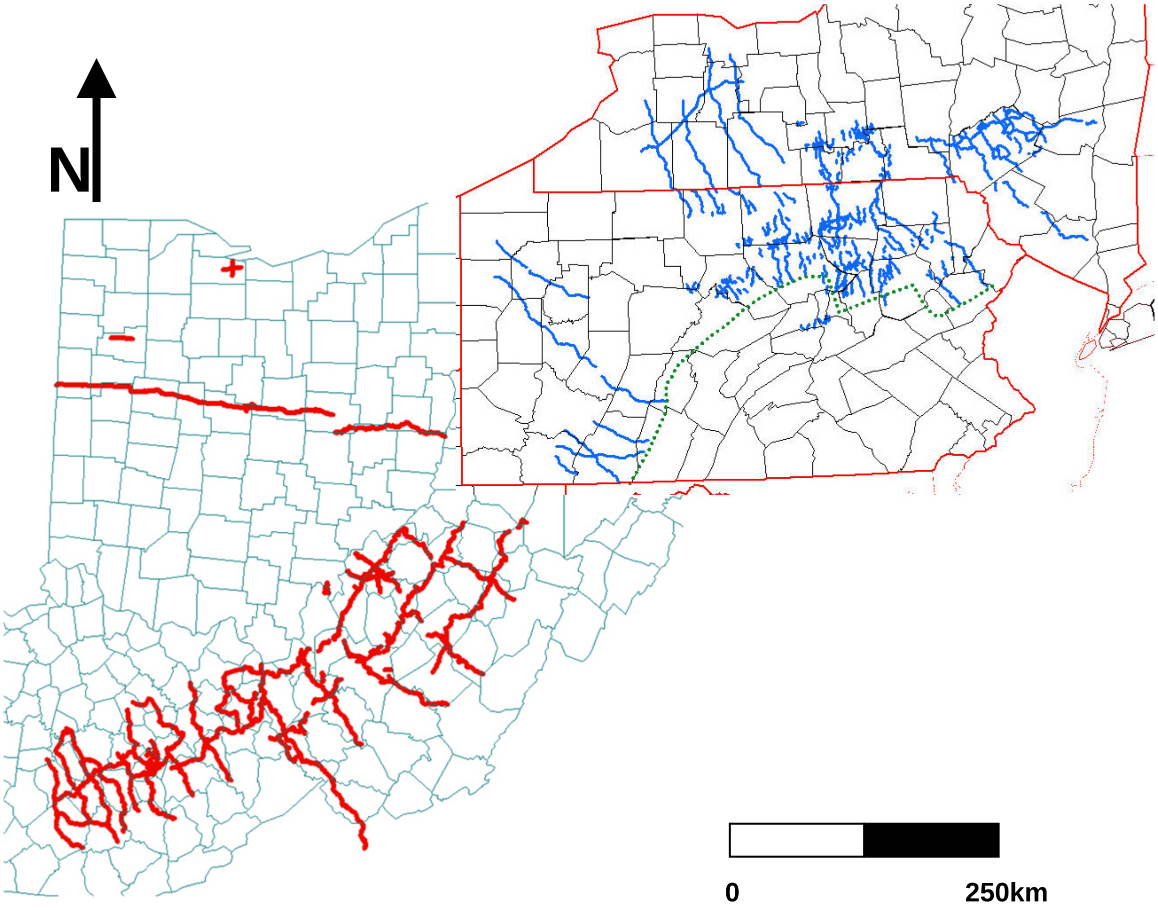


Figure 1. Map of the study area showing the location of currently loaded seismic data.

In addition, discussions concerning the possibility of obtaining additional data for the study are currently underway with the following consortium members and others):

- Seneca Resources for data in Pennsylvania
- Petro Evaluation for data in part of Muskingum County, Ohio (with the possibility of some other additional data)
- Exxon data for the Appalachians
- Ultra Petroleum Corp. for data in Pennsylvania
- CGG data for data in the Appalachians
- Talisman Energy for data in south-central New York
- Seismic Exchange, Inc. for Appalachian data licensed by several of the sponsoring companies
- Equitable Production for data in Kentucky and other parts of the Appalachians

As can be seen from Figure 1, many areas have few available seismic data at this point in the study. These areas include most of Ohio, northeastern and extreme southeastern portions of Kentucky, several parts of western Pennsylvania, parts of West Virginia and several parts of southwestern New York.

In attempting to preserve the integrity of the seismic data provided, our approach has been to restrict access and interpretation of the data to just three geologists at the KGS and to hold the data secure in a locked interpretation room at KGS. These three geologists sample two-way-travel-times for several of the horizons discussed above at intervals along each line. The data derived from the seismic profiles are then used to calculate depth conversions based on estimated velocities for a particular area and interval. In this way, the actual data from the seismic profiles are not recorded on a map or table that is part of any report distributed to the consortium. The derived data are then used to construct the regional scale maps discussed above. All data profiles are returned to the owner upon completion of the process.

Currently, we have focused on U.S. data and have made limited overtures to sources in Ontario, Canada for seismic data. We have not attempted to collect gravity and magnetic data. These efforts will be carried out in the future.

Well Data

A total of 402 digital well log files have been loaded into Petra and Kingdom Suite software for this project, including sonic logs for 114 wells. The preliminary set of formation tops that has been loaded includes 831 KY wells, 103 OH wells, 644 NY wells, 101 PA wells and 22 WV wells.

The current set of stratigraphic (formation) tops being interpreted from well logs and recorded for the project are:

- Ohio Shale (Devonian)
- Top of Ordovician
- Kope Shale (Ordovician)
- Point Pleasant Formation (Ordovician)
- Trenton Formation (Ordovician)
- Black River Group (Ordovician)
- Deike and Millbrig bentonites (Ordovician)
- Wells Creek Dolomite (Ordovician)
- St. Peter Sandstone (Ordovician)
- Knox Unconformity (Ordovician)
- Rose Run Sandstone (Ordovician)
- Conasauga Group (Cambrian)
- Rome Formation (Cambrian)
- Basal & Mt. Simon Sandstones (Cambrian)
- Precambrian Unconformity

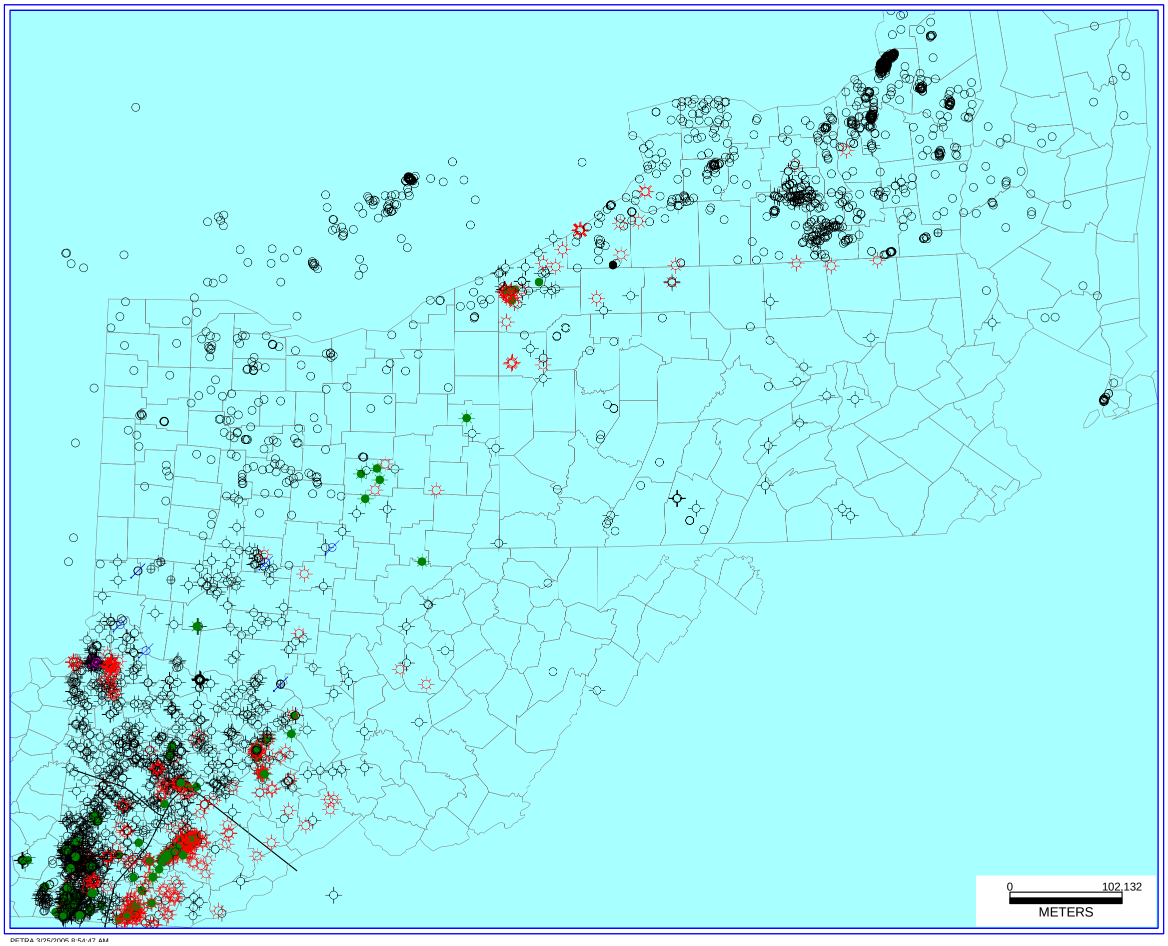


Figure 2. Map showing the location of the wells within the study area used for stratigraphic analysis and seismic correlation to date.

Structural and Seismic Investigations

Interpretation of several prominent reflecting horizons within the seismic data has begun in large portions of eastern Kentucky, West Virginia, north-central Pennsylvania and south-central New York. In addition to the original seismic data set, three new digital (SEG-Y) field-scale seismic lines from eastern Kentucky have been received (from Abarta) and loaded into Kingdom Suite™ software, two new digital (SEG-Y) regional seismic lines from central Ohio (reprocessed COCORP lines) have been loaded, and two new analog (paper copies) and three new digital (SEG-Y) Ohio seismic lines have been received and loaded into PetraSeis™ software.

Specific regional seismic horizons as well as numerous local horizons have been interpreted for the northeastern Pennsylvania/southern New York region. These horizons include, but are not limited to:

- Tully Limestone (Taghanic)
- Oriskany Sandstone (Deerparkian)
- Salina Group (Canastotan)

- Lockport Group (Lockportian)
- Clinton Group/Rochester Shale (Tonowandan)
- Queenston Formation (Richmondian)
- Trenton Limestone (Shermanian)
- Black River Group (Blackriverian)
- Knox/Beekmantown Group (Croixian)
- Basement (Grenville)

Two north-south cross-sections labeled *A* and *B* are provided (Figure 3) as an example of the level of work that has been carried out to date. The seismic data have been omitted in these figures for proprietary reasons. These seismic lines are partially constrained by wells that were converted to two-way time and projected along strike to the lines. Seismic resolution decreases with depth; however, it was possible to resolve the basement on these lines. Note that much of the thickening has occurred below the Beekmantown Group and within the Rose Run Formation. Also, note the connection with what appears to be Alleghanian salt tectonics, basement faults and Trenton sag features. Two additional interpretations of seismic lines are included, one (Figure 4) is a cross section across the northern edge of the eastern Rome Trough, and the other (Figure 5) crosses the northern edge of the northern Rome Trough in West Virginia. The syntectonic sediments within the trough can be observed between the Nolichucky Shale (dark green) and the basement (yellow).

Within the study area, two regional, 16-layer, velocity models were created to help further constrain the time-to-depth conversions of seismic horizons, and to aid in stratigraphic correlation in areas of low-resolution seismic data. The Kentucky, Ohio and West Virginia model was created from the formation tops contained in 763 wells and sonic logs from 54 wells. The New York and Pennsylvania regional model was created from the formation tops contained in 745 wells and sonic logs from 53 wells. Sonic-log data were averaged with petrophysical software (TerraStation™ and Petra™) within logical groups of strata, resulting in precise interval velocities. These values were then gridded over area in order to accommodate for subtle stratigraphic changes (and, therefore, velocity changes) within each layer over the 5-state area. In wells without sonic logs, calculated interval velocities for each layer were extracted from the appropriate Lat/Long position on these sonic log grids. These values then were used to calculate the depth of formation tops in time (seconds), as opposed to feet.

Preliminary structural maps for parts of the area have been generated using the interpretations from the wells and seismic data that are currently available. These initial maps will be updated as more seismic data become available and as additional velocity information from wells clarifies time-to-depth relationships. The interpretation of the important horizons within the study area allows the gridding of these surfaces to produce two-way time structure maps. Figures 6 and 7 are examples of the two-way time structure maps (in seconds). One (Figure 6) is a map of the Tully Limestone, and the other (Figure 7) is a portion of the Trenton Formation map from southern New York and northern Pennsylvania.

Well tops and depth-converted seismic horizons can be combined to generate structure and isopach maps of stratigraphic units within the study area. Figures 7, 8, 9a, 9b, and 10 show the process of generating a structure map of the basin from the initial seismic interpretation to a larger regional map. Figure 7 shows the two-way time structure map of the Trenton. Figure 8 shows that same map after it was converted to depth. Figure 9a shows the depth map of the basement from the seismic data gridded with well tops to expand the map outside the area covered by seismic data. Figure 9b shows the counterpart structure map generated in the southern area of this study. Finally, Figure 10 shows the regional map generated for the southern part of the study area combined with the map generated in the north.

Error checking is performed during the interpretation stages by mapping the time to these horizons and analyzing for any anomalies, and by comparing estimated depths and stratigraphic thicknesses with local well data. A regional, 3-D geological velocity model has been created in order to constrain time-to-depth conversions. In addition, sonic and density logs from available wells have been used to calculate interval velocities and acoustic impedance values for the creation of synthetic seismograms. These can then be used for comparison and verification of horizon interpretations in nearby seismic lines. An example of one of these correlations is shown in Figure 11.

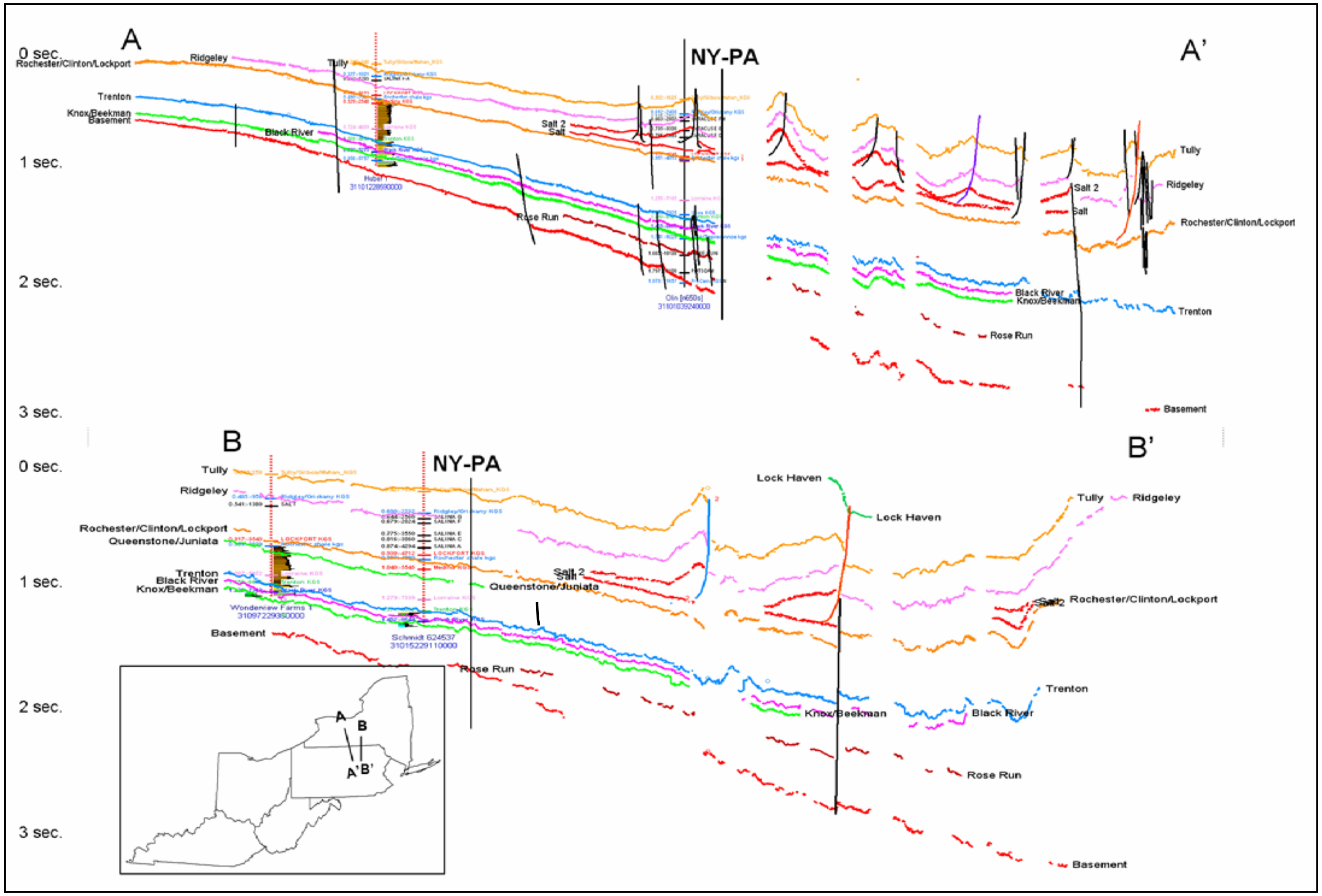


Figure 3. Two initial cross-sections in southern NY and northern PA. These dip lines are based on 2D seismic data (not shown here). Both lines end in the south near the Allegheny Front. Note the Alleghanian salt tectonics that occurred because of the mobilization of evaporites in the Salina Gp. Seismic resolution is poor at depth; however, with the help of well control it is possible to resolve the basement on these and other lines within the study area. There is a possible connection between the spatial distribution of the basement faults, Trenton sags, and the later salt tectonics. This is an initial interpretation and will be updated as the study progresses and as more seismic data becomes available.

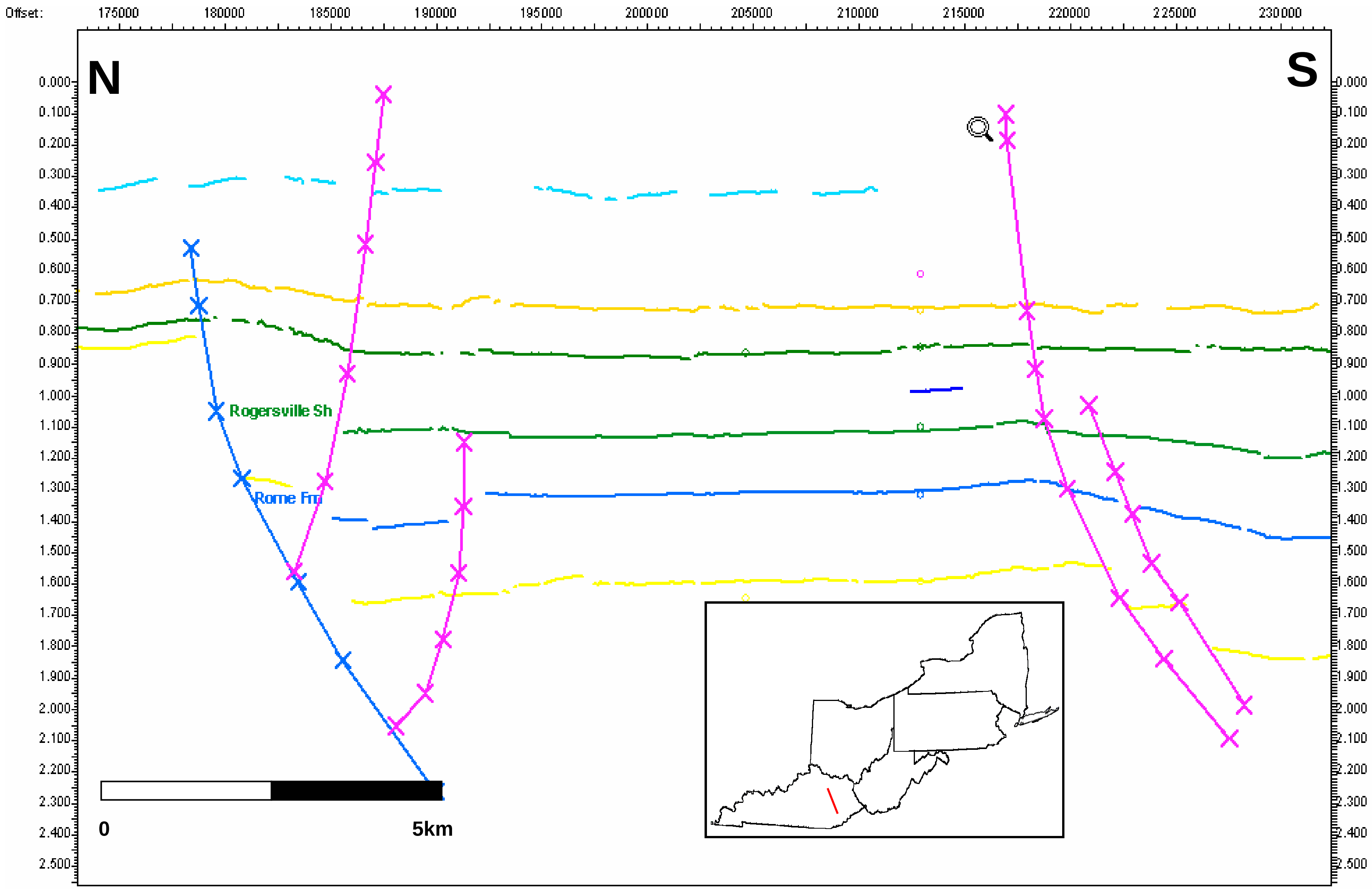


Figure 4. Northern edge of the Rome Trough in Kentucky. The syntectonic sediments within the trough can be observed between the Nolichucky Sh. (dark green) and the Basement (yellow).

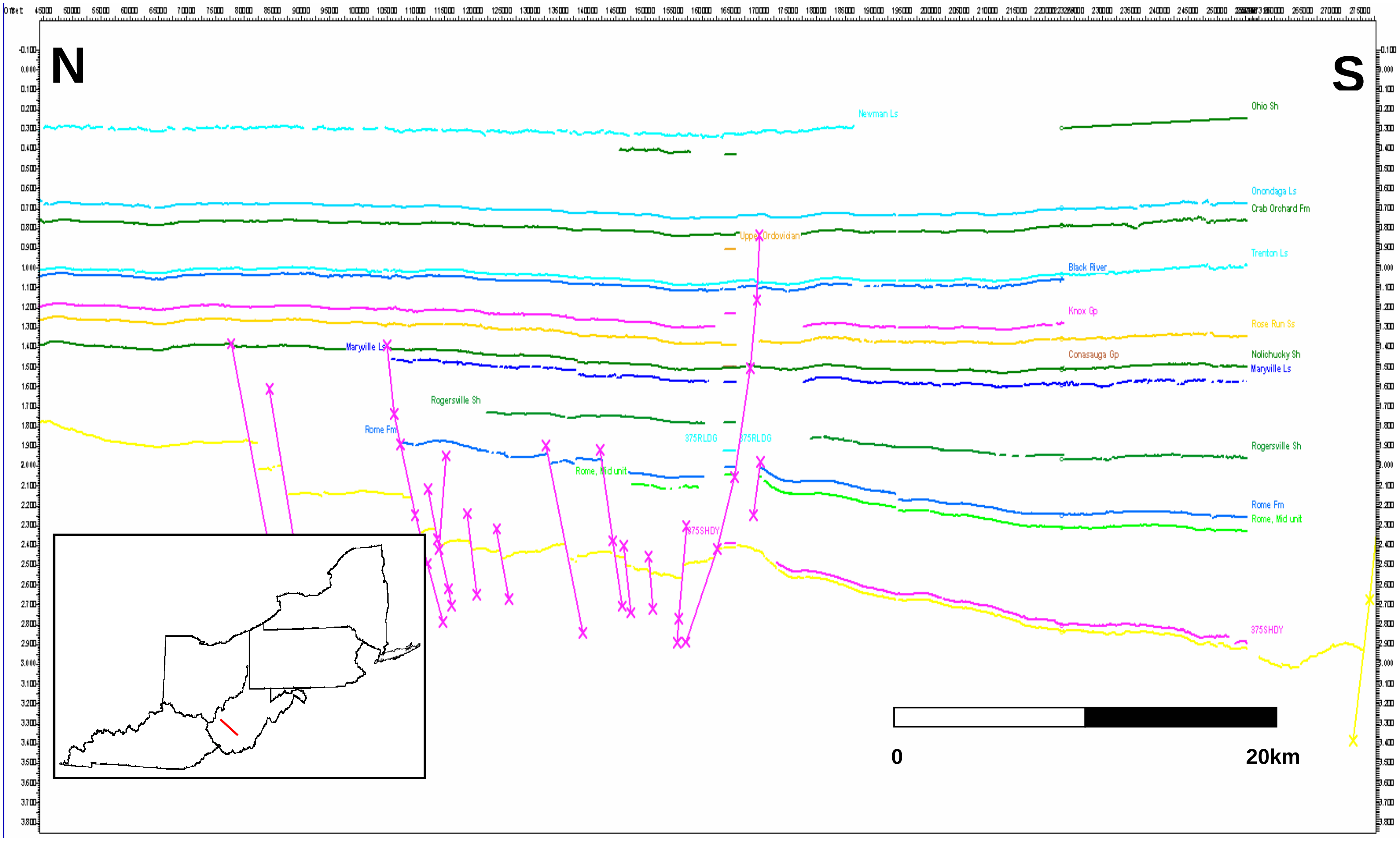


Figure 5. Northern Rome Trough in West Virginia. The syntectonic sediments within the trough can be observed between the Nolichucky Sh. (dark green) and the Basement (yellow).

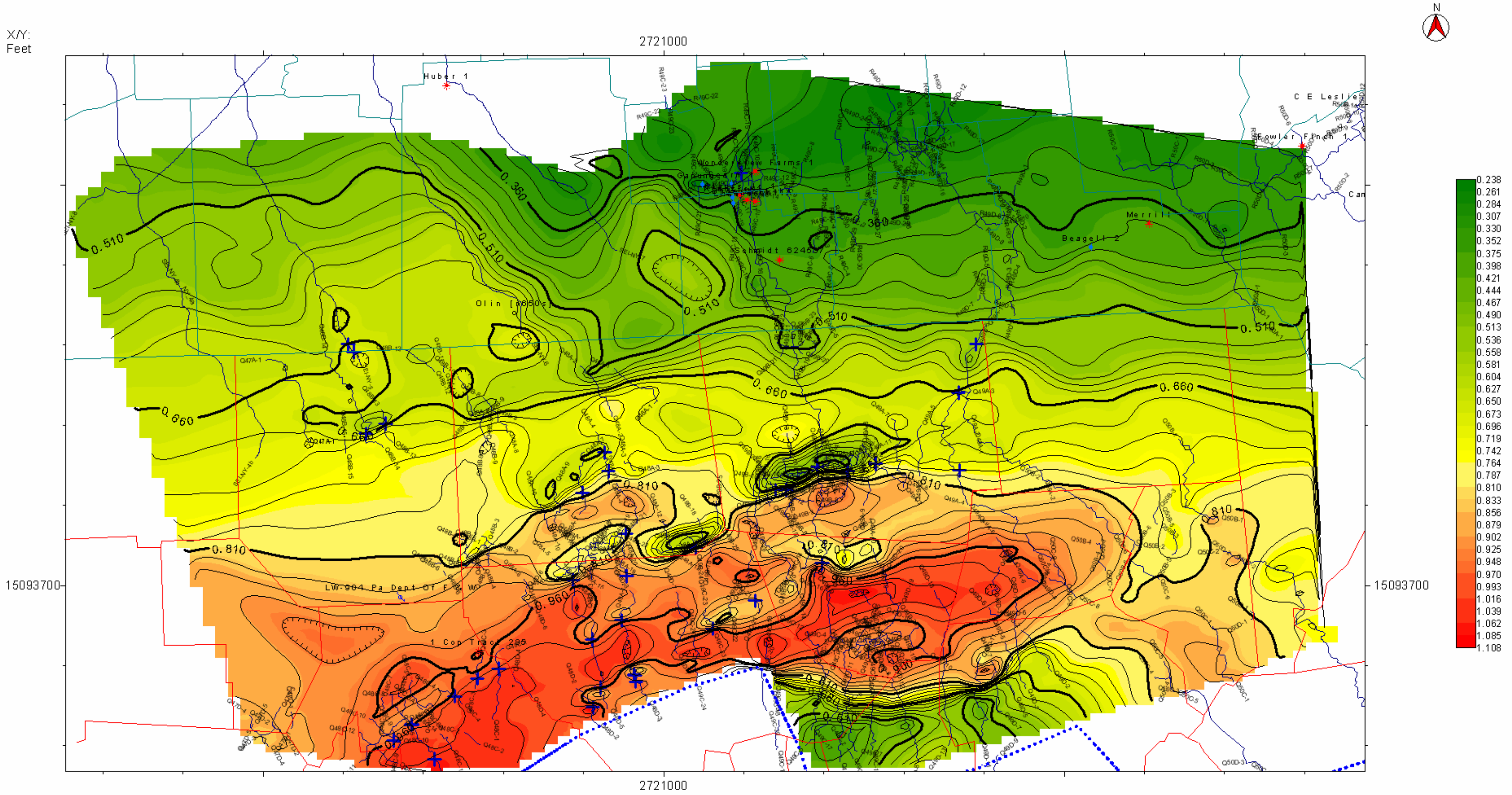


Figure 6. Time structure map of the Tully Ls. generated from the available 2D seismic data. The Tully Ls. is an important regional seismic reflector in New York and Pennsylvania (faults not shown).

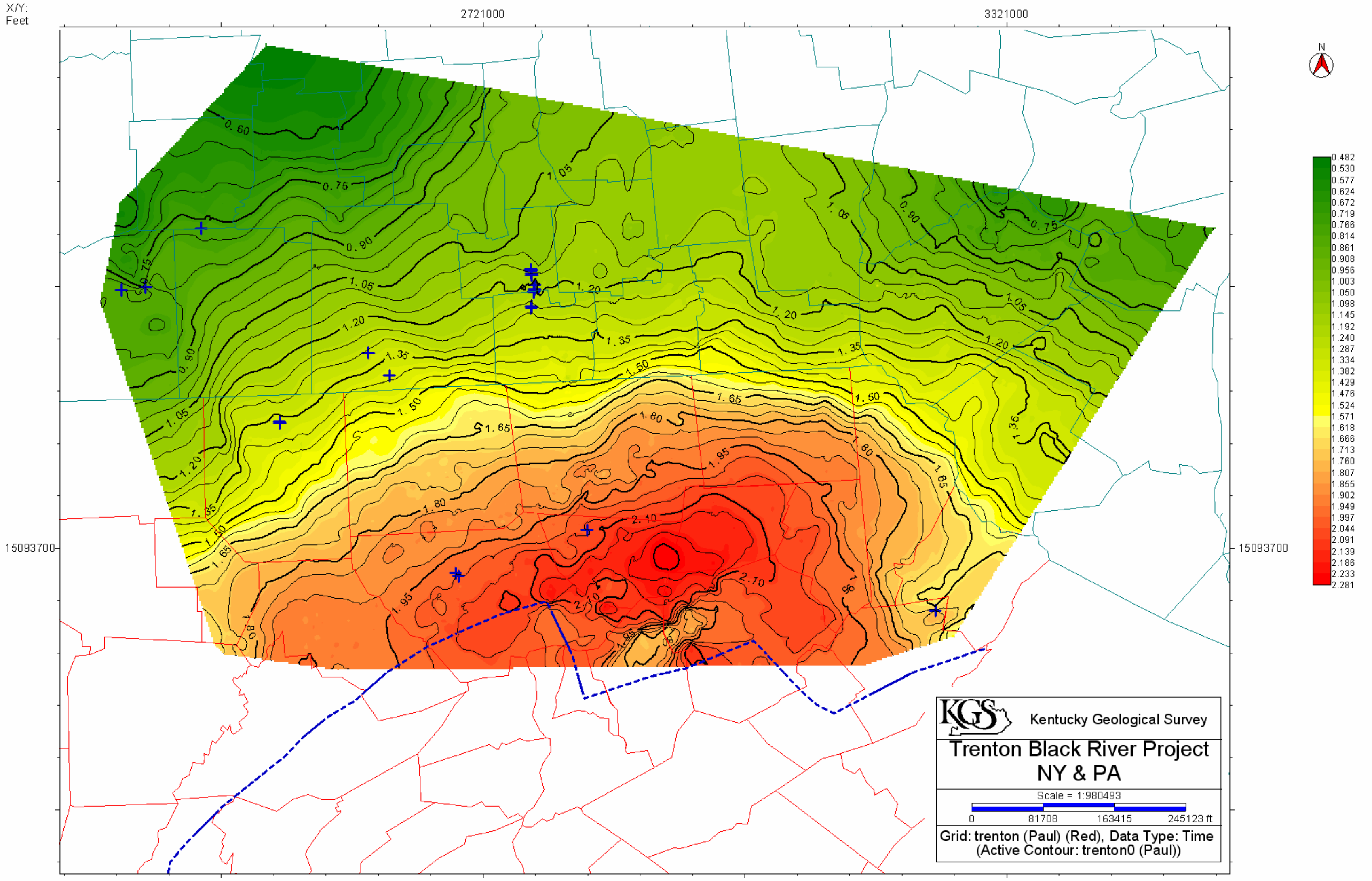


Figure 7. Two-way-time structure map for the top of the Trenton Ls. The formation of the Alleghanian foreland basin controlled much of the Trenton Ls. structure.

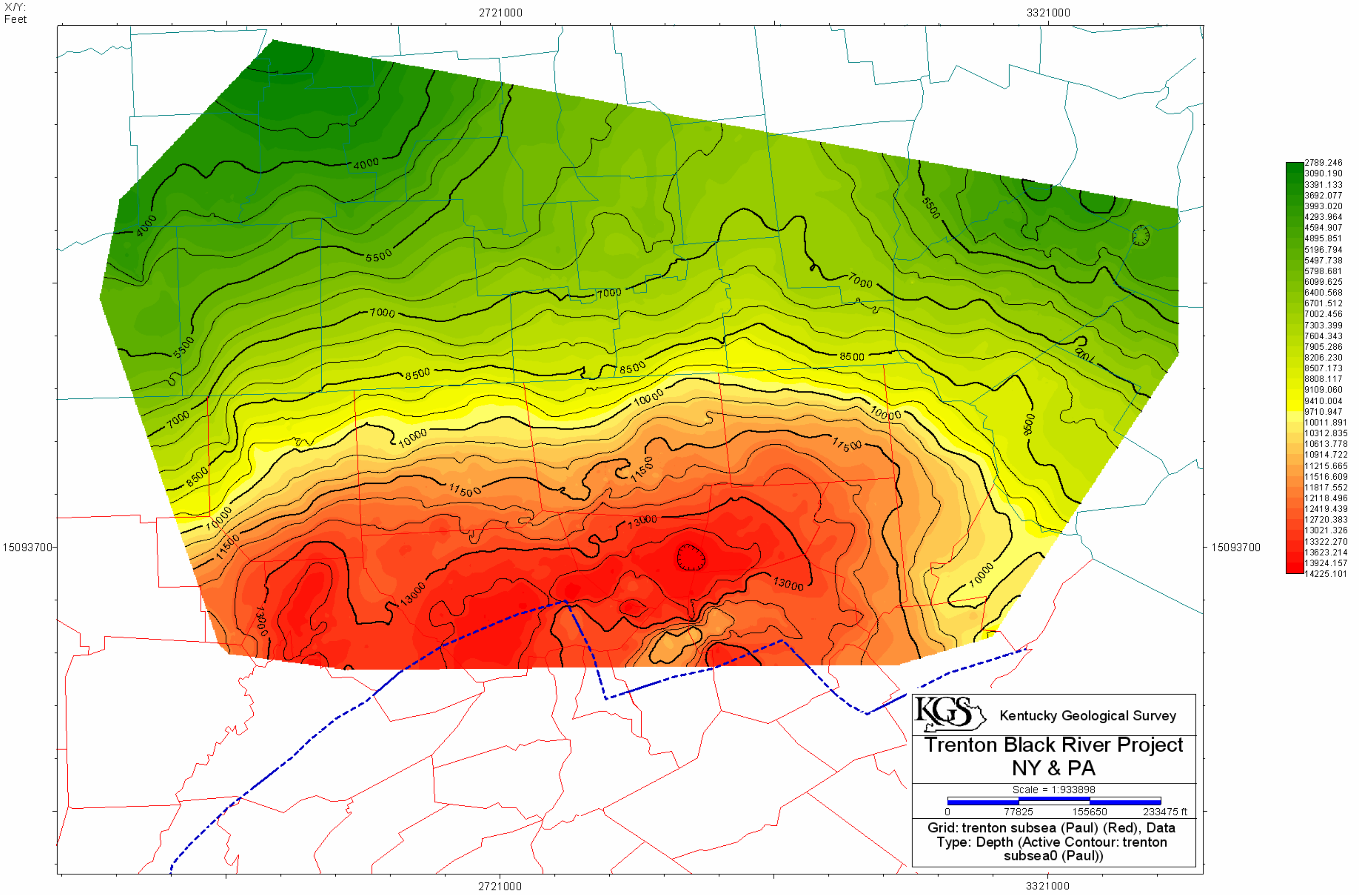


Figure 8. Structure map of the top of the Trenton Ls., based on 2-D seismic data converted to depth from time-to-depth curves calculated from the well data.

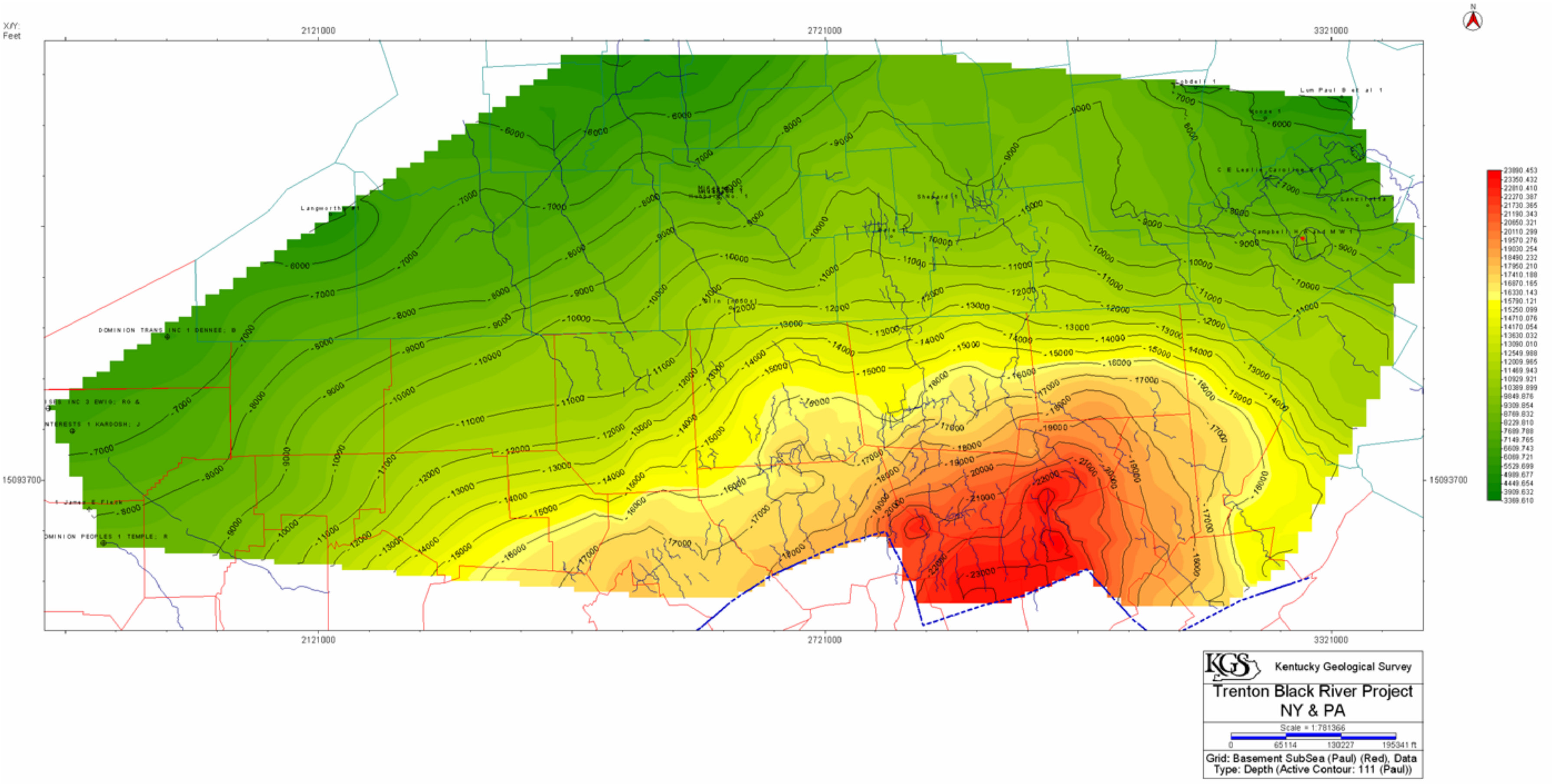


Figure 9a. Structure map of the top of the basement based on well tops and available seismic data (major fault systems not shown) in New York and Pennsylvania.

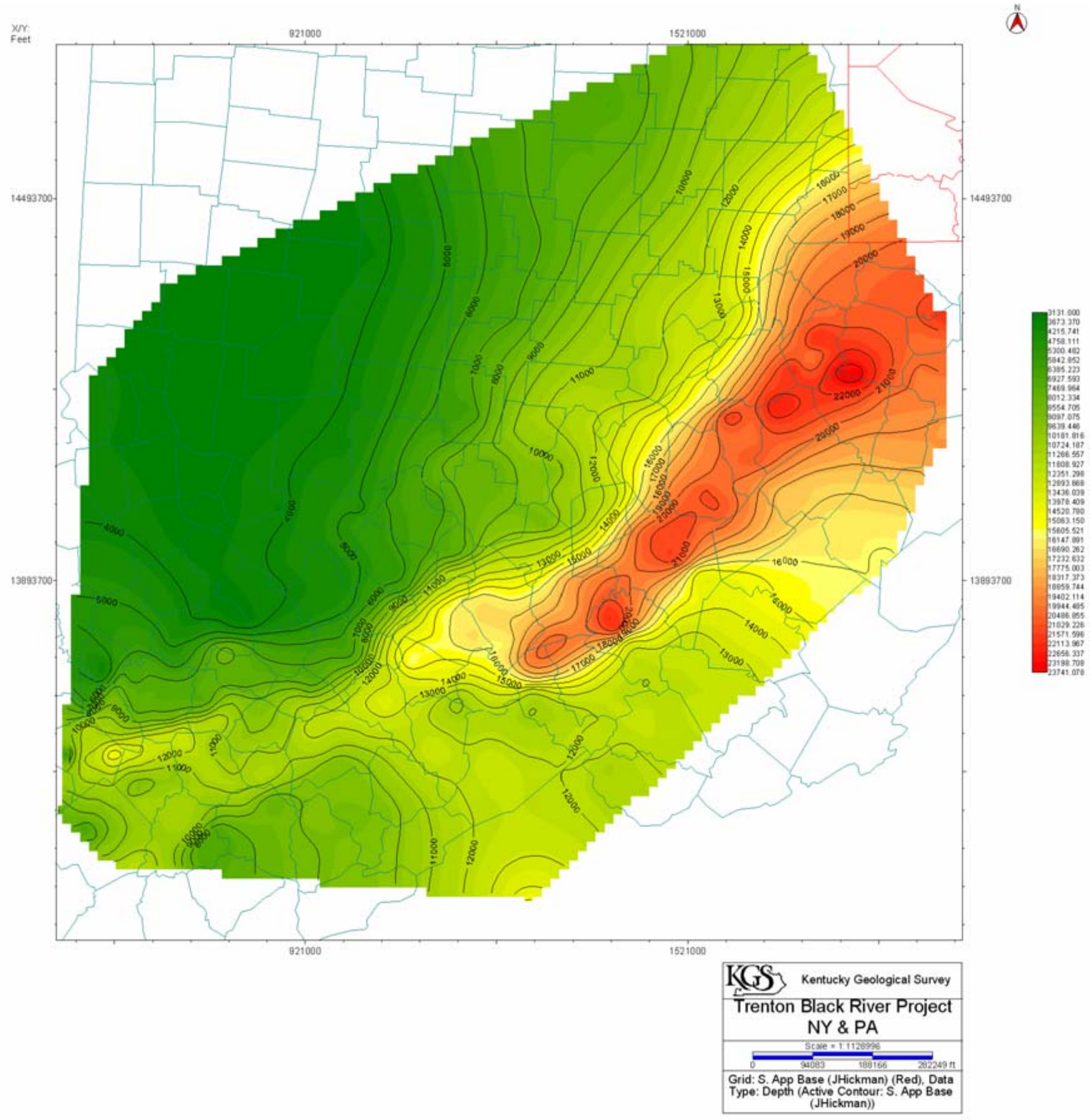


Figure 9b. Structure map of the top of the basement based on well tops and available seismic data (major fault systems not shown) in Kentucky, Ohio, and West Virginia.

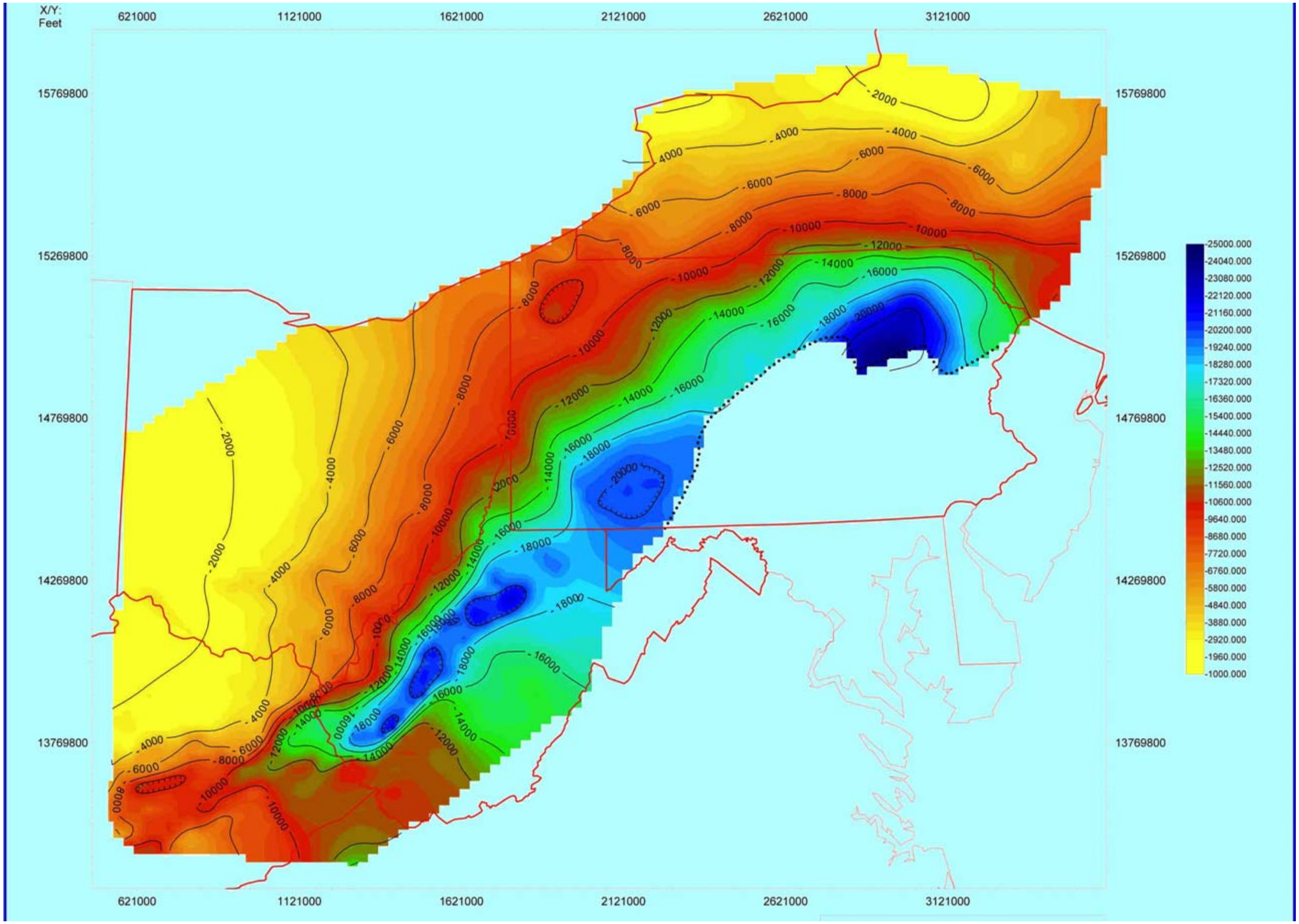
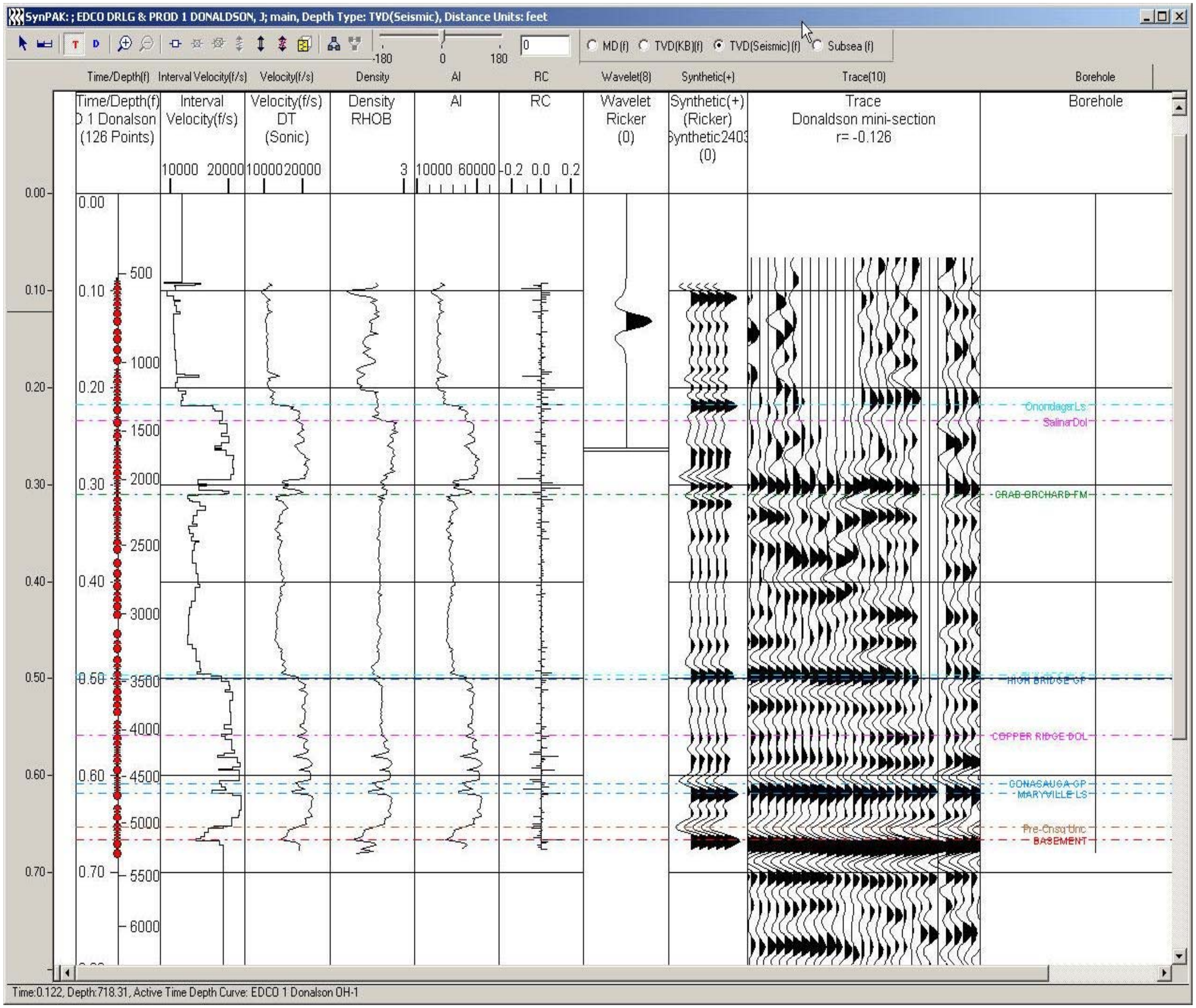


Figure 10. Structure contour map of the top of the basement in the Northern Appalachian Basin (major fault systems not shown). The structure of the basement is a result of Cambrian rifting and later Alleghanian compression and foreland basin formation



SynPAK: ; EDCO DRLG & PROD 1 DONALDSON, J; main, Depth Type: TVD(Seismic), Distance Units: feet

Time:0.122, Depth:718.31, Active Time Depth Curve: EDCO 1 Donalson OH-1

Figure 11. Interval velocity, acoustic impedance, and synthetic seismogram for a well in eastern Ohio. The calculated waveforms matches well with the wavelet traces taken from a nearby seismic line. For reference and comparison, the Trenton-Black River reflector occurs at about 0.50 seconds and the Grenville Basement reflector is around 0.67 seconds

Preliminary Conclusions from the Structural and Seismic Study

Past exploration for Trenton-Black River hydrocarbons has shown that basement faulting (often with a wrench component), structural sags and hydrothermal dolomite within the Trenton and Black River carbonates can indicate possible traps and reservoirs of oil and natural gas. Therefore, one of the major objectives of this project is to map the basement faults within the Appalachian Basin.

Though the numerous basement faults that exist in New York State exhibit evidence for cross-strike structural discontinuities, the well and 2-D seismic data examined to date show no evidence of Cambrian syntectonic sedimentation. In contrast, areas with significant basement offset as well as Cambrian syntectonic sedimentation observed in Pennsylvania (Figure 3) are similar to the Rome Trough of Kentucky and West Virginia (Figures 4 and 5). Cross-section B-B’ shows a basement offset in Pennsylvania near the New York border that exhibits growth on the southern, or downthrown side, but with little to no offset in the overlying strata. This same growth fault appears to have been identified by Beardsley and Cable (1983) as recorded by Ryder (1992). Initial structure maps of the basement (Figure 10) and past studies, including those of the Rome Trough consortium study (Harris, 2002), suggest that the Rome Trough transforms from a full graben in Kentucky to a half graben system in West Virginia. The boundary fault in West Virginia is to the southeast with less offset along the northwestern edge of the trough.

On the southern end of cross-section B-B’ another basement fault can be observed (though this may in fact be a seismic pushdown from the Salina Group evaporites); however, in this case the downthrown side is to the north, and strata are offset equally from the basement up to at least the Lockport Dolomite. This fault is far too young to be involved in Cambrian rifting. It is, however, important to note that this fault appears to have played an important role in the location of the overlying salt tectonic decollement thrust. These types of basement faults may be different in age from those associated with the Cambrian rifting, but they may still be important conduits for hydrothermal fluids. Therefore, surface thrusts and antiforms may help determine the location of faults that penetrate the basement but were not necessarily involved in Cambrian rifting. Isopach maps of various stratigraphic intervals will help in identifying those faults associated with Cambrian rifting as opposed to later tectonic events. However, both types of faulting likely will be important in identifying potential areas of hydrothermal dolomitization and possible Trenton-Black River reservoirs.

Another issue that has been discovered through this project is the regional change in the seismic character of the Trenton-Black River interval. Both the wavelets’ form and amplitude characteristics change across the basin. The cause of this variation is the changing nature of the lithology of both the Trenton-Black River carbonate interval, and that of the overlying strata. It is hoped that through further analyses researchers within this project will be able to predict differing local depositional environments of this interval even in areas with limited well data.

Regional Stratigraphy of the Trenton-Black River Interval

Introduction

Trenton-Black River carbonates have become a prominent exploration target in the Appalachian basin. Historic producing fields in the Michigan basin and the Arches Province (i.e., Albion-Scipio and Lima-Indiana trends) and more recent fields in the northern Appalachian basin (i.e., Glodes Corner Road field, New York and the York field, northeastern Ohio) have illustrated that Ordovician carbonates are potentially ideal hydrocarbon reservoirs (Figure 12). The dominant play type thought to enhance productive reservoirs is hydrothermal dolomite (HTD), which may be related to fluid movement along pre-existing faults and fractures. In addition to these HTD plays, a fractured Trenton-Black River limestone play exists in West Virginia (i.e., the Cottontree field). This fractured carbonate play in West Virginia has generated some of the highest initial producing rates (50 MMcfgd) of any wells in the Appalachian basin.

The primary focus of the stratigraphy task is to define Trenton Limestone, Black River Group, Utica Shale and equivalent lithostratigraphic units within a regional framework, model the depositional environment and basin architecture, and integrate the results with data developed by other task teams to delineate potential areas of exploration interest. The stratigraphic framework will establish regionally consistent formation/interval boundaries, which will be used in structure, isopach and facies mapping. A regionally consistent stratigraphic framework will provide a better understanding of the complexly interwoven geologic parameters controlling Trenton-Black River reservoirs. Given a consistent framework, we then can map and isolate lateral facies changes that may have been tectonically influenced during deposition and possibly later during reservoir development. The ultimate goal of the stratigraphy task is to integrate all results of the stratigraphic research with the results of other tasks into a stratigraphic-structural-diagenetic model for the origin of Trenton-Black River reservoirs and delineation of potential areas of exploration interest.

Methods

Geologists on the Stratigraphy team have examined 16 Trenton-Black River cores from across the basin. Observations from these investigations have been recorded and cores have been photographed. Continuous cores through the entire Trenton-Black River interval and cores with dolomitized zones were targeted for study and correlated to geophysical logs. Core examination focused on dolomitized zones, porous zones, intervals with oil shows and marker beds (i.e., bentonite beds and well-developed shale beds) to assist in refining regional correlations and analyzing zones with reservoir potential. Core and log data are being integrated with published work on Middle and Upper Ordovician outcrops and previous subsurface studies. A map showing the locations of all Trenton-Black River cores (230) available from the state Geological Surveys in relation to the Middle Ordovician outcrops has been prepared (Figure 13). Cores, and the data derived from them, are located primarily in the western portion of the Appalachian basin in western Ohio and central Kentucky and are sparse in the deeper portion of the basin in New York, West Virginia and Pennsylvania.

Throughout the basin, approximately 1,800 geophysical logs for unique wells containing the Trenton-Black River interval have been scanned (tiff format) and 500 wells have been converted to vector (LAS) format for use in regional cross sections. A network of 18 cross sections using scanned logs and LAS has been generated across the Appalachian basin to illustrate the regional stratigraphy of the Middle and Upper Ordovician succession of strata (Figure 14). Depositional strike of approximately northeast-southwest for the Trenton interval was established using a preliminary Trenton isopach map and published maps. We generally assume that parallel isopach contour lines showing thick to thin areas define a regional depositional strike direction. Cross section locations were oriented either parallel (strike) or perpendicular (dip) to the depositional strike. Wells were prioritized for use in cross sections that contained continuous Trenton/Black River cores or Precambrian penetrations. Formation picks on logs were correlated to described cores and digital photographs to refine the lithostratigraphic correlations. Dolomitized zones from geophysical logs and cores also are being noted and mapped to help delineate potential areas of fault trends.

Depositional strike used for this report follows a northeast-southwest trending area of thick, dark shale overlying thin Trenton Limestone that is adjacent to the historical Trenton producing area of central Indiana and northwestern Ohio (Freeman, 1953; Gutsatdt, 1958; Rooney 1966; Gray, 1972; Cressman, 1973; Schwalb, 1980; Keith, 1985; Wickstrom, et al., 1992; and Hohman, 1998). All of these workers recognized the correlation difficulties in the subsurface when attempting to correlate the productive Trenton Limestone fields of Indiana, Michigan and Ohio with the Lexington Limestone units, which are partially exposed on the outcrop in central Kentucky.

Preliminary isopach maps of the Knox unconformity to Black River, Trenton and Utica intervals were generated based on formation tops interpreted from approximately 1,000 well logs, cores and sample descriptions. Digital locations of Trenton–Black River oil and gas fields were obtained from the Appalachian, Illinois, and Michigan basin states (including Ontario) and a Trenton-Black River oil and gas fields map was generated to assist in relating stratigraphy to producing trends (Figure 12). Geographix software was used for constructing the cross sections and maps.

Stratigraphic Nomenclature

Numerous stratigraphic names have been applied to the Ordovician succession of rocks across the Appalachian basin. A correlation chart based on the formal nomenclature of each state Geological Survey was subdivided into columns representative of the stable craton, the Rome Trough and the eastern basin (Figure 15). The focus of this study is to develop a regionally consistent stratigraphic framework for the Black River-Trenton-Utica interval and coeval units (Figure 16).

Regionally widespread K-bentonite markers and C13 chemostratigraphy are being evaluated as potential tools to establish temporal relationships across the basin. The Millbrig bentonite is the most laterally extensive K-bentonite in the project area, although subsurface correlations become tenuous to the east in West Virginia, Pennsylvania and New York. Beds of altered volcanic ash or K-bentonites are widespread in the Ordovician in eastern North America and have been studied extensively over the past decade (Huff and Kolata, 1990; Haynes, 1994; Kolata et al., 1996). The source of the volcanic ash for these K-bentonites was probably to the south and southeast (present day Atlantic coast) originating from active island-arc volcanism associated with the Taconic Front (Kolata et al., 1996). The location of this source helps to explain the disappearance of some of these K-bentonites to the north and west of the source area.

The Middle and Upper Ordovician units are discussed in ascending stratigraphic order from the Black River Group at the base to the Trenton Limestone and equivalents (Lexington Limestone, including Curdsville, Logana and Lexington undifferentiated members), Point Pleasant Formation and Utica Shale at the top.

Idealized Depositional Model

Type logs illustrating the wireline character of the Black River to Utica interval are shown in Figure 17, which we define in a regional carbonate ramp setting. These type logs illustrate the variations in log character between the shallow water platform and margin and deeper water interplatform sub-basin facies. From these type logs and core descriptions we developed a preliminary model to illustrate the depositional setting and major facies of the Trenton Limestone and equivalents (Figure 18). This model follows work by Pope and Read (1997) in the central Appalachian basin of Kentucky and Virginia, and facilitates discussion of the stratigraphic framework using the cross section network. As stratigraphic work is completed and integrated with results from the petrographic work, we will update the model as required. Gross facies shown here have been described by previous researchers (Cressman, 1973; Weir and others, 1984; Keith, 1985; Stith, 1986; Wickstrom and others, 1992; Holland, 1993; Pope and Read, 1997, Laughrey and others, 2003) and are recognized in core and outcrop by current project researchers.

The preliminary model presented here for Trenton and equivalent deposition is interpreted to include two low-relief platforms (the Trenton and Lexington platforms), separated by an interplatform sub-basin. The entire platform-to-basin model contains an overall ramp-like slope. Carbonate ramps are defined to “have gentle slopes (generally < 1^0) on which shallow wave-agitated facies of the nearshore zone pass downslope (without marked break in slope) into deeper water, low-energy deposits” (Ahr, 1973; Wilson, 1975; Read, 1985). “Homoclinal ramps have relatively uniform, gentle slopes (1m/km or a fraction of a degree) into the basin” (Read, 1985). A carbonate platform is defined as “carbonate bodies with a more or less horizontal top and abrupt shelf margins where high energy sediments occur. The normal process of sedimentation effectively turns ramps into platforms and creates narrow, steep shelf margin ridges. Slopes on some ramps may be so gentle as to make them commonly indistinguishable from platforms. Thus, these terms are often used interchangeably. Rare platforms have gently sloping margins (ramp-like profiles)” (Read, 1985**).** The Trenton and Lexington platforms do not display steep-sided margins, but do exhibit a change in slope with gently-sloping platform margins.

These low-relief platform margins contain nodular skeletal packstone-wackestone facies that grade laterally into dark shales of a deeper, more open marine environment referred to in this report as an interplatform sub-basin. This sub-basin previously has been termed the “Point Pleasant” basin (Wickstrom and others, 1992) and includes the narrow “Sebree Trough” feature. Schwalb (1980) first applied the name “Sebree Valley” to a northeast-southwest trending feature in western Kentucky that he described as a “trough-like, clastic filled depression.” Other researchers used the term “Sebree trough” and extended this feature from western Kentucky through southeastern Indiana into northwestern Ohio (Bergström and Mitchell, 1987; Wickstrom, 1988; 1990; Mitchell and Bergström, 1991; Wickstrom, et al., 1992; Bergström and Mitchell, 1992; 1994; Keith and Wickstrom, 1993; Bergström and Mitchell, 1994; Kolata, et al., 1996; Pope and Read, 1997; Hohman, 1998; Kolata, et al., 2001; Ettensohn, et al., 2002; Richardson and Bergström, 2003; Brett, et al., 2004; Ettensohn, et al., 2004; Ludvigson, et al., 2004; and McLaughlin, et al., 2004).

These complexly interwoven stratigraphic elements and their relative timing are very important to our understanding of the depositional and diagenetic history of the productive Trenton reservoirs. The origin and regional extent of the Sebree feature are problematic and not fully understood. Therefore we are withholding use of the term "Sebree Trough".

Description of Lithostratigraphic units

Lithostratigraphy of the mapped units varies regionally. We discuss regional correlations relative to the historic producing areas on the Trenton platform, platform margin and sub-basin, where well control (including continuous core) is most dense. Correlations east and northeast of the Lexington platform into West Virginia and New York, respectively, are being finalized. The top of the Black River Group, typically marked by the Millbrig bentonite (mud cave or α), is used for the datum. Well-developed Trenton carbonate grainstones on the Trenton platform margin become thin to the southeast in a sub-basin with increasing shale content of the Lexington Limestone. Within this sub-basin the overlying dark Utica shales are thickest where the Trenton is the thinnest. These dark Utica shales appear to be coeval with the Point Pleasant Formation and Lexington Limestone to the southeast. The Kope Formation overlies the Point Pleasant Formation and also appears partially coeval with the Utica Shale. At this time we cannot unequivocally conclude the stratigraphic relationship of the Utica and Trenton of southwestern Ohio and adjacent Indiana and Kentucky. The same problematic stratigraphic relationships occur between the Utica Shale and Lexington Limestone where the Utica is thickest.

The Lexington Limestone is subdivided, in ascending order, into the Curdsville Member, the Logana Member and the Lexington undifferentiated. The lowermost portion of the Trenton on the platform margin correlates to the Curdsville Member. The correlation of the Lexington and its members is relatively straight-forward from the sub-basin onto the Lexington platform to the southeast. However, defining the top of the Lexington is somewhat problematic due to facies intertonguing with the overlying Point Pleasant Formation. For this project, the top of the Lexington is chosen using the best-developed carbonate bed at the base of the Point Pleasant.

The Trenton platform continues from northwest Ohio into southwestern Ontario where the Trenton Group (Cobourg, Sherman Fall and Kirkfield formations) thickens and consists primarily of grainstones and wackestones (Coniglio and others, 1994). The overlying Blue Mountain is considered to be roughly coeval with the Utica Shale. The Trenton platform (Trenton shelf of Keith, 1985) extends eastward into New York where the Trenton interval also thickens. In New York, the upper portion of the Trenton becomes more argillaceous and has a more gradational contact with the overlying Utica Shale than to the west. Various researchers have shown a facies change in western

Ontario indicative of this eastward transition from a clean carbonate to a more argillaceous carbonate (Keith, 1985; Wickstrom and others, 1992).

Black River Group

The Black River Group directly overlies the Wells Creek Formation, or Knox paleotopographic highs where the Wells Creek is absent. The Black River has a rather uniform lithology across the region, consisting of a light-medium brown to gray, burrow-mottled, stylolitic mudstone (Figure 19). Fossils are not abundant, but occur locally. Chert is present locally, especially in the upper part of the unit. Localized zones of rip-up clasts are present locally indicating higher energy deposition. Geophysical gamma-ray log response typically is very low due to low shale content. Up to 5 cycles, characterized by more argillaceous carbonates at the base passing upward into relatively cleaner carbonates, can be correlated regionally within the Black River. Further work is necessary before establishing a sequence stratigraphic hierarchy for these cycles and their significance to potential reservoirs.

Within the study area, the Millbrig (mud cave/alpha), Deicke (pencil cave/beta) and Ocoonita (gamma) are the most continuous and correlatable of these K-bentonites in outcrop and subsurface (Figure 16). In western and southern Ohio cores, the Millbrig occurs near the top of the Black River and marks a change from a bioturbated mudstone lithology typical of the Black River to the overlying highly fossiliferous, grainstone-packstone lithology of the Trenton (Figure 17). The Black River-Trenton contact generally is gradational in that Black River and Trenton lithologies are interlayered through a zone up to 10 feet thick. Wickstrom and others (1992) noted a sharp contact in cores from Logan and Butler counties, Ohio. Hardgrounds have been observed on the Black River-Trenton contact in cores in Butler and Wyandot counties, Ohio (Wickstrom and others, 1992) and in Indiana (Keith, 1985). On the basis of the contact relationship, the Black River-Trenton boundary appears to be diachronous.

At the Union Furnace outcrop in central Pennsylvania, the Millbrig occurs in the Salona Formation (Trenton equivalent), approximately 40 feet above the Nealmont mudstone (Black River equivalent). We use the Millbrig because it is a reliable marker on geophysical logs for Black River subsurface correlations, particularly in much of Ohio, Indiana and Kentucky. Where the Millbrig is absent we use a correlation point on geophysical logs tied to cores or sample descriptions.

Trenton Limestone

The Trenton Limestone consists of thinly laminated mudstone-wackestone tidal flat facies, skeletal grainstone-packstone shoal facies, and nodular skeletal wackestone-packstone facies. On the platform and platform margin, cores and geophysical logs (low gamma-ray response) indicate a sharp contact between the Trenton and overlying Utica Shale (Figures 17 and 20). This contact is characterized in cores by the presence of pyrite, increased phosphatic mineralization and hardgrounds. Schwalb (1980) describes this contact as a subaqueous erosion surface and other researchers have used the terms “corrosion” and/or “omission” surfaces (Mitchell and Bergström, 1991; Bergström and Mitchell, 1992; Kolata, et al., 2001; Brett, et al., 2004; and McLaughlin, et al., 2004). Hohman (1998) considered this contact a regional unconformity.

The top of the Trenton Limestone is sharply defined on the Trenton platform margin, but to the southeast in the interplatform sub-basin the top of the correlative Lexington Limestone is more gradational. This Trenton-equivalent interval can be subdivided into the Curdsville, Logana and Lexington undifferentiated members of the Lexington, in ascending stratigraphic order (Figure 17). Examination of both core and geophysical well logs indicates that the Logana and Lexington undifferentiated members are relatively higher in shale content than the Trenton Limestone on the platform. The Curdsville Member is a cleaner carbonate represented by a lower gamma-ray response similar to the Trenton. The Curdsville consists of medium-gray to brownish-gray, medium-to fine-crystalline wackestone to grainstone and has a gradational contact with the overlying Logana (Figure 21). The Logana consists of olive-gray to black, calcareous, medium- to thin bedded, fossiliferous (primarily thin-shelled brachiopods) shale and thin beds of coarse-to fine-crystalline, argillaceous, fossiliferous, olive gray limestone (Figure 22). The distinct lithology of this unit can be identified on geophysical logs (higher gamma-ray response) and can be correlated throughout central and eastern Ohio and adjacent Kentucky and western West Virginia. The Lexington undifferentiated consists of interbedded limestone and shale. The limestone is a medium to dark gray, fine- to coarse-grained, argillaceous, fossiliferous, thin- to thick-bedded wackestone to packstone. The contact with the underlying Logana Member is gradational. We choose the highest well-developed limestone bed as the top of the Lexington/Trenton, which appears conformable and is gradational in core and geophysical logs (Figure 23).

Utica Shale and Point Pleasant Formation

The facies relationships between the Trenton/Lexington and overlying Utica/Point Pleasant units are the most complex across the region. The Trenton/Lexington Limestone grades laterally and upward to dominantly dark gray to brown to black, platy, finely laminated, locally calcareous Utica Shale and interbedded limestone and calcareous shale of the Point Pleasant Formation. The Utica appears partially coeval with the Trenton of the platform and entirely coeval, as well as overlapping with the Point Pleasant of the interplatform sub-basin. The Utica is absent over most of the Lexington Platform due to facies transition with overlying gray shale of the Kope Formation.

We tie cores and geophysical logs for these units in southwestern Ohio to work by Cressman (1973) and Stith (1986). However, correlation of these units from southwestern Ohio to the north and east remains problematic. Wickstrom and others (1992) correlated the Point Pleasant into northwest Ohio and give a detailed discussion of this unit. The Point Pleasant of Wickstrom and others (1992) is recognized on geophysical logs by the interbedded calcareous shale and limestone indicated on the gamma-ray signature. We use the top of a shaly limestone bed to mark the top of the Point Pleasant. Recognizing the upper contact of the Utica Shale with the overlying Kope Formation is problematic unless core is available. In the absence of core, we use sample descriptions along with geophysical logs to interpret the presence or absence of a Trenton-Utica contact.

Cross Sections Illustrating Middle and Upper Ordovician Stratigraphic Relationships

A network of cross sections (Figure 14) was developed to unravel the regional stratigraphic and facies relationships, which are very important to our understanding of the productive Trenton-Black River reservoirs. Four of those cross sections are discussed and shown within this interim report. Cross sections are tied to open-file reports, published reports, continuous core, geophysical well logs and Geologs. For all cross sections in this report, the top of the Black River Group is used for the datum.

Dip cross section X-X' is oriented northwest to southeast from Randolph County, Indiana to Cabell County, West Virginia (Figure 24). This cross section illustrates subsurface lithostratigraphic correlations of the productive Trenton platform margin area on the northwest to the Lexington platform area on the southeast. Well-developed Trenton carbonate grainstones on the Trenton platform margin are approximately 110 feet thick and thin to about 30 feet to the southeast into a sub-basin of increasing shale content of the Lexington Limestone and then onto the Lexington platform. Within this sub-basin the overlying dark Utica shales are thickest where the Trenton is the thinnest. These dark Utica shales appear to be coeval with the Point Pleasant Formation and Lexington to the southeast. The Kope Formation overlies the Point Pleasant Formation and is partially coeval with the Utica Shale within the sub-basin. At this time we cannot unequivocally determine the stratigraphic relationship of the Utica Shale and Trenton Limestone of southwestern Ohio and adjacent Indiana and Kentucky. The same problematic stratigraphic relationships occur between the Utica Shale and Lexington Limestone, where the Utica is thickest. The Lexington is subdivided in ascending order into the Curdsville Member, the Logana Member and the Lexington undifferentiated. The lowermost portion of the Trenton on the platform margin correlates to the Curdsville Member. The correlation of the Lexington and its members is relatively straight-forward from the sub-basin onto the Lexington platform. However, the top of the Lexington is somewhat problematic due to facies intertonguing with the overlying Point Pleasant Formation. The top of the Lexington is chosen using the best-developed carbonate bed at the base of the Point Pleasant.

Dip cross section I-I' trends northwest-southeast from Williams County, Ohio to Randolph County, West Virginia and roughly parallels the previous cross section (Figure 25). Similar facies relationships are evident to the previous cross section as shown by the Trenton platform, the interplatform sub-basin and the Lexington platform. On the productive Trenton platform, the Trenton carbonates obtain a thickness of 250 feet and thin to approximately 120 feet in the interplatform sub-basin. The upper portion of the Trenton appears to be, in part, coeval with the Utica Shale and Point Pleasant strata in this deeper-water sub-basin. Trenton equivalent strata (Lexington, Logana and Curdsville members) in the sub-basin thicken onto the Lexington platform where the unit reaches a thickness of 400 feet. The overlying Ordovician shales and the underlying Black River both indicate basinward thickening to the east and southeast.

Dip cross section K-K' extends from Huron County, Ontario to Bedford County, Pennsylvania and also depicts the basin architecture as defined by the Trenton platform, interplatform sub-basin and Lexington platform (Figure 26). The Trenton section reaches a thickness of 500 feet on the Trenton platform and thins to 120 feet in the sub-basin where the Trenton is in facies transition with the overlying Point Pleasant. On the Lexington platform the Trenton equivalents attain a thickness of 450 feet. As shown earlier, the overlying Ordovician shale section and underlying Black River carbonate section both thicken basinward to the southeast.

Strike cross section D-D' trends southwest-northeast along depositional strike from Casey County, Kentucky to Oswego County, New York (Figure 27. The southwestern portion of the cross section illustrates the Lexington platform where the Trenton equivalents obtain a thickness of 380 feet. This cross section extends across the sub-basin and onto the Trenton shelf where the Trenton reaches a thickness of 780 feet.

Isopach Maps

Preliminary maps based on a limited dataset were constructed for the Knox to Black River interval, Trenton Limestone and Utica Shale to illustrate stratigraphic thickness and depositional strike. Additional well logs will be interpreted and added to the dataset for the final phase of mapping. Contour intervals are 50 feet for the Knox to Black River and Trenton maps and 100 feet for the Utica Shale isopach map. In the mapped area, the average thickness of the Knox to Black River interval is 700 feet and ranges from 350 to 2,500 feet. Abrupt thickening of this interval is evident over the Rome Trough, with most of the thickening occurring in the Wells Creek interval. A north-south thick trend occurs in southern New York, which also is evident on the overlying Trenton isopach map.

The Trenton isopach map spans the interval from the top of the Trenton or equivalent (Lexington) to the top of the Black River (Figure 28). Average thickness is 250 feet and ranges from about 30 to 800 feet. Depositional strike is dominantly northeast-southwest, except for central New York where it trends north-south. This preliminary map illustrates the location of the interplatform sub-basin and the adjacent Trenton platform to the northwest and the Lexington platform to the southeast. The northeast-southwest thin trend adjacent to the Trenton platform has been previously identified as the "Sebree Trough." Various researchers have continued the "Sebree Trough" to the northeast through Pennsylvania and connected it with the Taconic foreland basin (Keith, 1985; Brett and others, 2004). Preliminary mapping and log correlations for this project do not indicate this eastward connection to the Taconic foreland basin. However, logs from recently drilled wells in north-central Pennsylvania are being obtained that should shed additional light on this problematic area.

The preliminary Utica isopach map has an average thickness of 200 feet and ranges from absent to 500 feet in the mapped area. Based on cores, wireline logs and Geologs (commercial sample descriptions), the Utica is interpreted as being absent in southern Ohio. Utica deposition was influenced by the underlying Trenton paleotopography as shown by thin Utica deposition over Trenton thick trends and Utica thickening over Trenton thins. Utica thin trends are evident in northwest Ohio and central New York over the Trenton platforms. Utica thickening is present within the interplatform sub-basin and "Sebree Trough" area.

Areas of Exploration Interest

Comparison of the Trenton-Black River producing fields with the Trenton isopach map and cross sections indicates a strong relationship between producing trends with the platform margins. The linear producing trends of the Lima-Indiana field in northwest Ohio are situated along the margin of the Trenton platform (Figure 28). It has been suggested that the trapping mechanisms in these producing fields may be related to updip facies changes that created variations in porosity and permeability along this platform margin, or to postulated extensional faulting along this platform margin that resulted in HTD reservoir development (Wickstrom and others, 1992). Additional work needs to be done to better understand these relationships. The position of the producing fields in New York also is situated along a platform margin (Figure 28). Many areas along this platform margin in New York remain untested and thus have exploration potential. Based on log character, reservoir quality along the Lexington platform does not appear as good as that observed along the Trenton platform in northwest Ohio and thus remains in question. Additional questions exist regarding the eastern extent of the interplatform sub-basin and platform margin in central Pennsylvania and are being studied in this project.

Future Work

During the next report period, the Stratigraphy team will focus on finalizing the mapping database, constructing regional isopach and facies maps, and integrating the resulting data with results from structural and seismic analysis and mapping, analysis of petrographic data, synthesis of depositional environments, and analysis of isotope geochemistry and fluid inclusion data. Cross sections and isopach maps will be tied to seismic reflection data and stratigraphic changes will be related to fault trends and possible reservoir development. Lithostratigraphy derived from cores, geophysical logs and sample descriptions will be integrated with thin section petrography to refine the depositional model, and to better define possible reservoir facies. Regional cross sections will be integrated with C13 isotope work to see if temporal relationships can be established for the Black River-Trenton-Utica interval between the platforms and sub-basin areas across the study area. Detailed field-scale mapping also will be done for selected fields and integrated with the other tasks to develop a better understanding of the entire petroleum system. In addition, the Stratigraphy group will evaluate the results of an ongoing basin-wide project (Schumacher and others) of chemical fingerprinting K-bentonites through apatite chemistry.

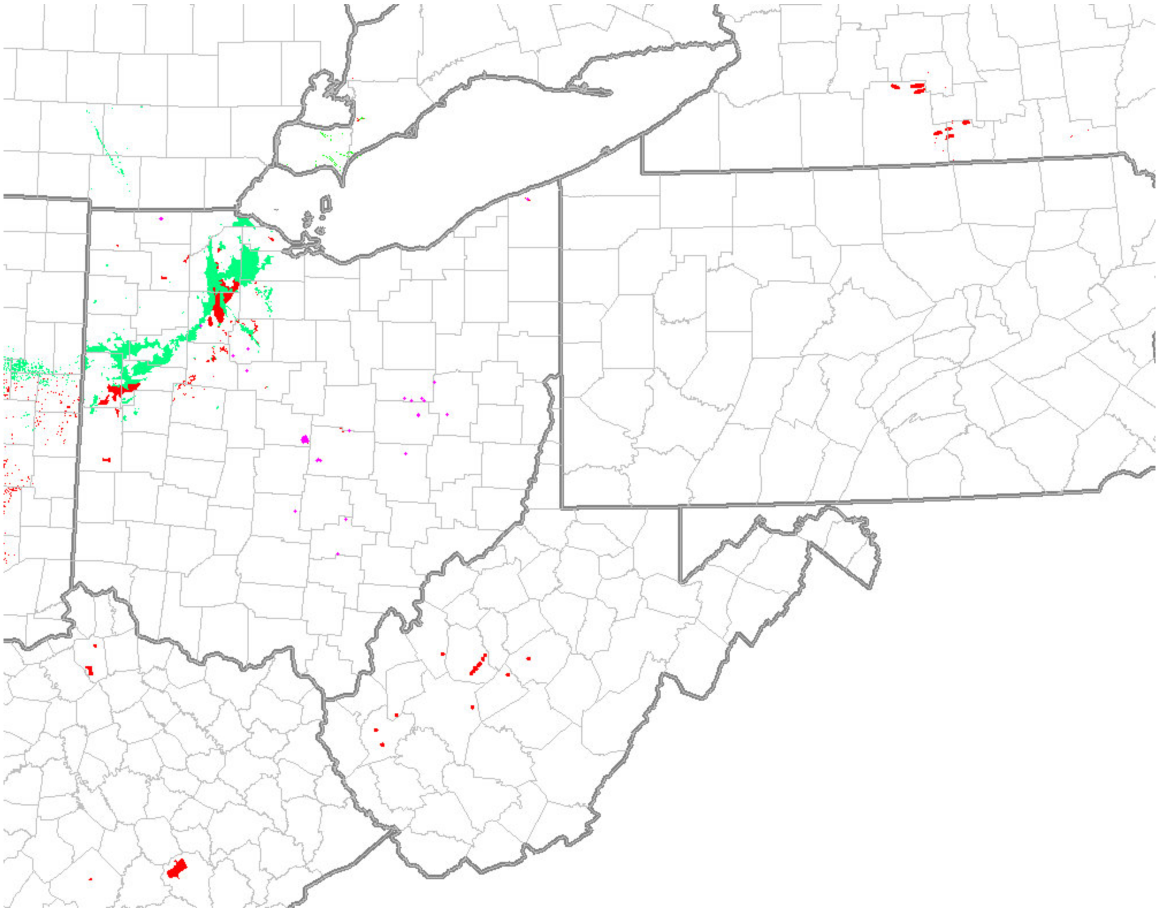


Figure 12. Trenton-Black River oil and gas fields map for the Appalachian basin. Oil fields are shown in green; gas fields are shown in red.

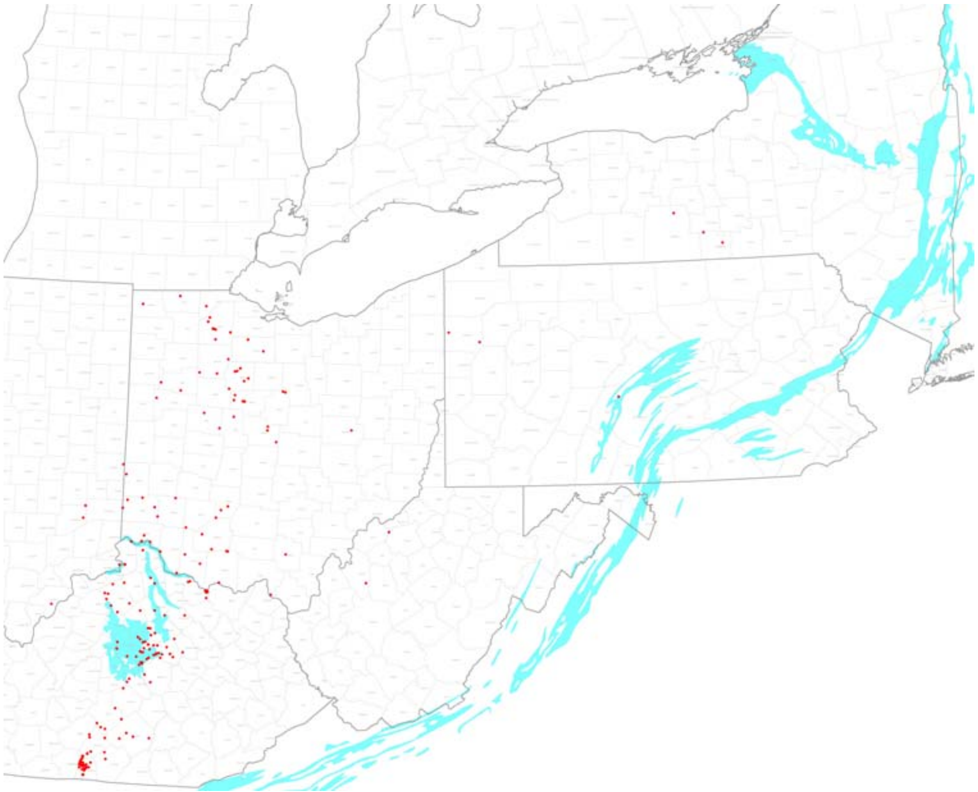


Figure 13. Trenton-Black River core map and Middle Ordovician outcrops for the Appalachian basin. Core locations are shown in red; outcrops are shown in blue.

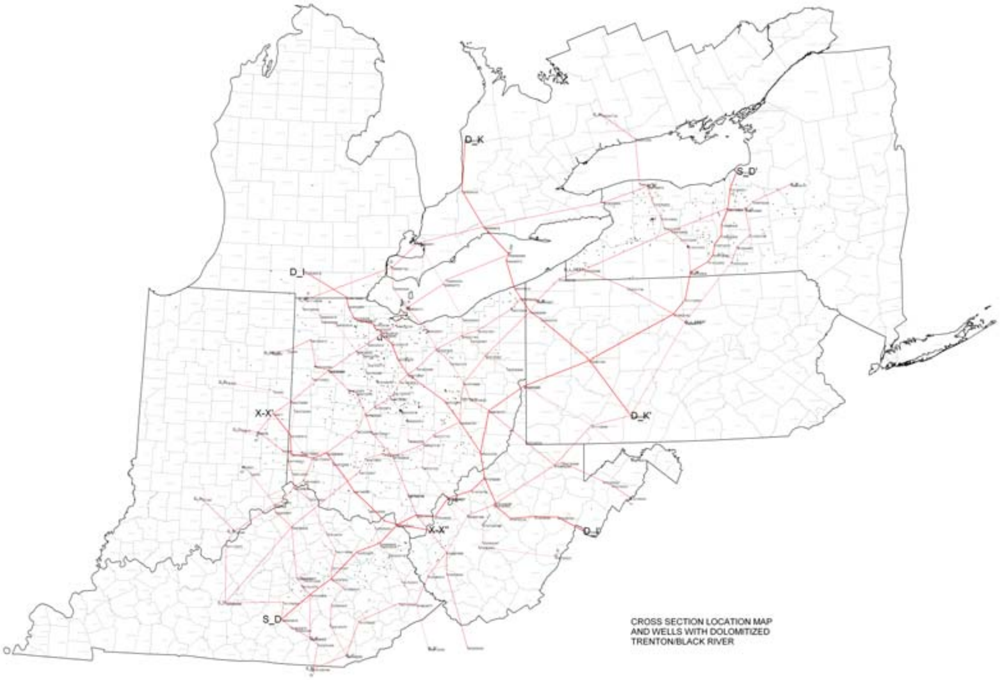


Figure 14. Map showing location of cross section lines.

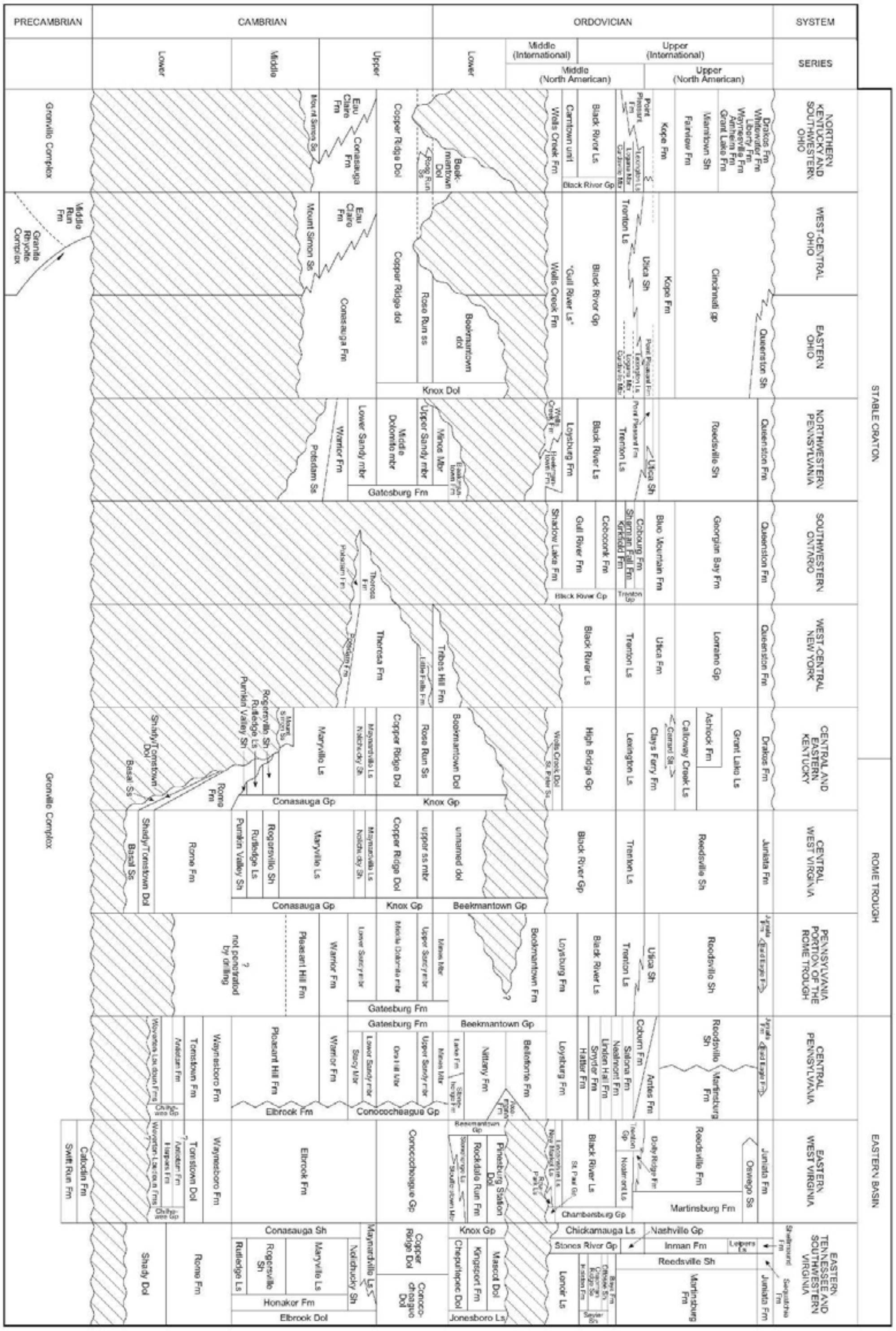


Figure 15. Correlation chart for Cambrian-Ordovician rocks in the Appalachian basin.

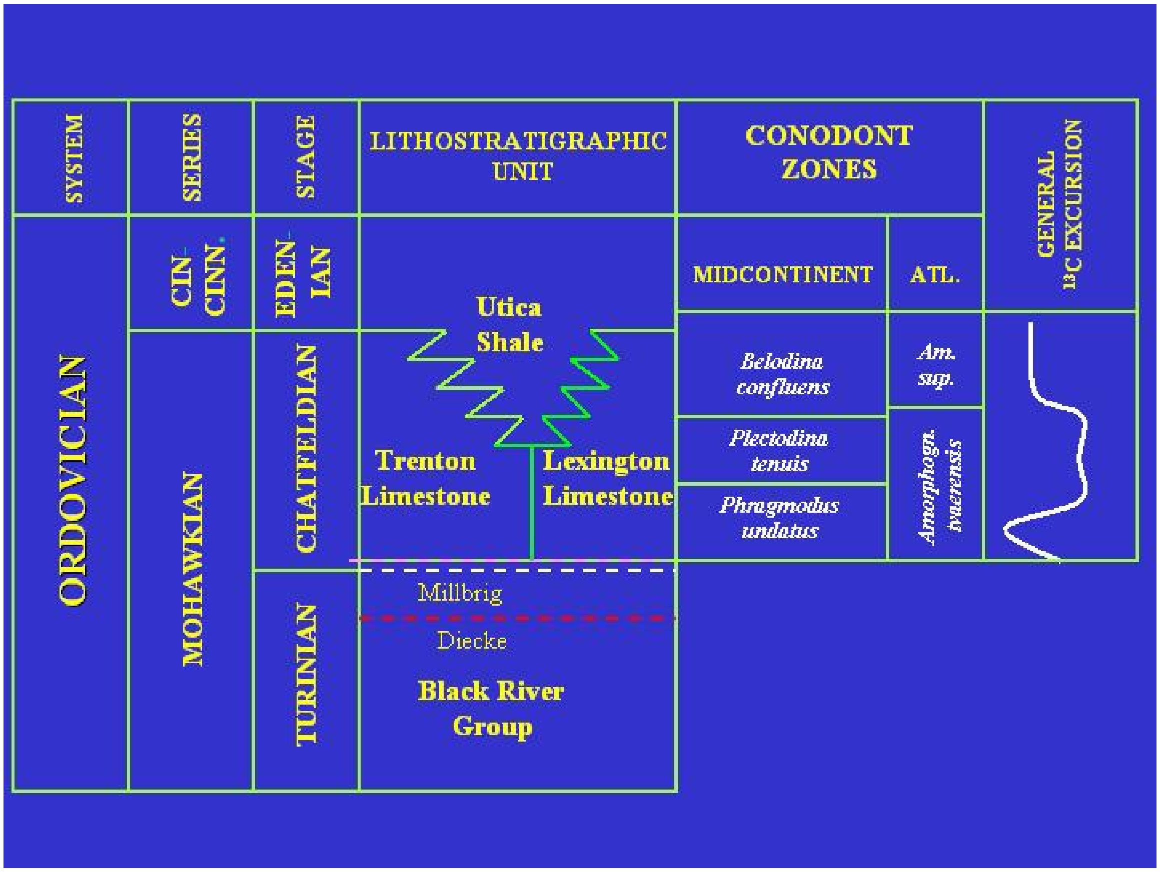


Figure 16. Lithostratigraphic units, conodont zones and general C13 excursion for Mohawkian and Cincinnatian units.

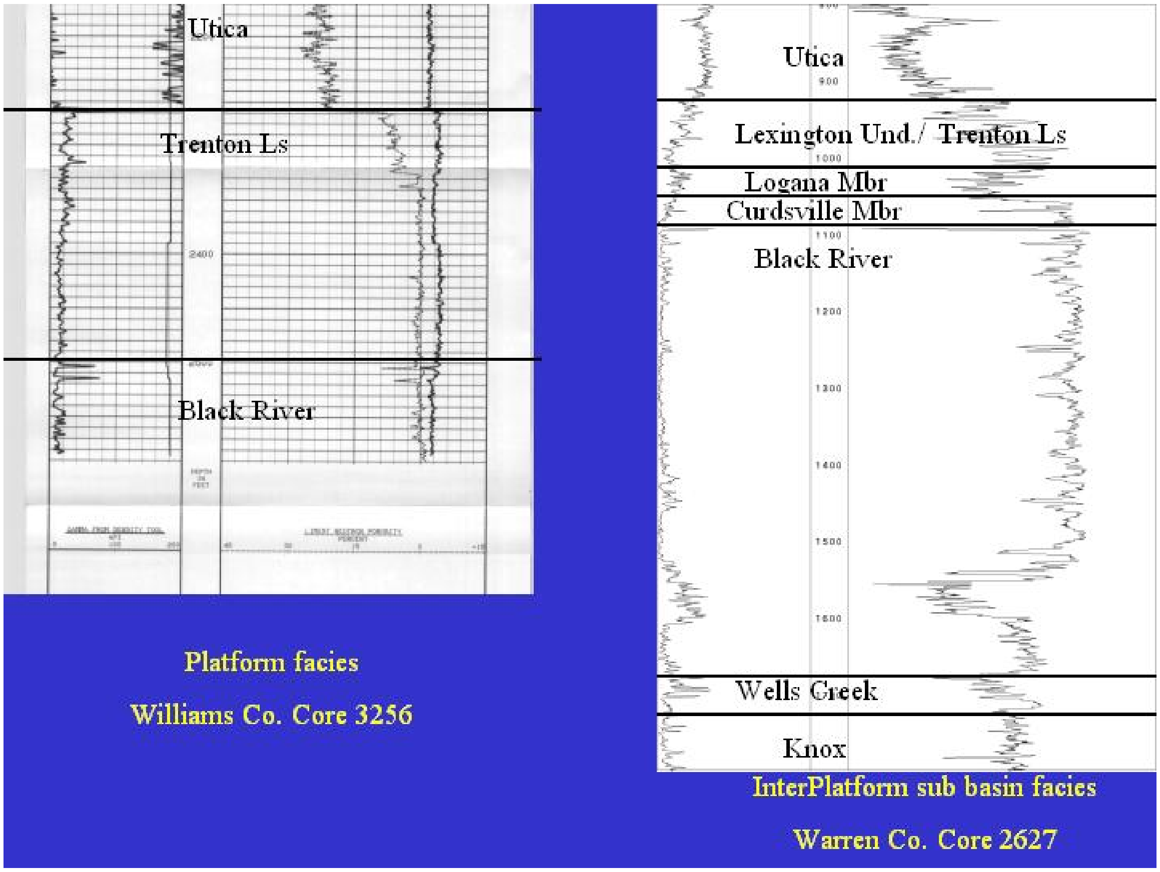


Figure 17. Geophysical logs showing the type sections for the platform and interplatform sub-basin regions.

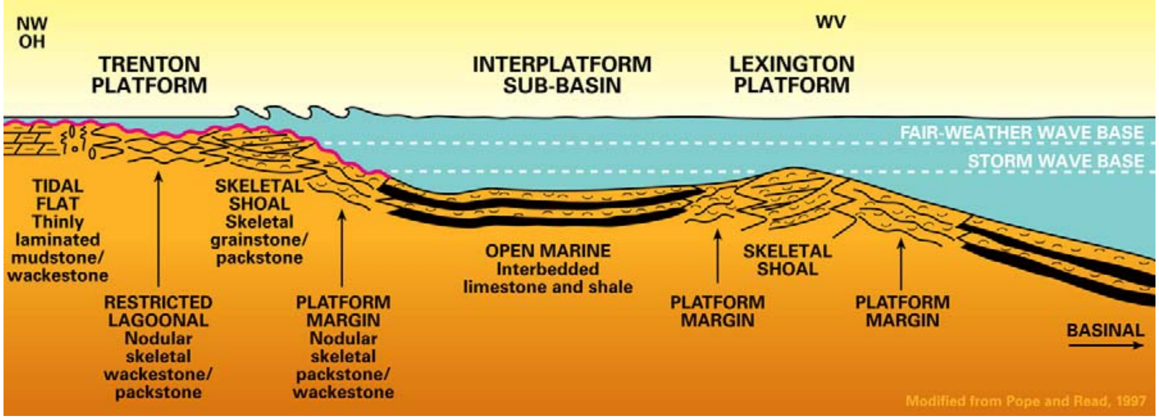


Figure 18. Preliminary depositional model and major facies of the Trenton Limestone. Modified from Pope and Read (1997).

Figure 19. Photo of representative Black River in Warren County, Ohio (core 2627).

Figure 20. Photo of the Trenton-Utica contact in Williams County, Ohio (core 3256).

Figure 21. Photo of representative Curdsville Member in Warren County (core 2627).

Figure 22. Photo of representative Logana Member in Warren County, Ohio (core 2627).

Figure 23. Photo of the Lexington Undifferentiated in Warren County, Ohio (core 2627).

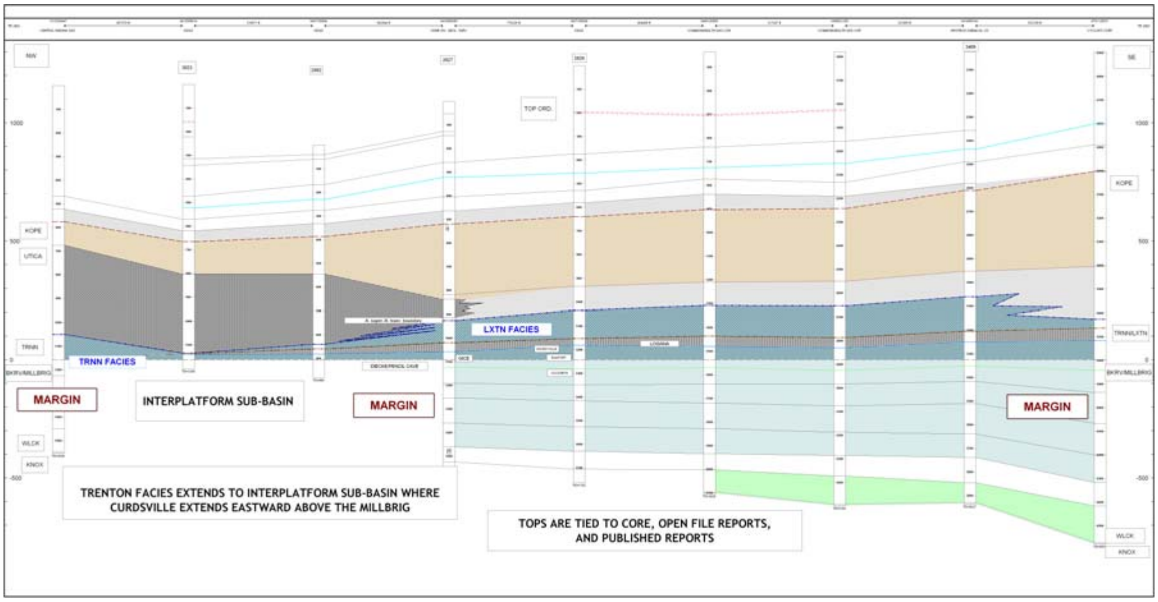


Figure 24. Regional stratigraphic dip cross section X-X' from Indiana to West Virginia illustrating Cambrian-Ordovician units.

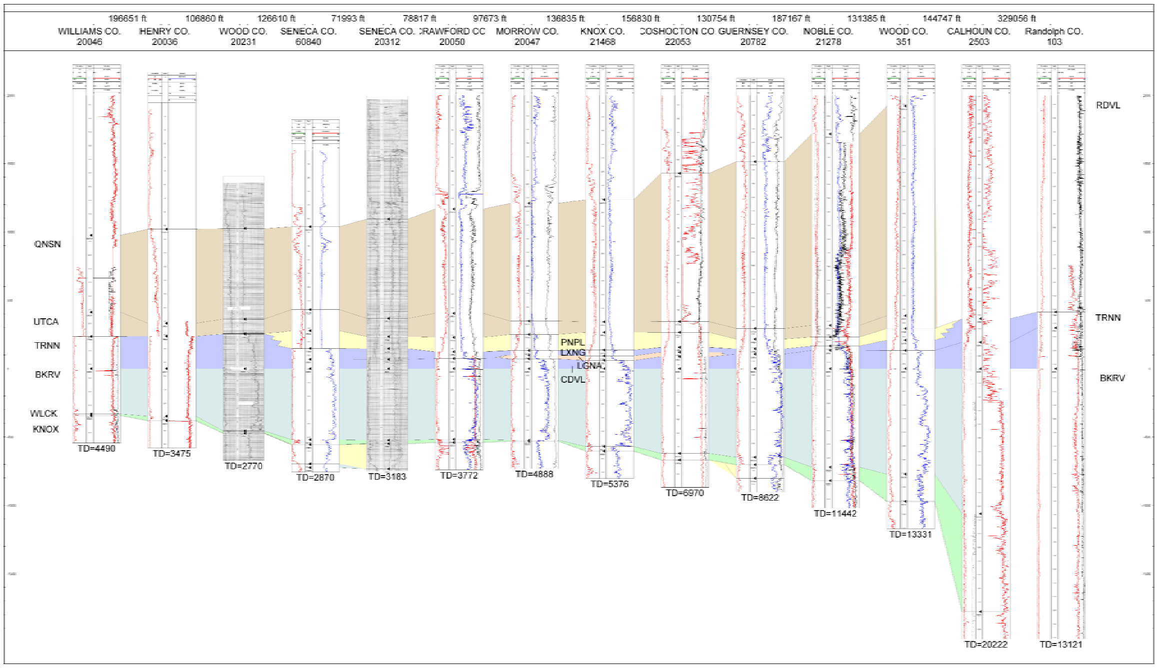


Figure 25. Regional stratigraphic dip cross section I-I' from Ohio to West Virginia illustrating Cambrian-Ordovician units.

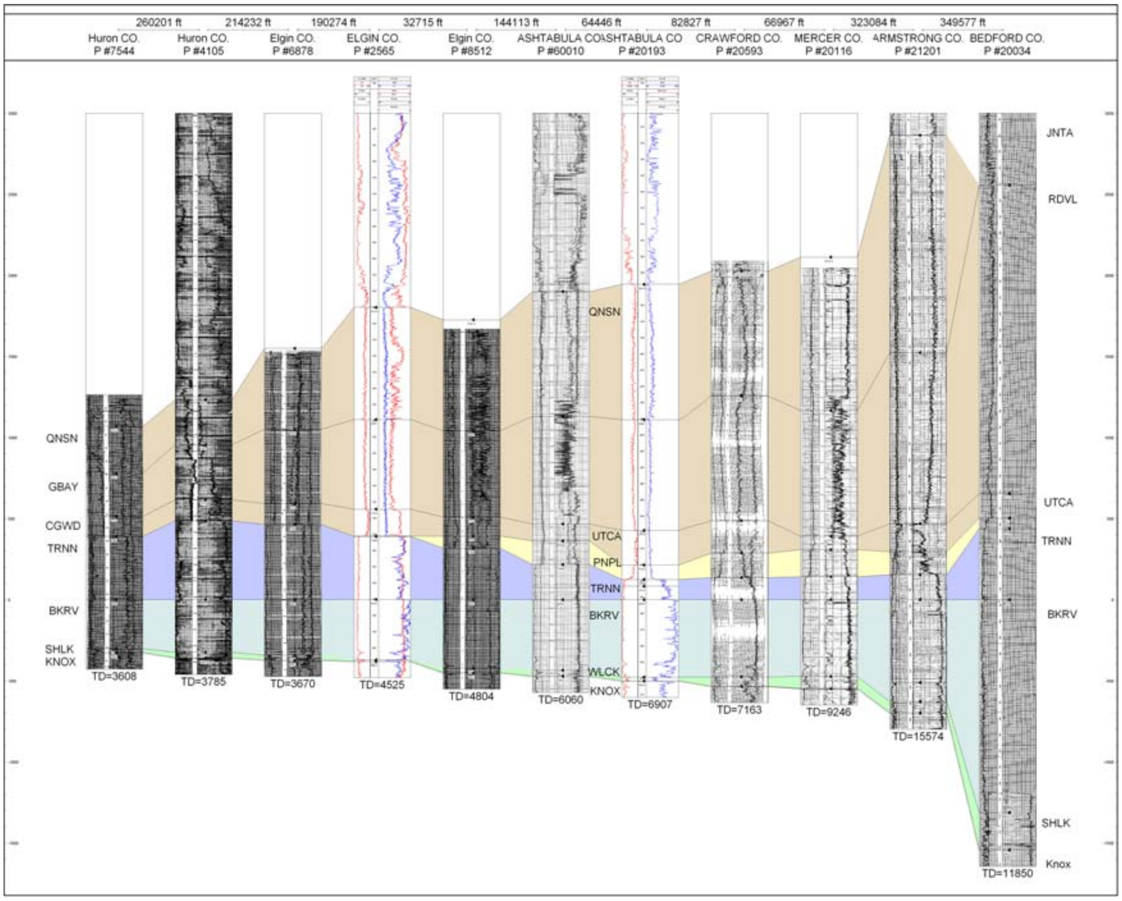


Figure 26. Regional stratigraphic dip cross section K-K' from Ontario to Pennsylvania illustrating the Cambrian-Ordovician units.

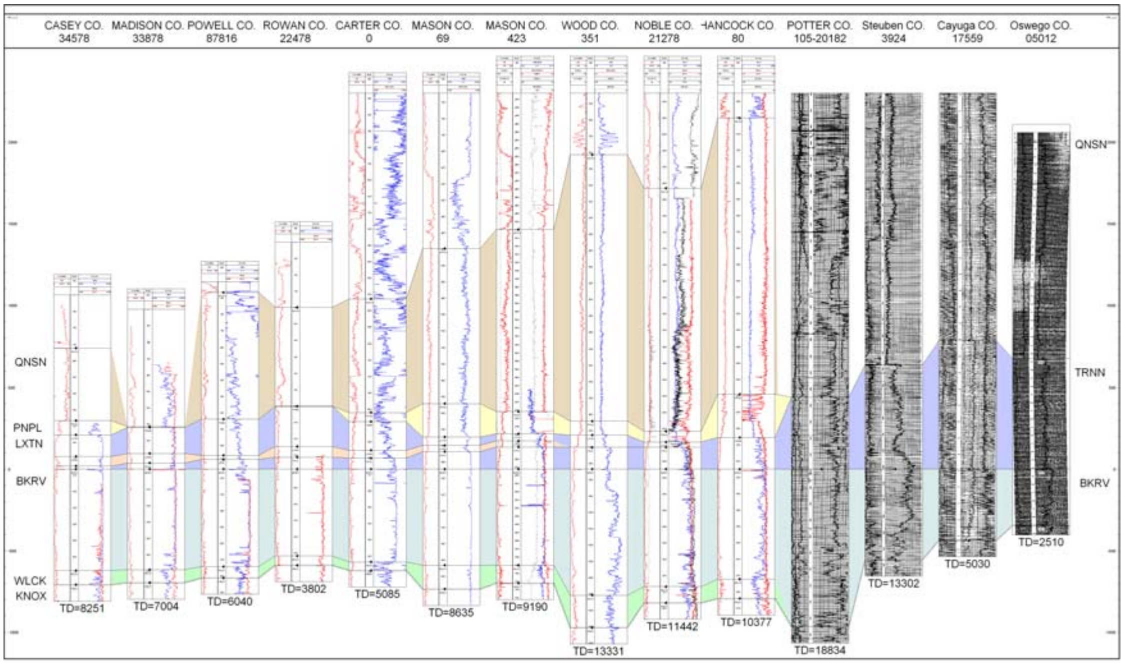


Figure 27. Regional stratigraphic strike cross section D-D' from Kentucky to New York illustrating the Cambrian-Ordovician units.

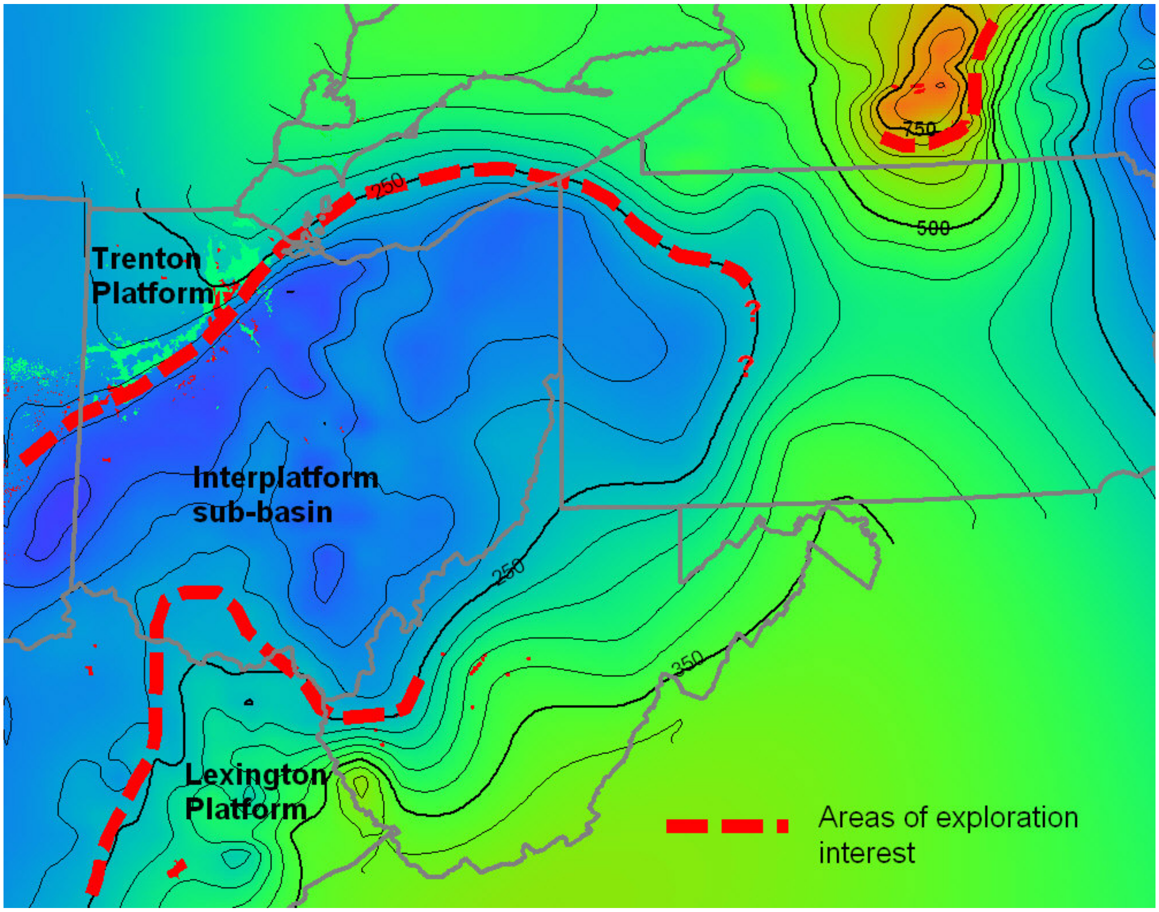


Figure 28. Trenton isopach map showing areas of exploration interest.

Petrography of Carbonate Reservoir Rocks in the Upper Ordovician Trenton and Black River Groups

Introduction and Summary of Previous Work

The purpose of the petrographic portion of this study is to: 1) support the project's field studies and core descriptions through the recognition of regional carbonate microfacies; 2) detail the diagenetic history of the rocks (especially as to how it relates to the timing of cementation, porosity preservation and development, and hydrocarbon emplacement); and, 3) provide a frame of reference for geochemical studies of the dolomitization processes that affected Trenton and Black River reservoir rocks in the Appalachian basin. The petrography data also will be useful in the geochemical study of source rock potential. To date, we have analyzed 605 thin sections by conventional petrographic microscopy, and examined 130 core samples with scanning electron microscopy (SEM) and energy dispersive x-ray spectroscopy (EDS). This work includes the regional petrography of Trenton and Black River limestones, and detailed petrography of local dolomitization fabrics in productive reservoir rocks.

Regional Petrography of Trenton and Black River Carbonate Rocks

We addressed the broad spectrum of carbonate rock types that occur in the Trenton and Black River Groups in our last semi-annual report, and will provide a comprehensive review and atlas of these rocks in the final report. During this report period, we continued to examine and describe numerous thin sections from various cores and outcrops around the basin. Of more immediate interest to the petroleum industry is the emerging picture of regional limestone diagenesis in the Trenton and Black River carbonates. Thus far, we have documented a consistent basin-wide pattern of marine and burial diagenesis that resulted in relatively low porosity and permeability in the subtidal facies of these rocks across the study area. We still need to look more closely at peritidal facies to see if there is any evidence of meteoric diagenesis anywhere in the basin. Indeed, we anticipate it, but we have not encountered such diagenetic textures to date. Likewise, we have not seen any record of exposure or meteoric diagenesis in any of the other facies thus far, but we very well may encounter such fabrics in this next semi-annual period. What we do see thus far is a dominance of extensive marine and burial diagenesis that yielded rocks with low reservoir potential, except for fractured limestone and dolostone reservoirs. As we discuss below, commercial amounts of porosity, permeability and petroleum accumulation appear to be restricted to areas where secondary porosity developed in association with hydrothermal fluid flow along faults and fractures related to basement tectonics.

Regionally, the Trenton and Black River rocks that we have examined thus far contain the record of six diagenetic stages (before local dolomitization and porosity/permeability development):

Marine diagenesis:

1. Micritization
2. Subtidal cementation by meniscus-type cement (in high energy environments only – see Laughrey and others, 2003)
3. Isopachous calcite overgrowths
4. Pore-filling calcite spar

Burial Diagenesis:

5. Chemical compaction (pressure solution)
6. Neomorphism

Dolomite Textures in Trenton and Black River Carbonate Reservoir Rocks

Dolostone Textural Classification.

We chose to use the combined dolomite textural classification of Gregg and Sibley (1984) and Silbey and Gregg (1997), as modified by Wright (2001) (Figure 29). The scheme published by Sibley and Gregg (1997) is popular with sedimentary petrographers and is the one most widely used by geologists today (Tucker and Wright, 1990; Machel, 2004). Thus, the jargon should be familiar to most readers of this report. Wright's (2001) modifications are useful for describing saddle dolomites.

The advantage of the dolomite textural classification illustrated in Figure 29 is that it is simple and mostly descriptive. Disadvantages are the fact that it is restricted to the microscopic scale, and that it implies some genetic information. The descriptive characteristics favor its utility in our work.

Crystal size distributions are categorized as unimodal or polymodal. Crystal shapes are described as planar-e, planar-s, or nonplanar-a, which refer respectively to euhedral, subhedral and anhedral dolomite crystals. Planar-c refers to cement. Planar-p and nonplanar-p refer to porphyrotopic textures. Saddle dolomite is nonplanar due to its unique, apparently curved crystal faces. Nonplanar-c describes saddle dolomite cement. The dolomite descriptions in this classification scheme also allow for the recognition of allochems, matrix and void filling minerals. Carbonate particles and cements may be replaced, partially replaced, or unreplaced, and, depending on crystal size, replacement may be mimetic or non-mimetic.

Pore Classification in Dolostones

We use two carbonate pore classifications in this work, those of Choquette and Pray (1970) and Lou and Machel (1995). Choquette and Pray (1979) discriminated basic pore types on the basis of whether the voids are (1) fabric selective, (2) not fabric selective, or (3) either fabric selective or not. The grains, crystals, or other physical structures in a carbonate rock control the distribution of fabric selective voids; the pores do not cross these primary boundaries. Interparticle, intercrystal, intraparticle and moldic voids are examples of fabric selective pores. Pores that are not fabric selective, or fabric selective or not, can crosscut primary components and depositional fabrics. Fractures, channels, vugs and breccia voids are examples of pore space that is not fabric selective. Choquette and Pray (1970) provided a list of genetic, size and abundance modifiers that can help to interpret the process, direction and time of pore formation. The Choquette and Pray (1970) carbonate porosity classification has experienced widespread acceptance over thirty-five years of application, and is useful in a textural and genetic sense, but it is independent of pore size (Machel, 2004).

Luo and Machel (1995) developed a pore size classification for carbonate rocks that is more applicable to petroleum geology and engineering (Figure 30). It is based on the textural and petrophysical classifications of Archie (1952), Choquette and Pray (1970), and Pittman (1979).

Mostly, we have collected detailed petrographic observations of the dolostone reservoirs of Ohio and New York at this point in the study. We have not yet begun to interpret these observations in terms of geologic processes, or to integrate these observations with the geochemistry presented elsewhere in this report. These efforts will be forthcoming, but first we have more fundamental petrographic work on many more samples to complete. Therefore, we decided to offer a comprehensive glimpse of our observations thus far in the way of several figures. First, we make a few general comments on what we have observed, and then offer what we have seen so far.

Dolograinstone and Dolopackstone Reservoirs

Dolograinstones and dolopackstones in the Trenton Group comprise important reservoir rocks in the Ohio portion of the once-prolific Lima-Indiana oil and gas field (Wickstrom and others, 1992). The depositional texture of these rocks may or may not be recognizable to the unaided eye, but their considerable porosity and permeability are dramatically obvious (Figure 31). These lithologies were deposited in shallow subtidal platform and platform margin environments (see the Stratigraphy section of this report). Dolostones originally deposited in the latter are the so-called facies dolomite of Wickstrom and others (1992). The rocks originally consisted of crinoid-brachiopod-bryozoan grainstones and packstones whose primary textures were partially to wholly obliterated by subsequent dolomitization (Figures 31 and 32). Dolomite in these rocks mostly consists of planar-s to nonplanar-a (transitional) dolomite and saddle dolomite. Macroporosity is not fabric selective and consists of small- to medium-size vugs and fractures. Mesoporosity is fabric selective and consists of moldic and intercrystalline voids. Microporosity is also fabric selective, occurring as intracrystalline and intercrystalline pore space.

Cloudy cores of planar-e and planar-s dolomite can be discerned in many of the crystals, and zoning is evident in some of the crystals (Figure 33). These observations suggest that there are two dolomite populations in the rocks, an earlier matrix-selective dolomite and later-formed dolomite cements that grew on the earlier dolomite. Halley and Schmoker (1983) referred to this later dolomite cement as “overdolomitization.” This process severely reduced porosity and permeability in these rocks.

About 25% of the dolomite in these rocks partially to wholly takes a stain with Alizarin Red-S indicating calcification. Some workers refer to this process as "dedolomitization," but we consider this term as imprecise and prefer the term "calcification" (see discussion and examples in Scholle and Ulmer-Scholle, 2003). The dolomites contain ubiquitous pyrite inclusions, and are stained by bitumen.

Pore diameters in the rocks range from approximately 2 micrometers to about 4 mm (small mesopores to small vugs). Some microporosity is evident, but not readily observed. Vugs and molds are the most significant voids in these dolostones. This porosity is associated with an advanced stage of dolomitization and developed through (1) dissolution of dolomite, and (2) dissolution of calcite that replaced dolomite. Note (Figures 33, 34, 36, and 37**)** the dolomite and replacement calcite groundmass immediately surrounding the molds and vugs are both more coarsely crystalline and more porous than the bulk of the rock. Also, note the oversized pores and abundant dissolution pits in the dolomite that indicate that these textures developed through dolomite dissolution.

Late-stage cements in these rocks include anhydrite, pyrite, calcite, quartz (along with chalcedony and chert) and fluorite.

Dolowackestone and Dolomudstone Reservoirs

Muddy dolowackestones and dolomudstones comprise the principal reservoir rocks in south central New York and Pennsylvania. They also are historically important in northwestern Ohio. The depositional fabric is readily recognizable in these dolostones (Figures 40 and 41). The rocks are mostly bioturbated or laminated dolomudstone and dolowackestone deposited in shallow subtidal and peritidal environments. The depositional texture is recognizable in hand sample, even when dolomitization is advanced to obliterate at the microscopic scale. These dolostones consist of polymodal planar-s to nonplanar-a (transitional) dolomite and saddle dolomite, with both mimic and nonmimic replacement of fossil allochems (echinoid and brachiopod fragments). The rocks are mostly medium to coarsely crystalline; crystal sizes range from 0.05 to 1.5 mm.

Vugs, channels, and molds dominate porosity in the dolomudstones and dolowackestones. These pore textures developed through dissolution of dolomite and calcite that replaced some of the dolomite. Fracturing and brecciation of the rocks and the related development of dolomite zebra fabrics are important (Figure 42). Late-stage calcite, quartz, anhydrite and fluorite fill some porosity. These rocks exhibit unique bitumen coatings around nonplanar-c dolomite cements (Figures 42D, 43, and 44). In some instances, the nonplanar-c dolomite was dissolved away, enlarging the pore space in the rocks, and leaving the earlier-formed bitumen coatings behind (Figure 44).

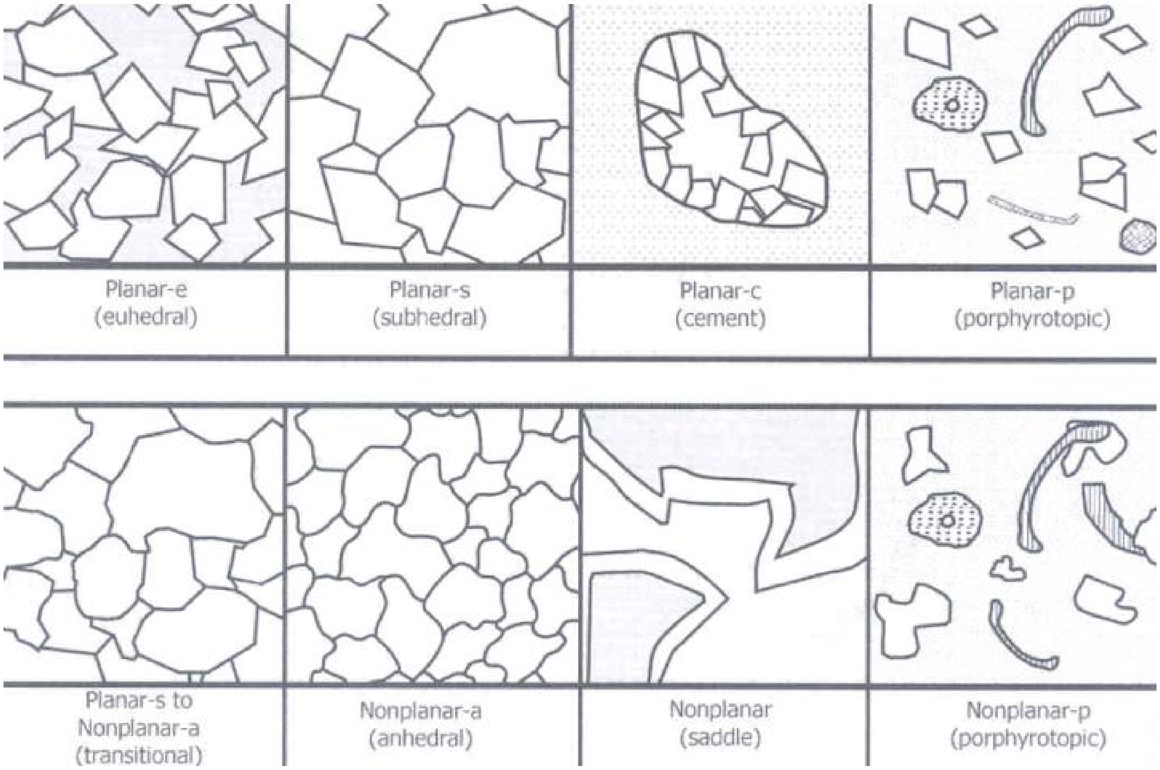


Figure 29. Dolomite textural classification from Gregg and Sibley (1984), Sibley and Gregg (1997) and Wright (2001).

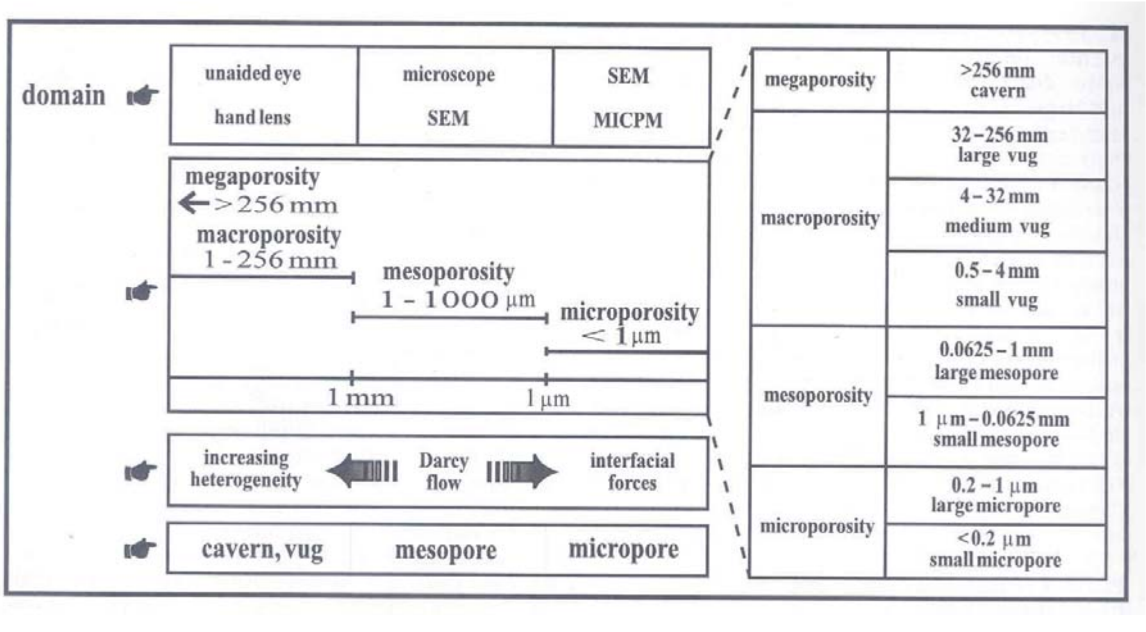


Figure 30. Pore size classification for carbonate rocks (Luo and Machel, 1995).

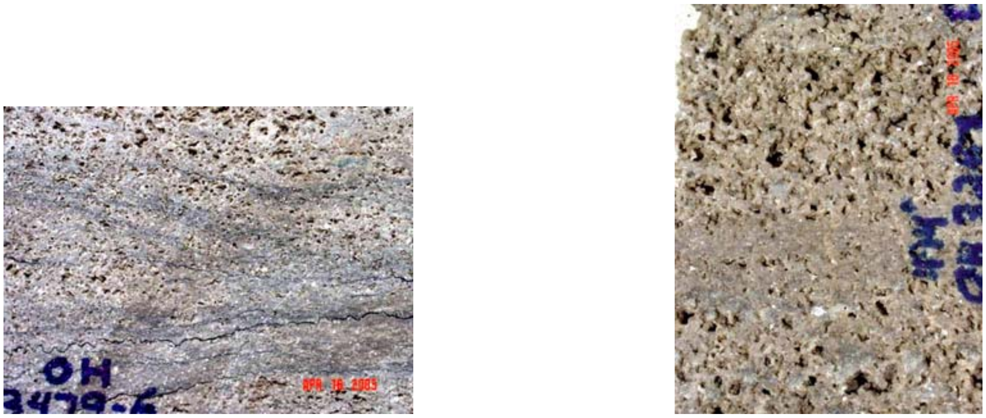


Figure 31. Dolograinstones from Trenton Group reservoirs in northwest Ohio. **A.** Dolograinstone with recognizable depositional texture. The rock consists of cross-bedded, coarse-grained crinoid-bryozoan grainstone interbedded with stylolitic dolomudstone/dolowackestone. These cyclic lithologies consist of shoaling-upward, grainstone-capped subtidal parasequences. Note the large crinoid allochem, which is mimetic planar-s to nonplanar-a (transitional) dolomite (also see Figure 32). The visible porosity consists mostly of small vugs, 0.5 to 4 mm in diameter, and molds. (OH 3479, Hancock Co., Palladin Enterprises, Anderson well, 1337.8 ft.). **B.** Interpreted dolograinstone without recognizable depositional texture. Dolomitization has obliterated all of this rock's primary and earlier diagenetic fabrics. The interpretation of this sample as a former grainstone is based on the presence of allochem ghosts, and both mimetic and non-mimetic replacement textures observed in thin section (Figure 33). (OH 3267, Auglaize Co. Meridian, Bousher #1 well, 1174 ft.).

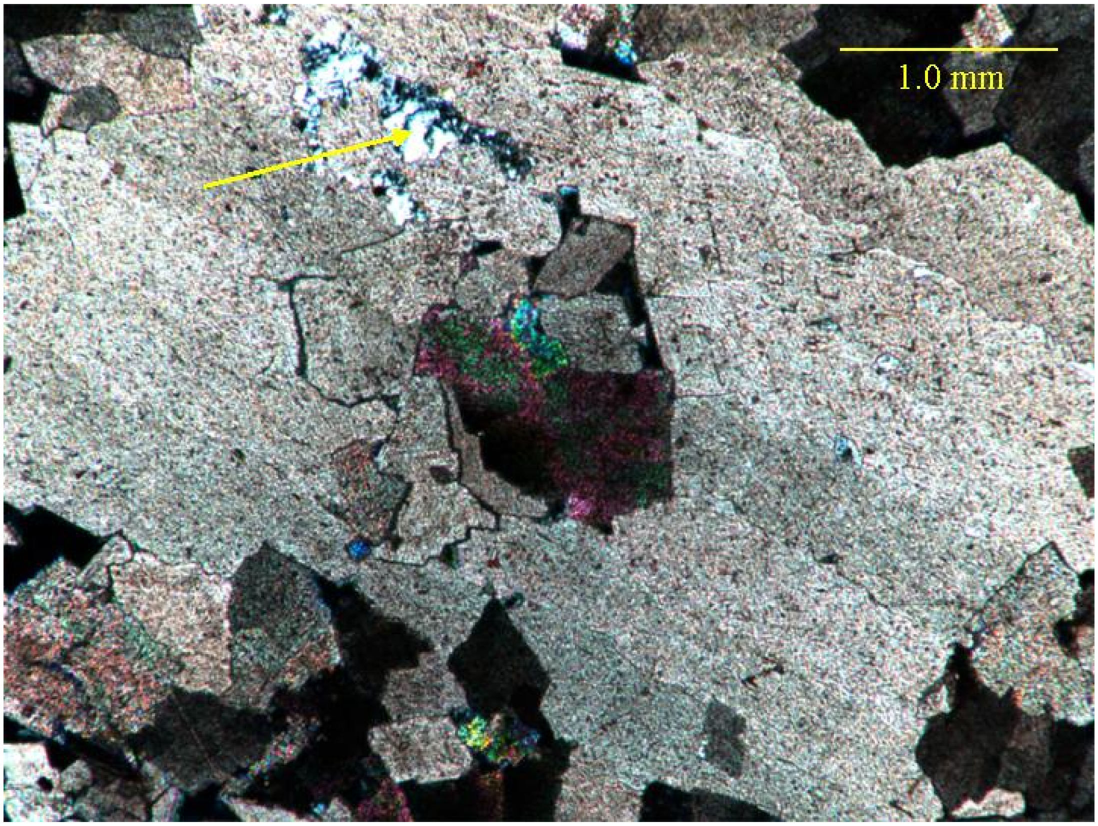


Figure 32A.

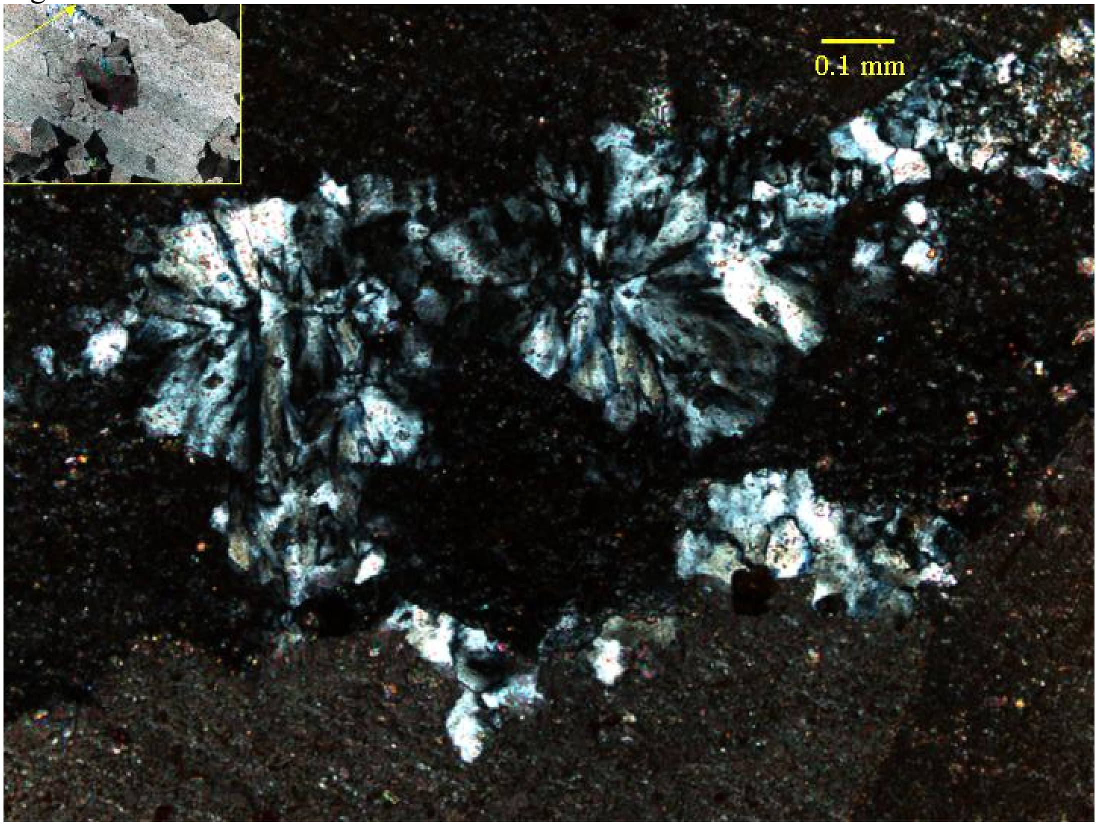


Figure 32B.

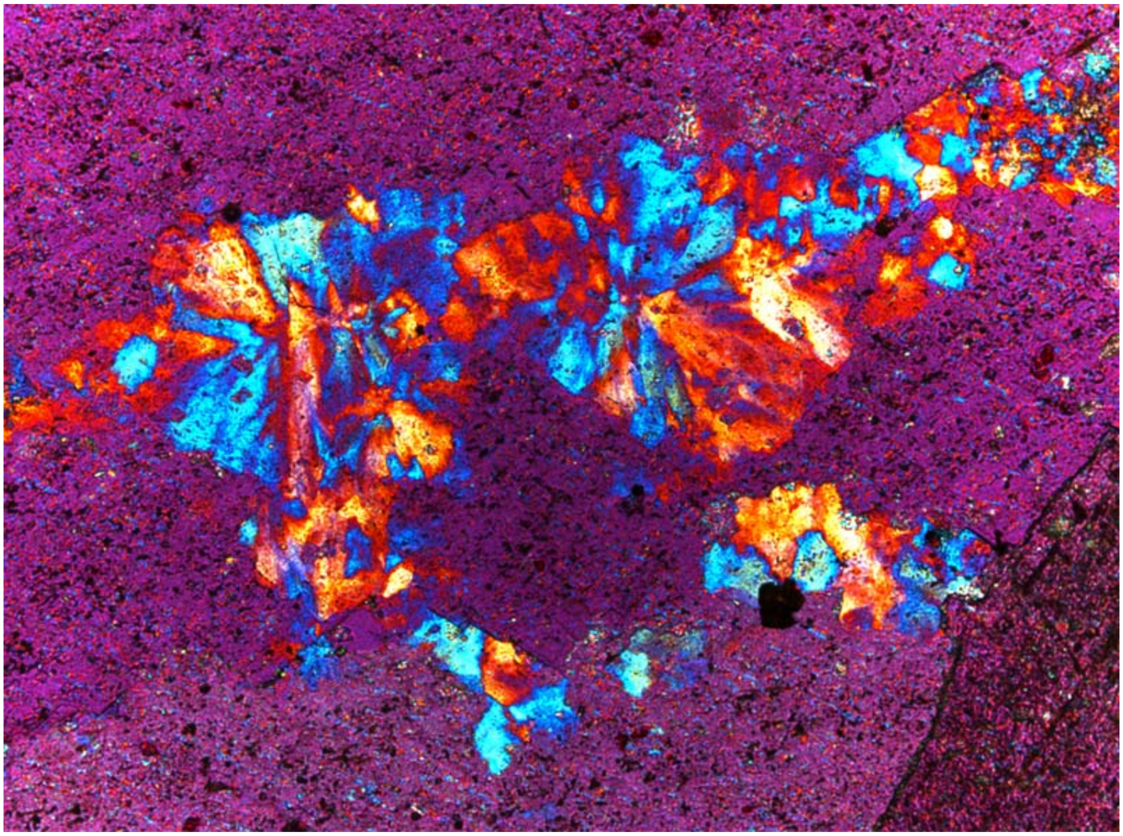


Figure 32C.

Figure 32. Thin section photomicrographs (cross polarized light) of a crinoid grain replaced by mimetic planar-s to nonplanar-a (transitional) dolomite. **A.** A longitudinal section of the dolomitized crinoid stem showing seven articulated columnals. Intraparticle pore space, developed through dissolution enlargement of the lumen, is mostly filled with planar-c and nonplanar-c (saddle) dolomite. The latter is partially replaced by calcite. Note that the dolomitized crinoid grain is partially replaced by chert and chalcedony (yellow arrow). **B.** High magnification view of the chert (microcrystalline quartz) and chalcedony (radiating splays) replacing dolomite in the crinoid grain. **C.** Same view as **B**, but with the gypsum plate (Quartz Red I plate) inserted. The gypsum plate was inserted from the SE quadrant. Note that the birefringence colors in the NE and SW quadrants increased and the colors in the NW and SE quadrants decreased. This indicates length-slow chalcedony, a clue that the replacement may have taken place in fluids with a high sulfate concentration (Scholle and Ulmer-Scholle, 2003). (OH 3479, Hancock Co., Palladin Enterprises, Anderson well, 1337.8 ft.).

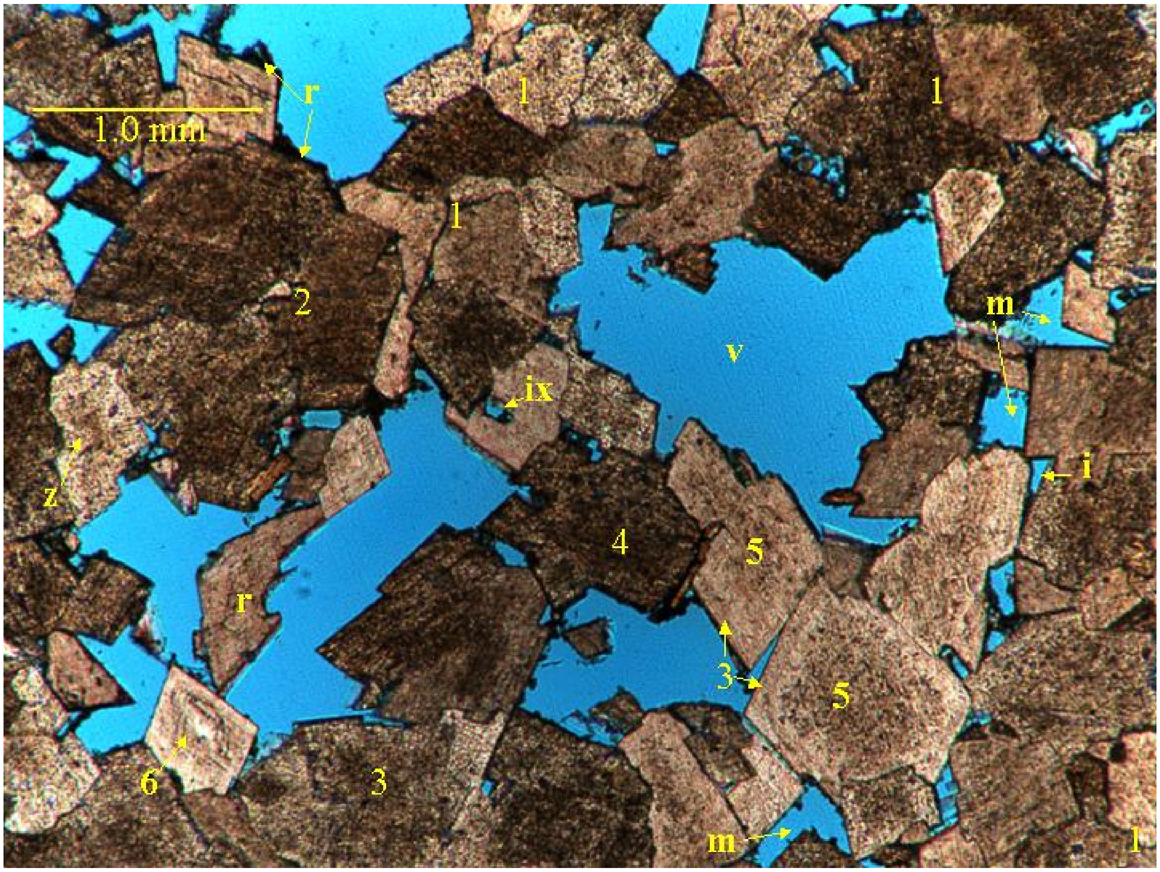


Figure 33. Dolomite texture and porosity in dolograinstone reservoir rocks, northwest Ohio. This is a photomicrograph (plane polarized light) of a dolostone with recognizable depositional texture (same sample shown in Figure 31A). The sample is polymodal, coarsely to very coarsely crystalline dolostone. Crystal size ranges from 0.1 to 1.2 mm, with a mean of 0.6 mm. The rock consists of (1) planar-s to nonplanar-a (transitional) dolomite, (2) nonplanar (saddle) dolomite, and (3) nonplanar-c dolomite. About 25 percent of the dolomite crystals present in the rock partially to wholly take a stain with Alizarin Red S indicating partial calcification of the dolostone (4). Cloudy cores of planar-e and planar-s dolomite, revealed by inclusion patterns incorporated in the dolomite crystals, have overgrowths of nonplanar-c or saddle dolomite cement (5). Relicts or ghosts of zoned crystal growth can be discerned in some crystals (6). Mesopores (intercrystalline, i, moldic, m, and intracrystalline, ix) are fabric selective. Macropores consist of small vugs 0.5 to 4mm in diameter (v). Partial to almost complete dissolution of calcified dolomite crystals created the macropores (small vugs). Note the remnants and residues of partially to completely calcite-replaced dolomite (r). Dissolution of dolomite resulted in some of the moldic voids.

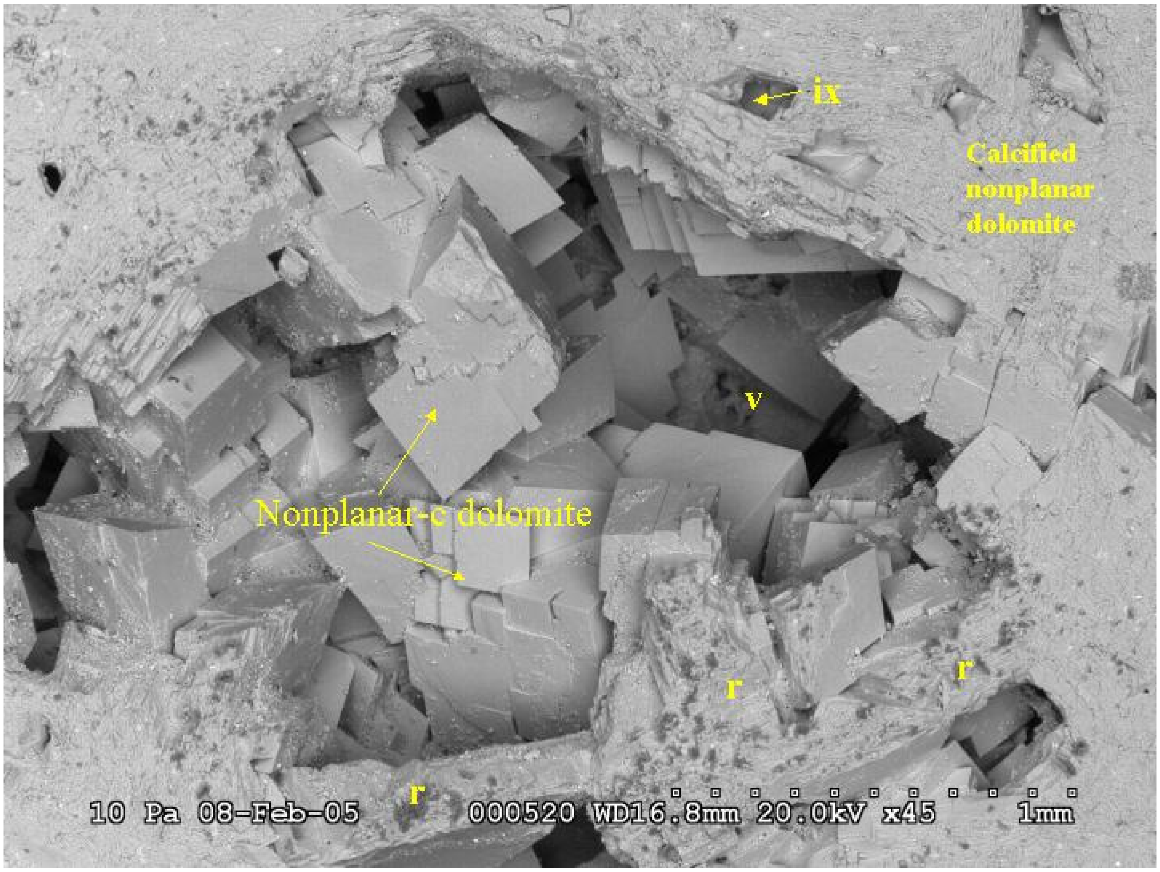


Figure 34. Backscattered electron (BSE) image obtained by scanning electron microscopy (SEM) of the dolograinstone shown above in figures 31A and 34. The small vug (v), about 2.5 mm across, formed through dissolution of calcified nonplanar dolomite (see Figure 36 below). Note the remnant (r) of the latter near the bottom of the void. The vug is partially filled with nonplanar-c (saddle) dolomite. Some of these crystals are also corroded due to dissolution. Some small (<0.1 to 0.2 mm) intracrystalline voids occur in this sample.

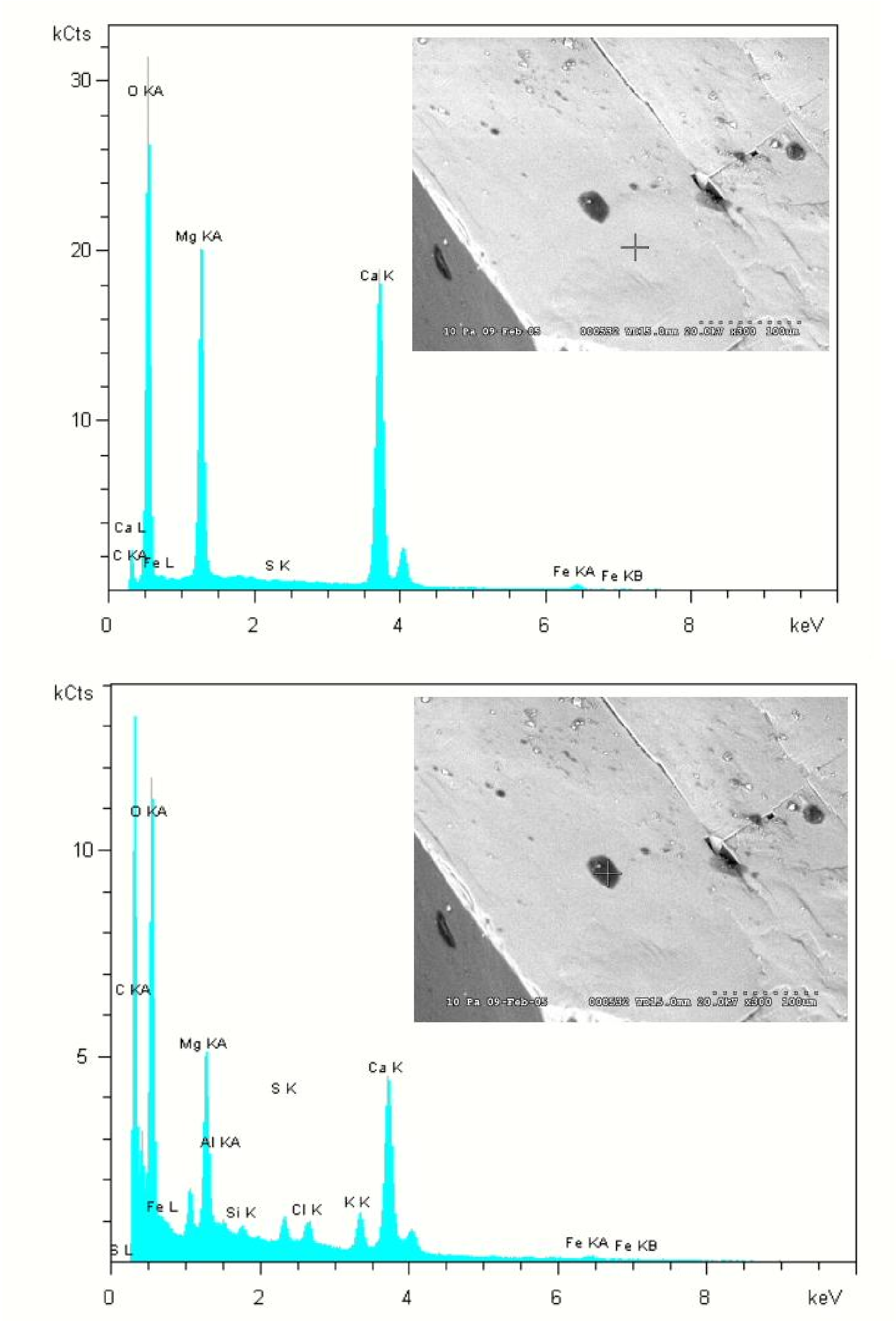


Figure 35. Hydrocarbon stains on nonplanar-c dolomite (saddle dolomite cement). **A.** SEM and energy dispersive x-ray spectroscopy (EDS) of cement crystals in dolograinstone. The cross shows the location of the EDS analysis of the crystal, which is clearly dolomite. **B.** EDS analysis of the black stain on the dolomite crystal reveals its high carbon concentration relative to the Mg and Ca of the dolomite itself. (OH 2549, Wood Co., 1168.25 ft.)

Figure 36A above; Figure 36B below.

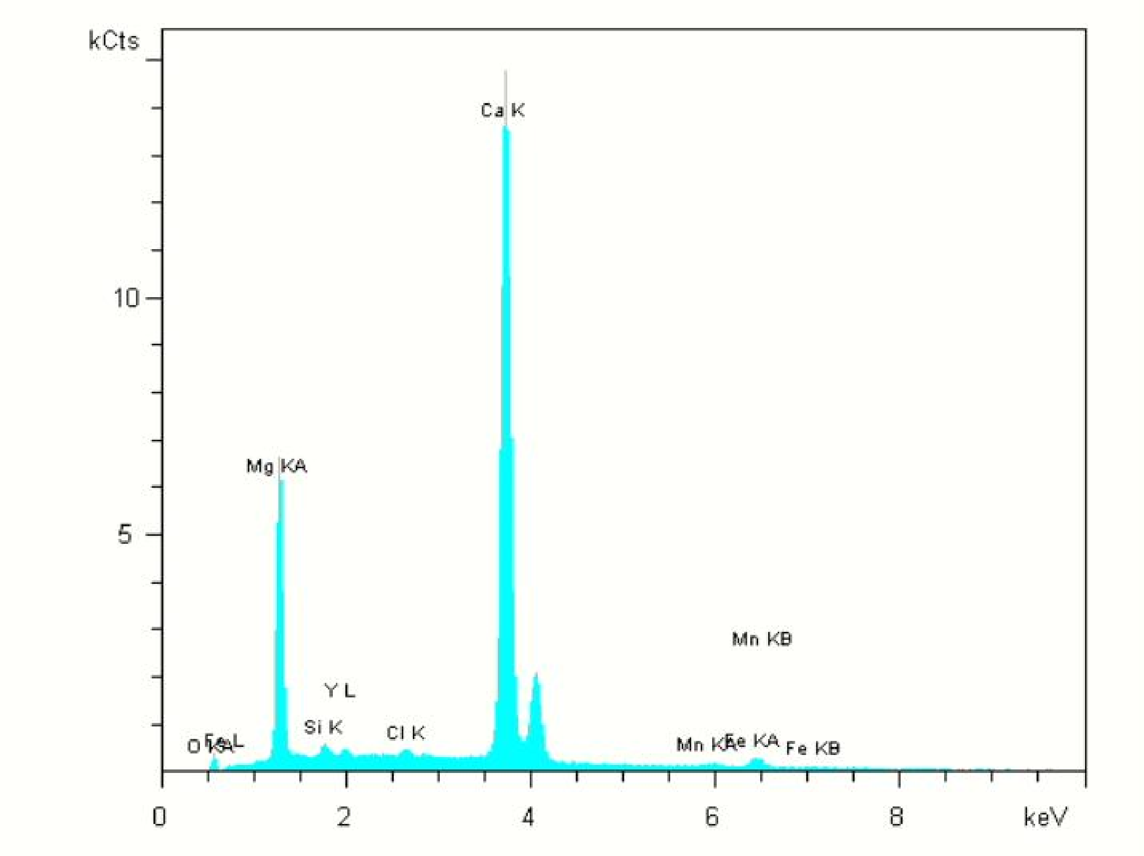


Figure 36C.

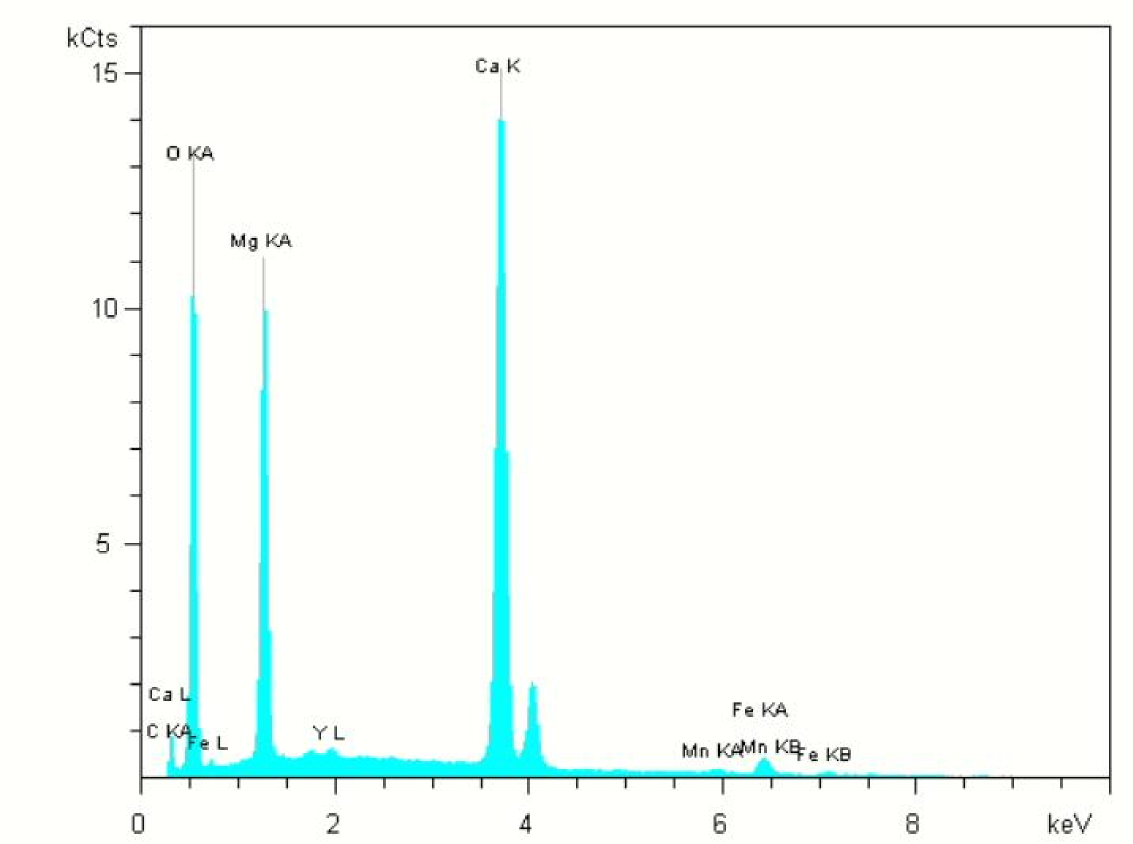


Figure 36D.

Figure 36. SEM and energy dispersive x-ray spectroscopy (EDS) of dolograinstone shown in Figures 31A, 33, and 34. **A.** BSE SEM image of nonplanar (saddle) dolomite. The white minerals are pyrite inclusions. The box shows the location of the quantitative EDS analysis shown in Figure 36B. **B.** Energy dispersive spectra of nonplanar (saddle) dolomite. Note the excess of calcium: the Mg/Ca ratio is 0.4. Saddle dolomites are commonly Ca-rich, and calcite relics are not at all unusual in replacement dolomite (Tucker and Wright, 1990; Scholle and Ulmer-Scholle, 2003), so this low Mg/Ca ratio is not surprising. **C.** BSE SEM image of nonplanar-c dolomite filling a vug. The cross marks the spot of the EDS analysis presented in Figure 36D. **D.** EDS of the nonplanar-c dolomite in Figure 36C. The dolomite is calcian, with a Ca content of 57.4%.

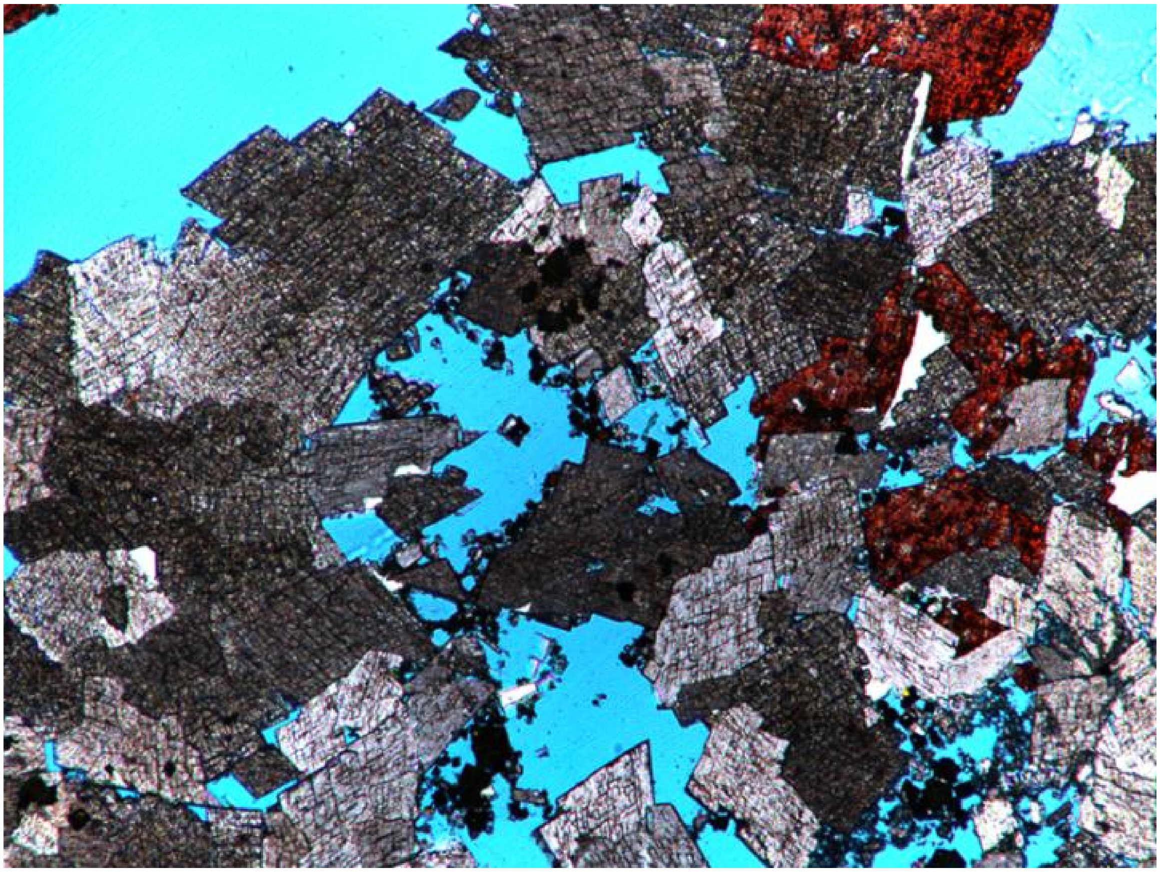
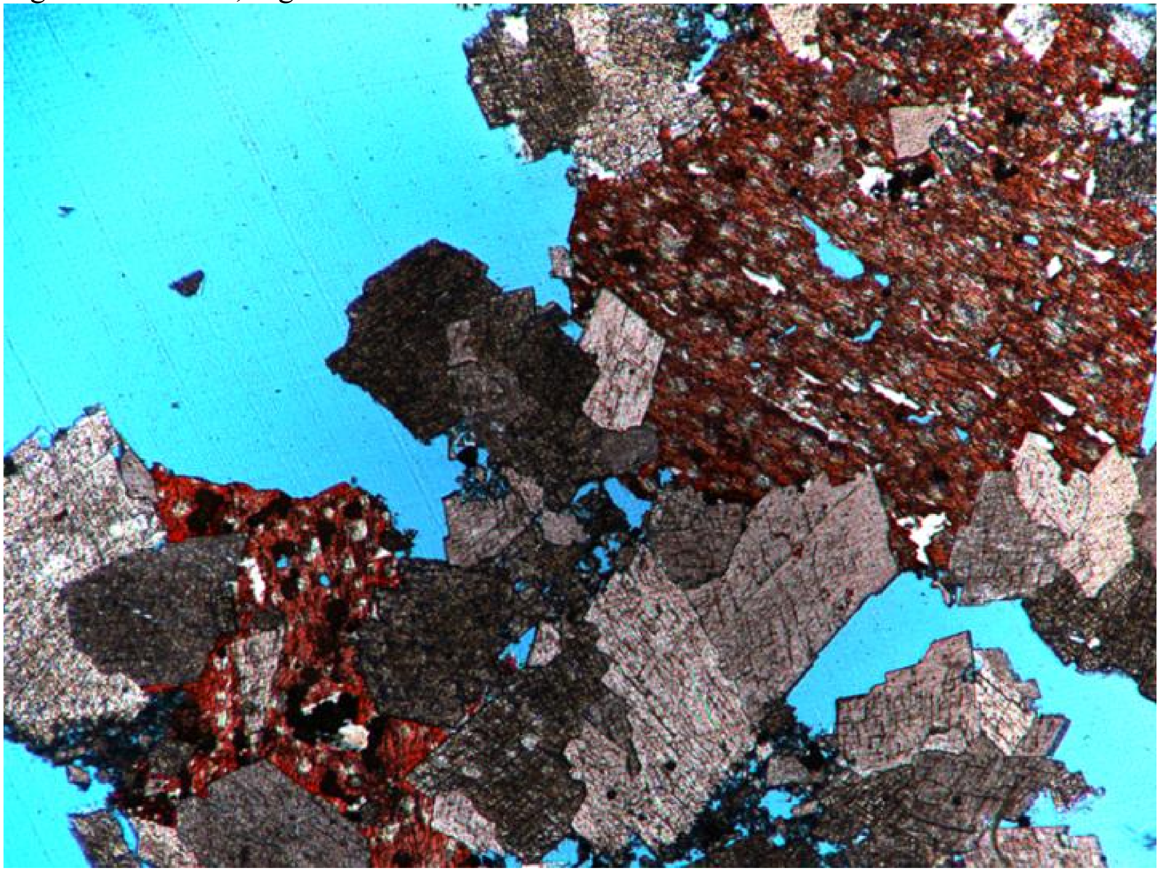


Figure 37A above; Figure 27B below.



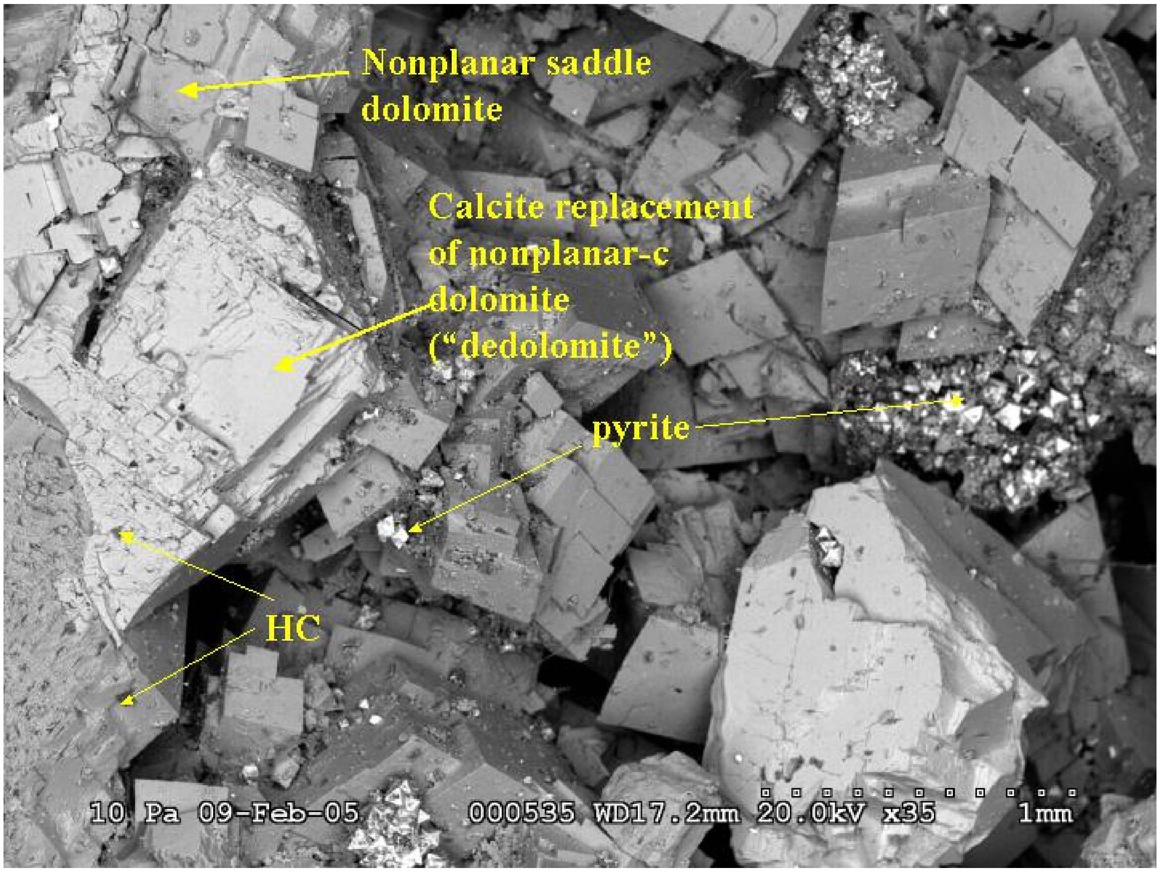


Figure 37C.

Figure 37D.

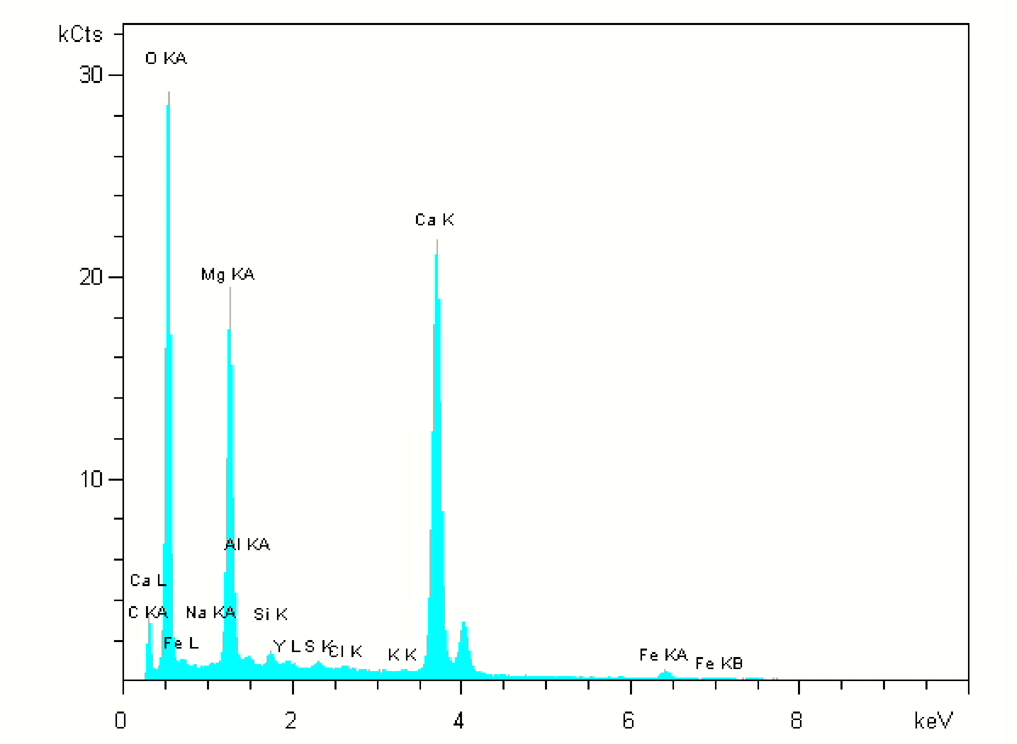


Figure 37E.

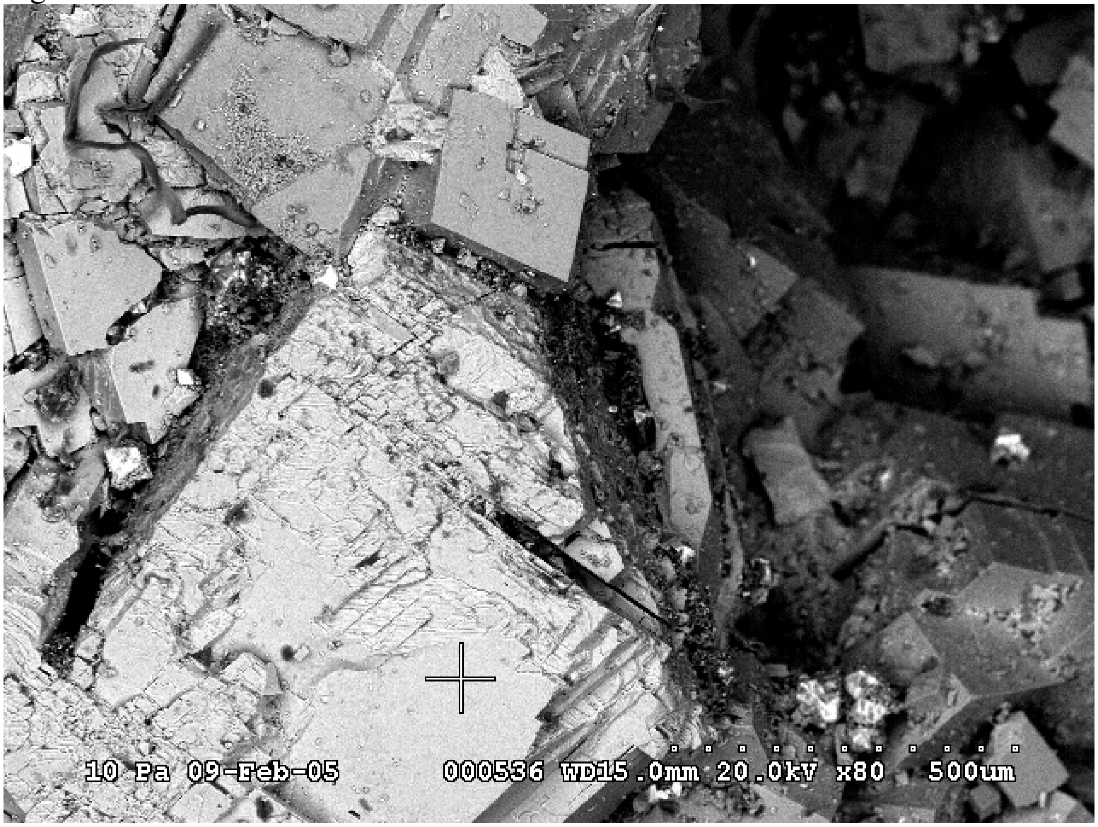


Figure 37F.

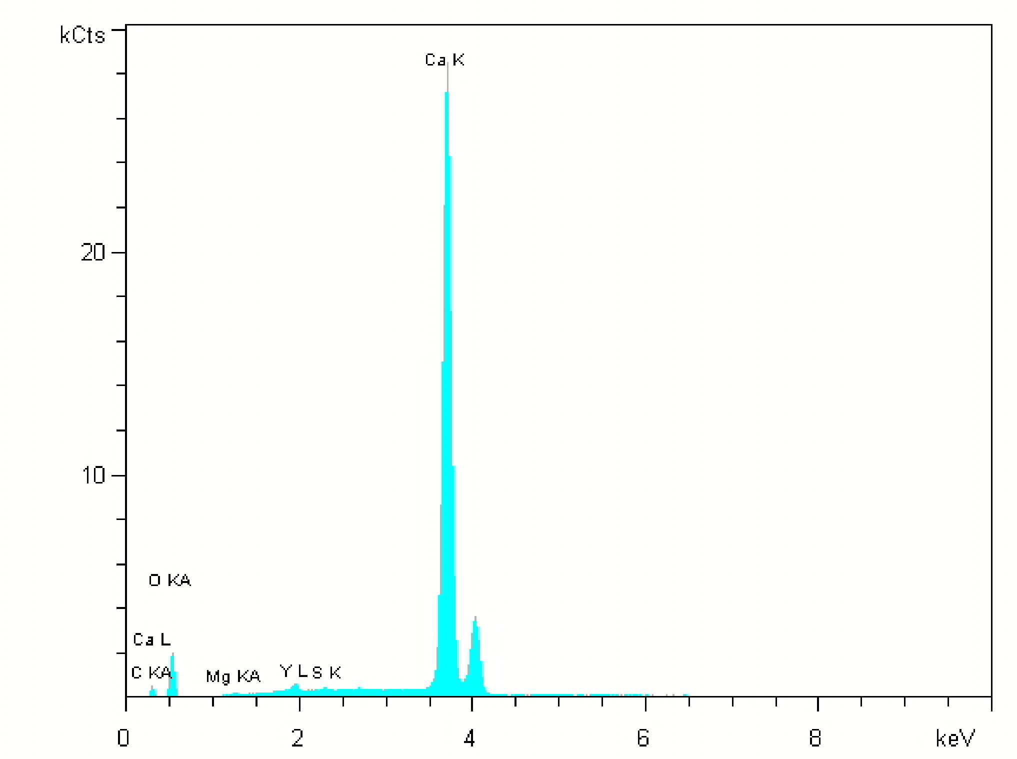


Figure 37G.

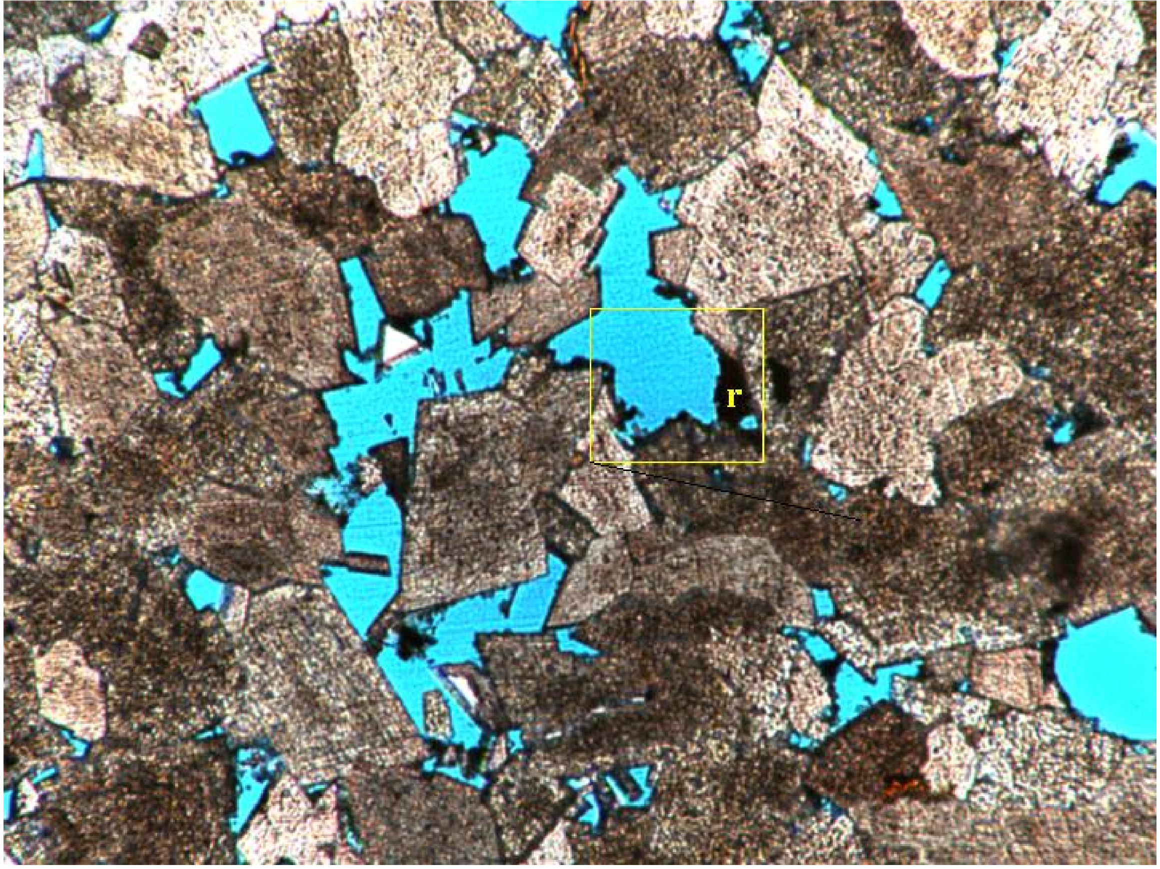


Figure 37H.

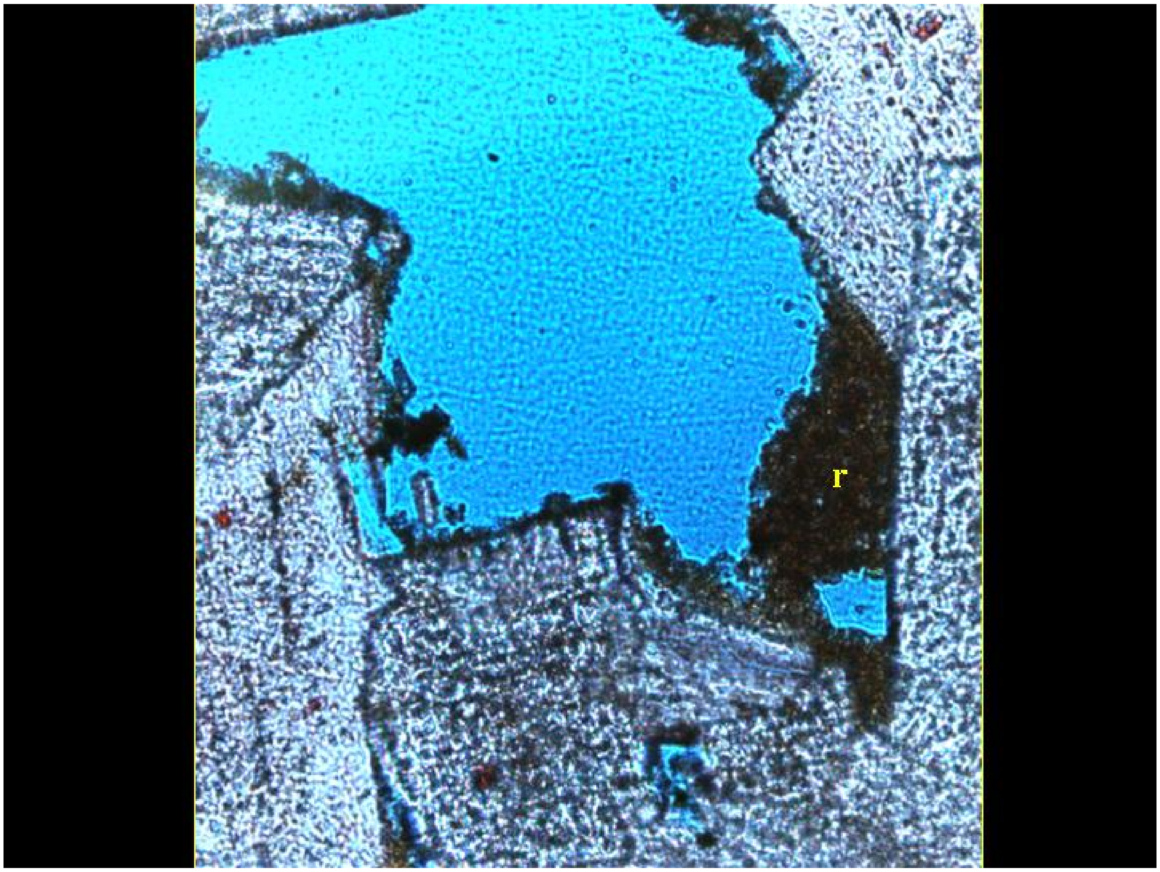


Figure 37I.

Figure 37. Calcite replacement ("calcification" or "dedolmitization") of dolomite in dolograinstone of the Trenton Group in northwestern Ohio. **A.** Thin section photomicrograph (plane polarized light) of highly porous dolograinstone from the Bousher #1 well, Auglaize County, Ohio (OH3267, 1175 ft.). Note that the calcite is clearly stained with Alizarin Red S. Also note the clusters of pyrite crystals within the calcite. Scattered minute crystals of fluorite also occur in the sample; these appear to predate the replacement calcite. Porosity is due to dissolution of both dolomite and the later calcite mineralization. Note the pyrite, calcite, and dolomite residues in the voids. **B.** Higher magnification view of the same thin section shown in **A.** Remnants of the dolomite that the calcite replaced, as well as clusters of pyrite and scattered fluorite crystals, float within the large calcite crystals. **C.** SEM photo of the same sample shown in **A** and **B**. Most of the vug is lined with nonplanar-c dolomite (darker gray tone), but the lighter gray crystals at upper center left and lower right are calcite. Also note the clusters of pyrite. SEM (**D)** and EDS (**E**) of nonplanar-c dolomite in this sample confirm the mineralogy of the darker gray material. SEM (**F)** and EDS (**G**) of the large light toned crystal confirm the mineralogy of the replacement calcite. **H.** Thin section photomicrograph of the dolograinstone shown above in Figures 31A, 32, 33, and 34. Note the residue(r) of calcite (red) remaining in the vuggy pore after dissolution. Similar remnants of dissolved calcite occur throughout the slide. **I.** Higher magnification view of remnant calcite lining part of a vuggy void in the same sample.

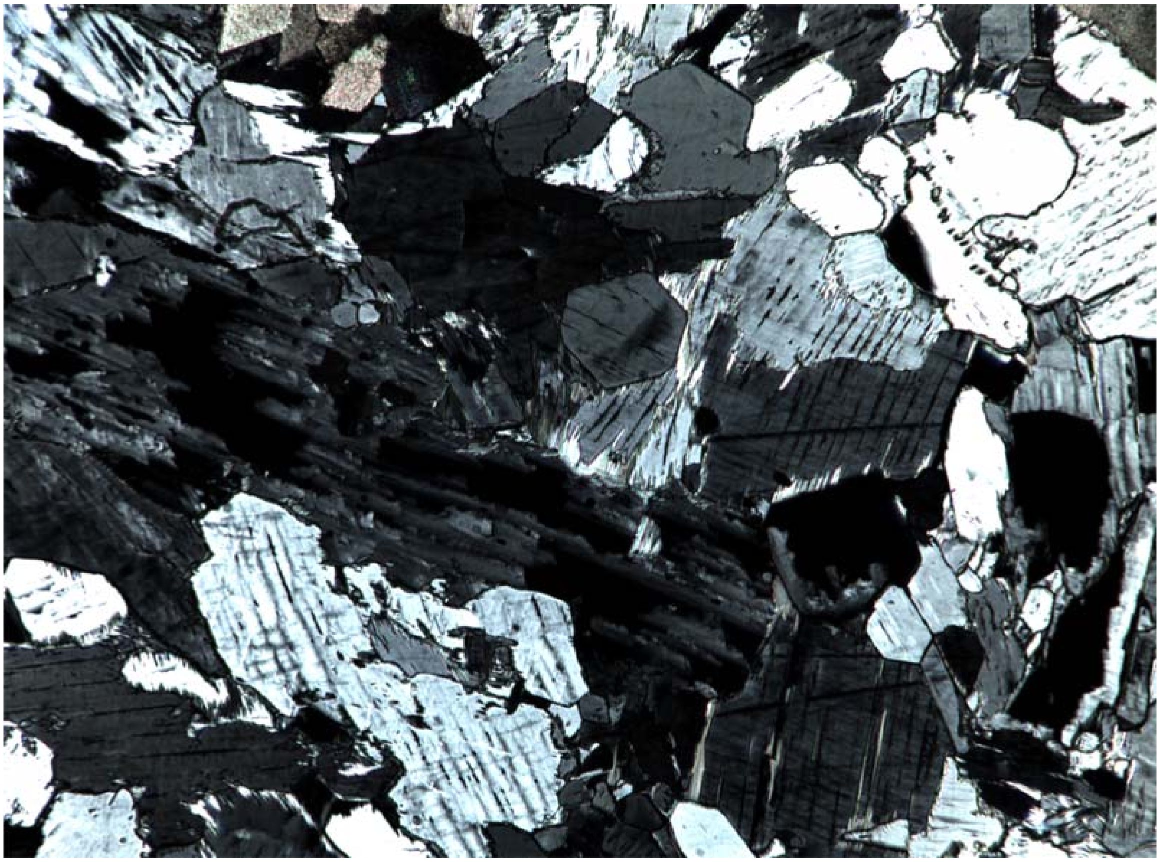


Figure 38. Late-stage anhydrite, quartz, and chalcedony in dolograinstone from northwest Ohio. Hexagonal quartz crystals, coarse chalcedony, and needle-like laths of bladed anhydrite fill this large vug. (OH 3478, Allen Co. Meridian, Strayer #1 well, 1218.4 ft.).

Bioturbated shallow subtidal lime mudstone, NW PA

Bioturbated shallow subtidal dolomudstone, NW OH

Figure 39. Bioturbated, muddy subtidal carbonates from the Trenton Group. The core on the left is lime mudstone (Mercer County, Pa, McKnight #1 well, 6841.5 ft). The core on the right is dolomudstone. The rock is completely dolomitized, but the depositional fabric is still recognizable (OH 3372, Marion Co., Prudential #1 well, 1840 ft.).

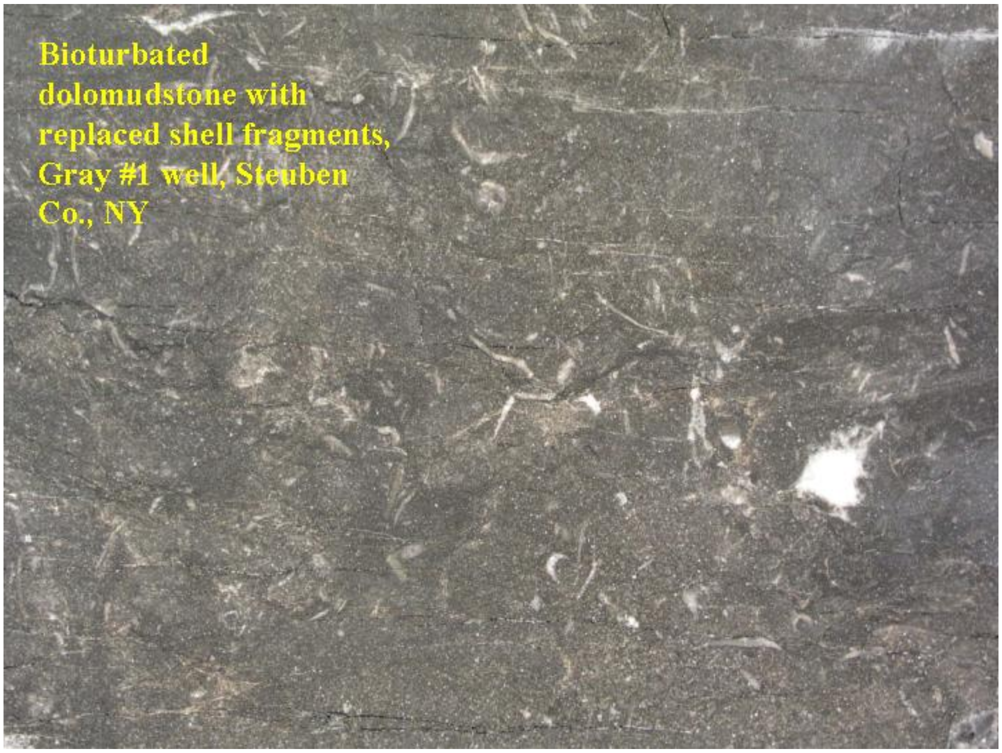


Figure 40. Bioturbated subtidal dolomudstone, with replaced shell fragments (Steuben Co., NY, Gray #1 well).

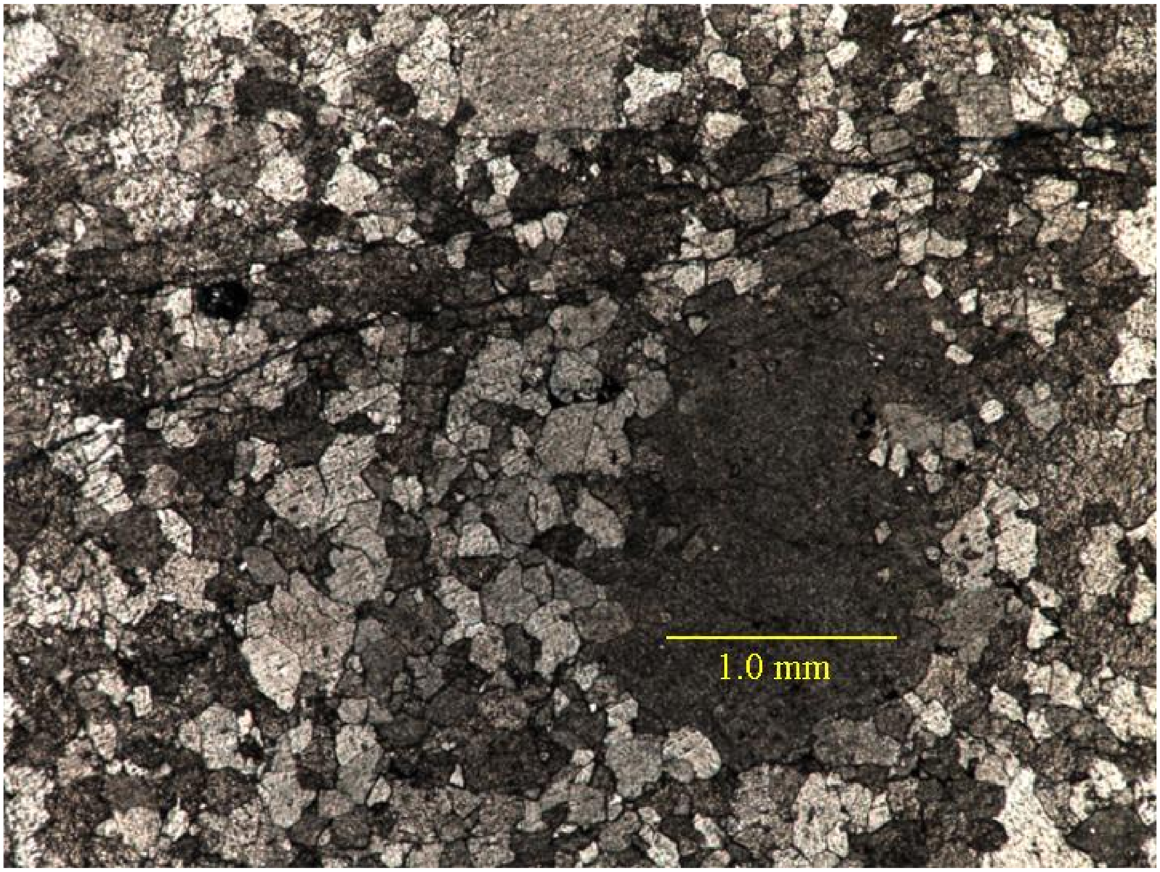


Figure 41A.

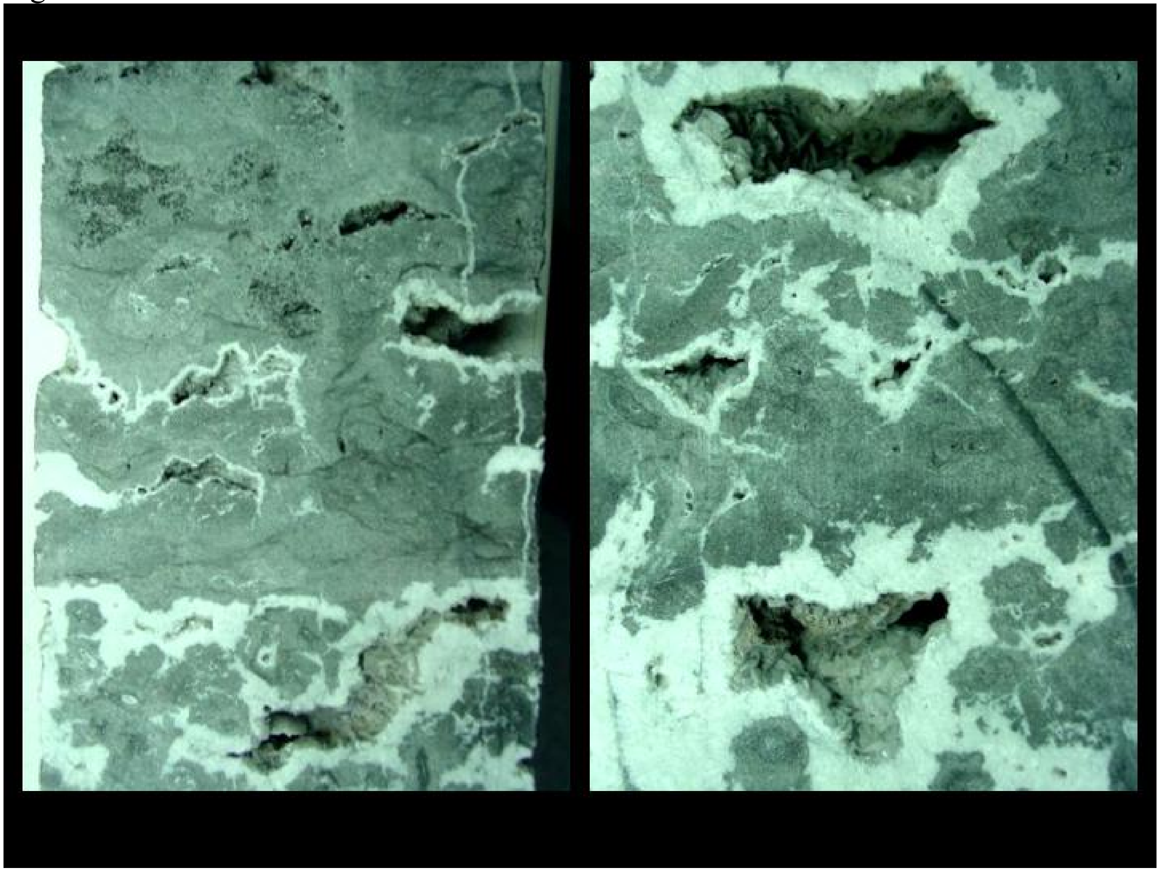


Figure 41B.

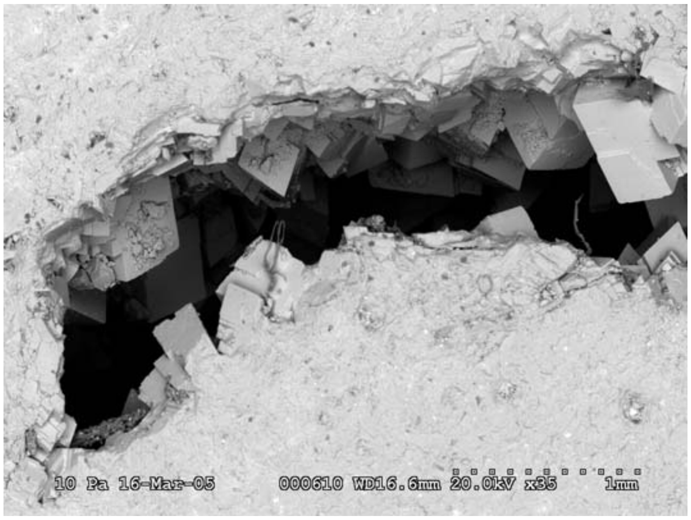


Figure 41C.

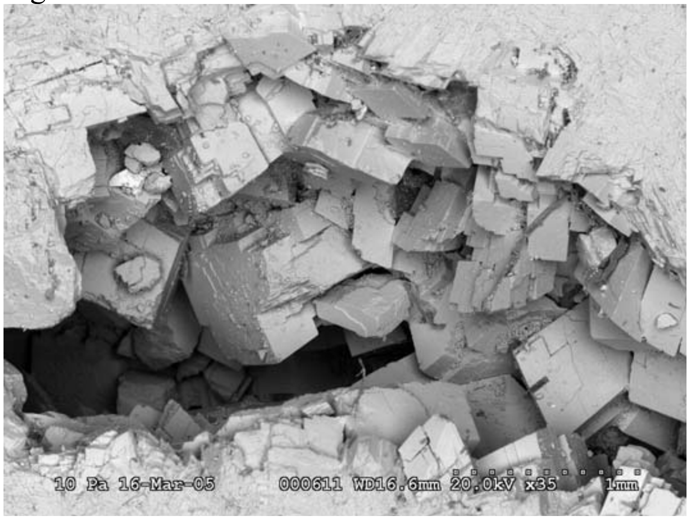


Figure 41D.

Figure 41. Dolomite texture and porosity in dolomudstone and dolowackestone reservoir rocks, south central New York state. **A)** Dolomudstone, Gray #1 well (Steuben CO., NY). The rock consists of polymodal planar-s to nonplanar-a (transitional) dolomite, with both mimic and nonmimic replacement of fossil allochems (echinoid and brachiopod fragments). The rock is mostly medium crystalline; crystal sizes range from 0.05 to 0.5 mm. Note the swarm of microfractures crossing the upper center of the photomicrograph. **B.** Moldic and vuggy porosity. Molds are fabric selective and occur within replaced allochems. Vugs are not fabric selective. They are lined by and partially filled with nonplanar-c (saddle) dolomite Note the vertical fracture on the right side of the sample pictured on the left. (Fortuna Whiteman #1 well, Chemung Co., NY). **C** and **D**. SEM photomicrographs of molds (**C**) and vugs (**D**) in the same sample shown in Figure 41A and 41B. The shape of the mold shown in **C** suggests that it formed through dissolution of a brachiopod grain, but it is not clear if the void formed through dissolution of calcite, or dolomite that replaced the grain. Observations from other parts of this slide suggest the latter. Nonplanar-c dolomite lines the mold. The medium vug shown in **D** is largely filled with nonplanar-c dolomite, although the vug itself appears to have originally formed through dolomite dissolution.

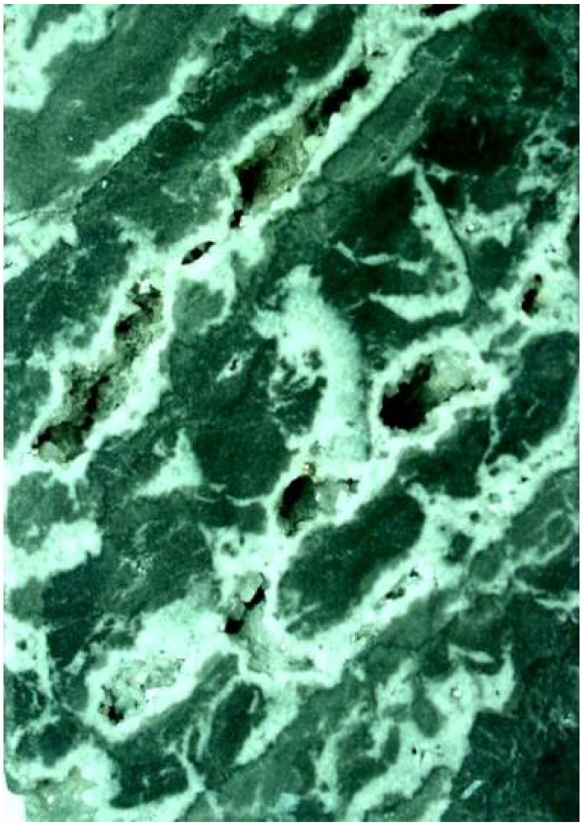


Figure 42A.

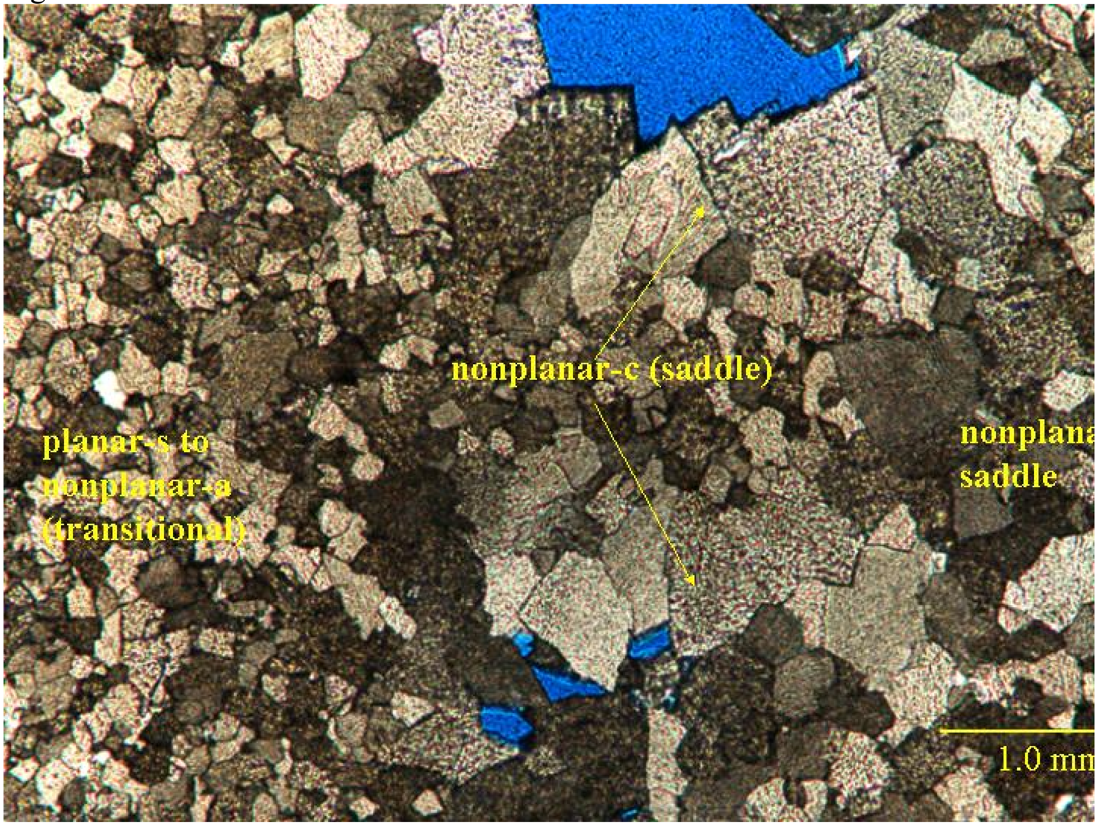


Figure 42B.

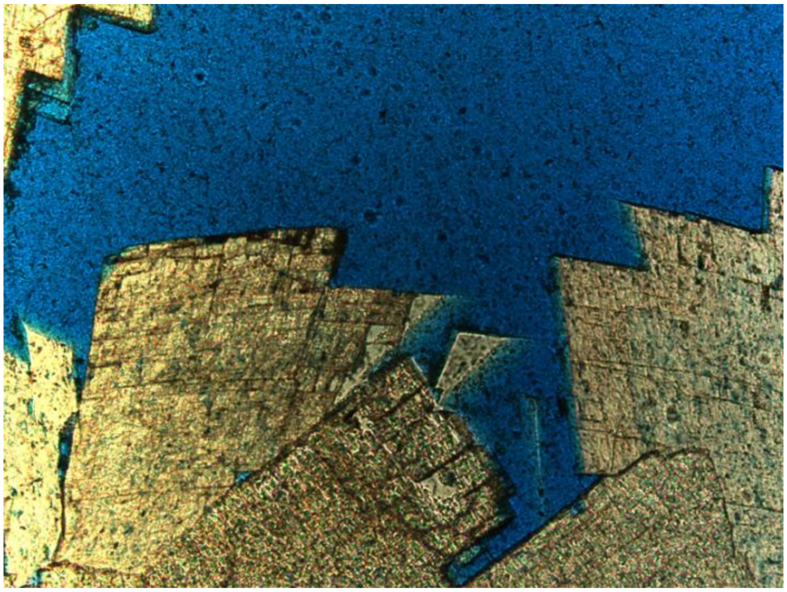


Figure 42C.

Figure 42D.

Figure 42. Zebra fabric in the producing zone of the Fortuna Whiteman #1 well, Chemung Co., NY, 9531 ft.). **A.** Alternations of the dark host dolomite and the white cavity-filling saddle dolomite yield the zebra fabric apparent in this core. Vug diameters range from small to large, and some voids approach 400 mm in diameter qualifying as cavern-type megaporosity (see Figure 30). The zebra fabric is inclined to the bedding, and the dolomudstone is brecciated. **B.** Thin section photomicrograph of sample shown in **A**. This dolomudstone consists of polymodal, medium- to coarsely-crystalline dolomite; crystal size ranges from 0.07 mm to 1.3 mm, with a mean of 0.4 mm. **C.** Close-up photomicrograph of nonplanar-c (saddle) dolomite lining a vug in the sample shown in Figure 42A and B. Note the dissolution of the saddle dolomite along the outer edges of the crystals. **D.** SEM photomicrograph of same sample shown in Figure 42A through 42C. The view of nonplanar-c (saddle) dolomite cement lining a large vug is similar to that in Figure 42C, but note the dark hydrocarbon coatings on the crystals and in the intercrystalline voids and channels.

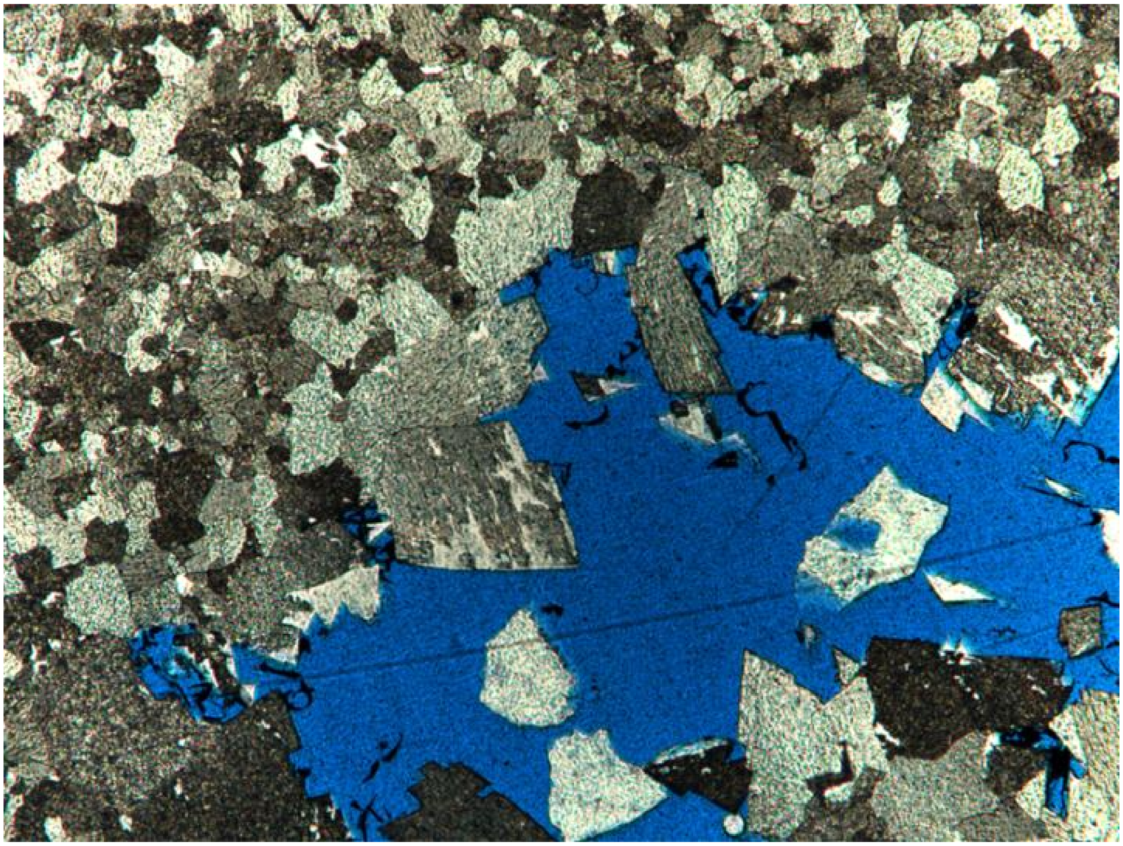


Figure 43A.

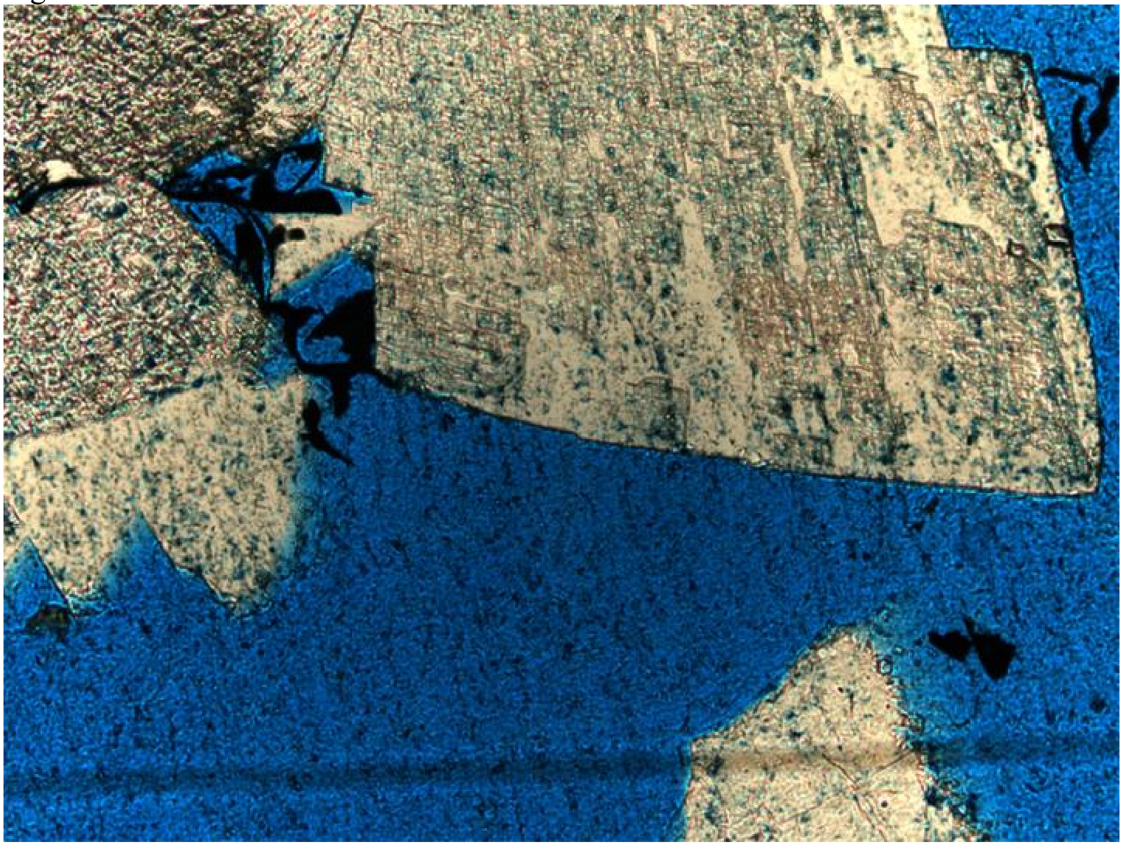


Figure 43B.

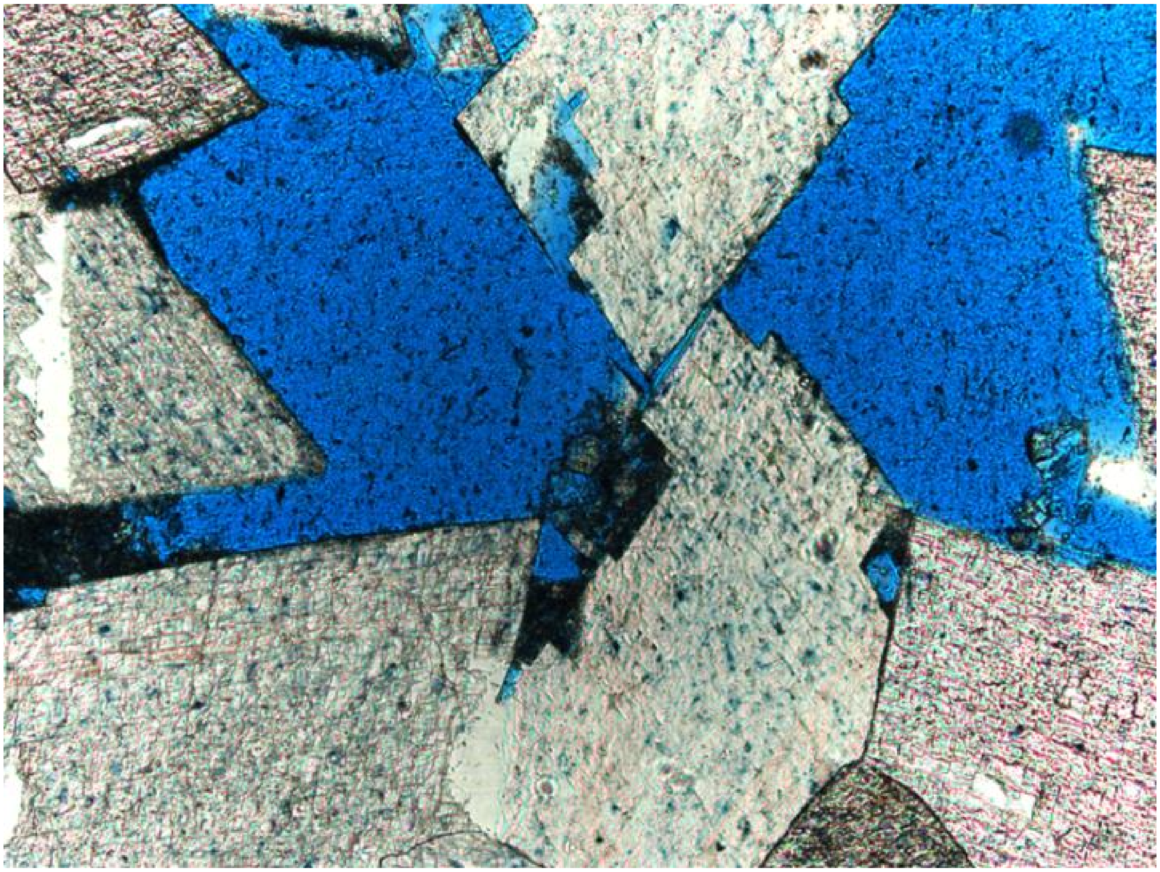


Figure 43C.

Figure 43. Thin section photomicrographs of zebra fabric dolomudstone, Fortuna Whiteman #1 well, Chemung Co., NY, 9531 ft. **A.** Planar-s to nonplanar-a dolomite groundmass, nonplanar-c (saddle) dolomite cement, and large vug. Note that some of the dolomite crystals are stained with Alizarin Red S indicating calcite that replaced the nonplanar-c dolomite. Some of the dolomite crystals are partially replaced by anhydrite, and possibly fluorite (triangular, isotropic material inter-grown with the replacive calcite and anhydrite. Also note the strands and flakes of formerly intercrystalline bitumen left behind due to dolomite dissolution. **B**. Higher magnification view of nonplanar-c (saddle) dolomite cement partially replaced by anhydrite. Note bitumen flakes and the corroded dolomite crystals. **C.** Corroded, partially dissolved saddle dolomite crystals adjacent to vuggy pores, and residues of dissolved calcite that partially replaced dolomite.

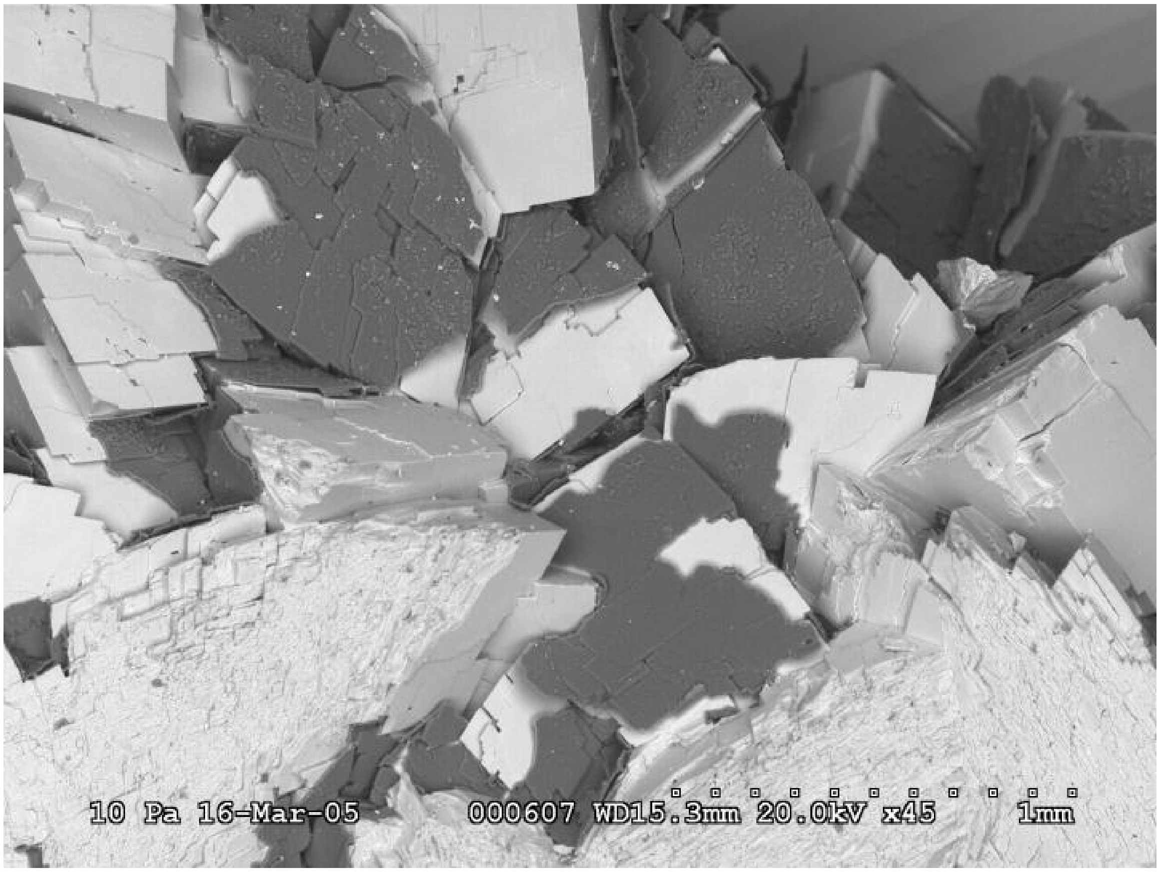
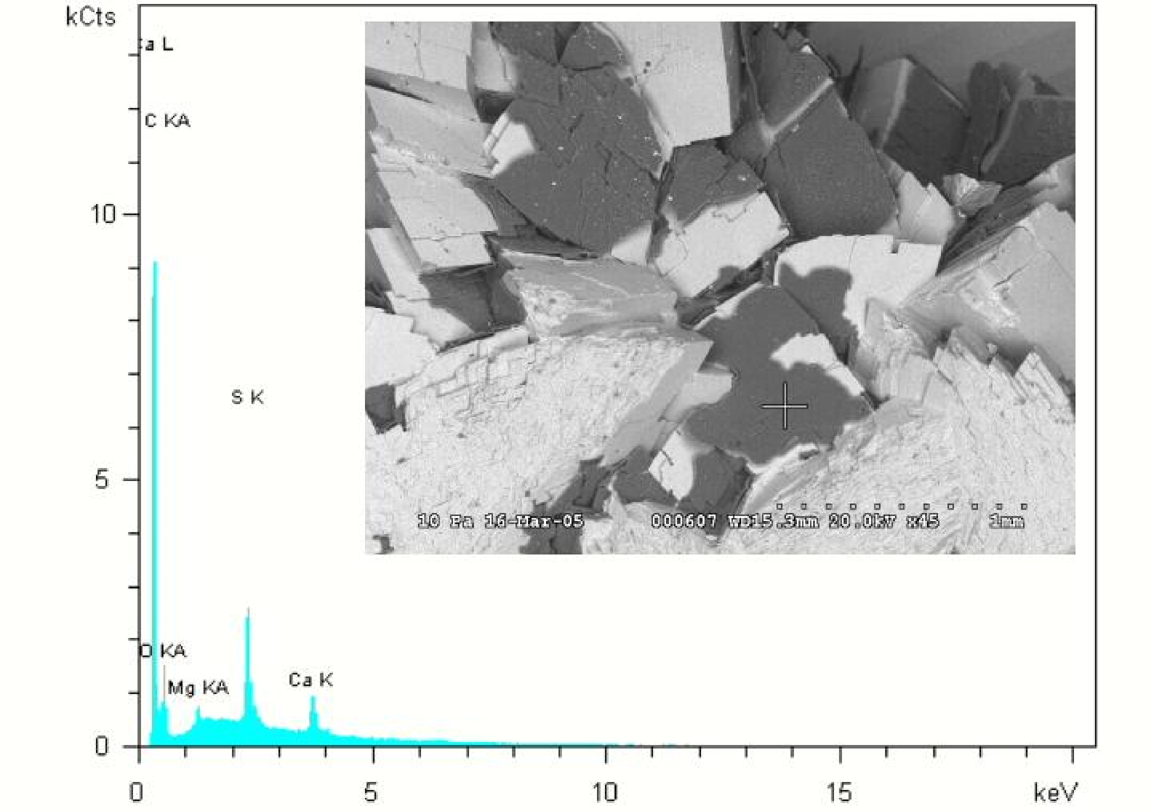


Figure 44A above; Figure 44B below.



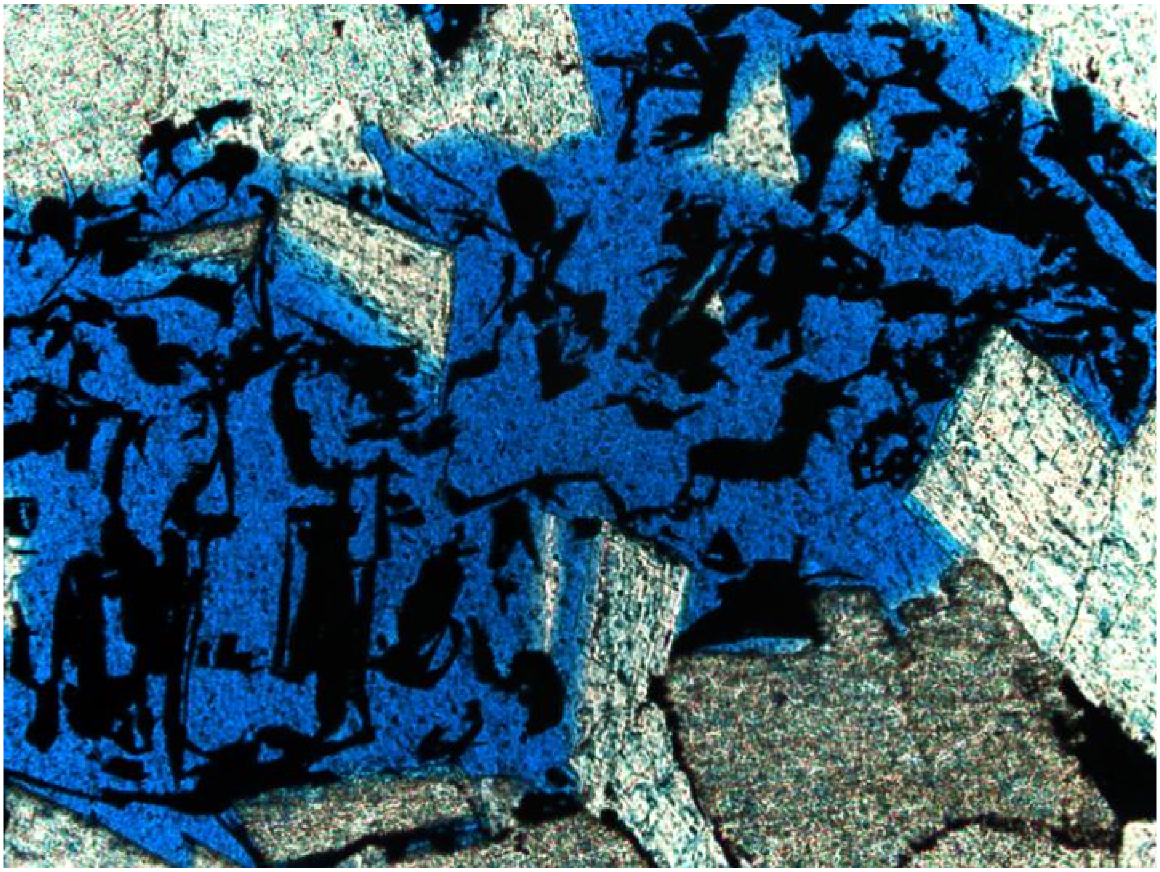


Figure 44C.

Figure 44. A. SEM (BSE) photograph of bitumen coats on nonplanar-c dolomite crystals, Fortuna Whiteman #1 well, Chemung Co., NY, 9531 ft. **B.** EDS analysis of the bitumen coats in Figure 44A. In addition to the high carbon peak, note the relatively high sulfur peak. **C.** Thin section photomicrograph of reservoir dolomite from the Fortuna Whiteman #1 well, Chemung Co., NY (9531 ft.). Nonplanar-c dolomite was dissolved, enlarging the pore space, and leaving the bitumen coats like those shown in Figures 44A and 44B behind.

Geochemical Studies

Introduction

We are in the process of conducting a range of geochemical and fluid inclusion analyses on the Trenton and Black River limestones and dolomites. These analyses are helping to understand the origin of the dolomite in the Trenton and Black River Groups across the study area.

In order to better understand the origin of the dolomite, we have been conducting stable isotope, strontium isotope, trace element and fluid inclusion analyses. The combination of these analyses helps to build confidence in any interpretation. Each of them by themselves can be equivocal but together they can build a strong case. It is our hypothesis that these dolomitized reservoirs are of a fault-controlled hydrothermal origin.

In general, hydrothermal dolomites have:

- Light ^{18}O isotopes (-2 to -18). Oxygen stable isotope values in dolomites are directly dependent on the temperature and composition of the water. If the water has a composition of +5 or +10, even hot fluids can make heavy (positive ^{18}O value) dolomites. Incorporation of CO3 from the precursor limestone could also produce heavier (more positive) ^{18}O values. Because the value of the water and the rock water ratio are not known, these are the least reliable of all of the tests by themselves. When conducted in combination with other analyses, however, they can be very valuable and they also are the least expensive.
- Radiogenic $^{87}Sr/^{86}Sr$ ratio. The radiogenic signature shows that fluids have flowed through continental basement rocks or feldspar-rich sediments overlying the basement. However, there are exceptions, such as mafic basement rocks, resetting and incorporation of original strontium from limestone. All of these can create problems.
- Relatively high Fe and Mn contents. Exceptions: most hydrothermal fluids pick up Fe and Mn in the basement or overlying feldspar-rich sandstones, but some may not. It all depends on the composition of the basement rocks.
- Fluid inclusions with homogenization temperatures >75ºC and salinities between 10 and 30 wt% (average ~20 wt % to 6 times normal seawater).

We also have learned in our early work on this project that there are significant changes in ^{13}C within the limestones and dolomites. Carbon-13 is a stable isotope of carbon that is routinely analyzed when doing stable isotope analysis. These changes in ^{13}C are abrupt and they can be used as a correlation tool when the study interval is sampled and analyzed at different sections. It is believed that these changes reflect secular variations in seawater chemistry so the changes in 13C should occur in all carbonates that are of the same age. This could be a very powerful tool when correlating between long distances. We will test this as a correlation tool on 7 wells.

Preliminary Data

Sampling

In an effort to understand the origin of the dolomite in the Trenton and Black River carbonates, we have sampled all of the different occurrences in the study area (Figure 45). In New York (Figure 46), dolomite occurs in the Black River around faults but is absent from the Trenton. Both matrix and saddle dolomite were observed (Figure 47). Matrix dolomite is gray and replaces what was initially limestone, and in New York samples, the matrix dolomite is generally impermeable. Saddle dolomite, which is white and lines vugs, fractures, zebra fabrics and breccia clasts, also is common. Both of these dolomite types are present in the dolomitized reservoirs of gas fields in New York.

In Ohio, four different dolomite types have been recognized: cap dolomite, facies dolomite, and fracture-related matrix and saddle dolomite (Wickstrom et al., 1992) (Figure 48). The cap dolomite occurs at the top of the Trenton Formation just beneath the Utica Shale and ranges from 10-50 feet thick and is impermeable. It occurs in northwest Ohio (and in parts of Indiana, Michigan and Ontario) but is absent in the rest of the study area. The facies dolomite occurs along the margin of the Sebree Trough in northwest Ohio (Figure 49). This is porous matrix dolomite that can be very coarse (up to 500 microns rhombs). This dolomite is differentiated from the obvious fracture-related dolomite because it generally lacks vugs, fractures and breccias. The dolomite is laterally discontinuous and occurs along linear trends. The "fracture-related" matrix and saddle dolomites are very similar to the dolomite types identified in New York (Figure 50).

Various models have been suggested in the past for these dolomite types. The fracture-related dolomites have long been interpreted to form from hot fluids migrating up faults (hydrothermal dolomite) (Wickstrom et al., 1992). The cap dolomite has been interpreted to form due to compaction of the overlying Utica shale and downward expulsion of magnesium–rich fluids, which were interpreted to have dolomitized the underlying limestone (Taylor and Sibley, 1986). The facies dolomite was interpreted to have formed in a similar fashion: compaction of the shale in the Sebree Trough and lateral migration of dolomitizing brine into the Trenton Group carbonates along the margin.

Wickstrom et al. (1992) suggested that perhaps all of the dolomite was of a fault-controlled hydrothermal origin. They pointed out the main problem with the shale compaction model for the other dolomite types: the Utica Shale overlies the Trenton everywhere but the upper Trenton is only locally dolomitized. In New York, for instance, there is no dolomite at the top of the Trenton anywhere. If this model was valid, the top of the Trenton (and maybe all limestones underlying thick shale sequences) probably should be dolomitized on a regional scale.

In the Kentucky portion of the study area, we are analyzing dolomite from a newly acquired core from an outcrop of fault-controlled dolomite, and from cores in the problematic Jeptha Knob structure (Figure 51). Jeptha Knob is a positive, round feature in outcrop that has been interpreted to be either an impact structure or a tectonic feature. Three cores were analyzed from Jeptha Knob: two were drilled into the core of the structure and one was taken on the flank of the structure.

The two cores from the center of the Jeptha feature show that the internal structure of Jeptha Knob is heavily faulted, fractured and jumbled. From top to base, Core JK-1 has a breccia of unknown affinity, an overturned, 127-foot thick dolomitized bed of High Bridge Group, an overturned, dolomitized bed of Lexington Limestone, a normally-bedded limestone from the Lexington Limestone and a partially-dolomitized, normally-bedded High Bridge (Black River) section overlying the Knox Dolomite. Some beds within the upper part of the core dip from 10 to 90 degrees. Core JK-3 has breccias at the top, which overlie about 800 feet of vertically dipping, dolomitized High Bridge Group. The Trenton and Black River equivalents (Lexington and High Bridge, respectively) in the two cores in the core of the structure have abundant matrix dolomite and porosity (Figure 52). Some of the dolomite is coarse (up to 500 microns) and in many respects it resembles the "facies" dolomite in Ohio.

The core that was taken from off the structure has a few beds of dolomite but is predominantly limestone. There was no obvious white saddle dolomite at Jeptha Knob. In fact, the Trenton and Black River equivalents are all limestone away from the structure.

Those investigators that have interpreted the feature as an impact structure suggest that the asteroid impact induced faults and caused the major disruptions of bedding and the overturned beds. Hot fluids are then interpreted to have used the impact-induced faults to flow upward and dolomitize the strata within the feature but not in the surrounding host rock. An alternative hypothesis is that Jeptha Knob is a positive flower structure associated with underlying wrench faults. The dolomitization would have occurred as it is interpreted to have occurred in Ohio and New York: hot fluids ascended active faults and dolomitized the strata adjacent to the fault zones. Black (1990) pointed out that Jeptha Knob occurs very near the major 38th parallel lineament and interpreted it to be a tectonic feature.

It is important to understand the origin of the dolomite and the porosity at Jeptha Knob for two reasons: it is a positive feature whereas most of the current Trenton-Black River gas production is from structurally-low features; and it is very porous dolomite (estimated at >25%). Positive features such as this one also may produce oil and gas given the appropriate charge/seal scenario. If they are linked to faults and not random impact features, this work may provide an exploration model for positive features associated with wrench faults.

In the core from the Sand Hill well in western West Virginia, there is what appears to be tight, dolomitized, tidal-flat facies in a formation that overlies the Knox Dolomite and underlies the Black River Formation. This is likely to be early reflux dolomite and not hydrothermal in origin. The dolomite is very fine - there are no fractures and there is no saddle dolomite. The fact that the facies type is one that is very commonly dolomitized by evaporate seawater near the surface supports a low temperature origin. This dolomite also was sampled and analyzed.

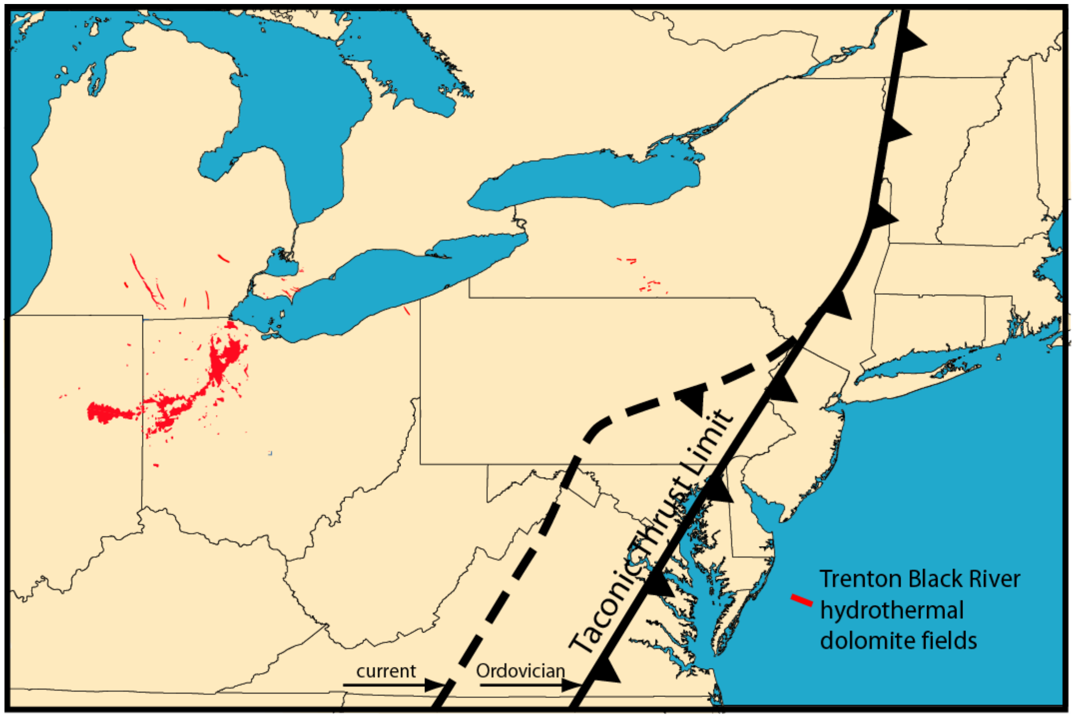


Figure 45. Distribution of Trenton Black River hydrothermal dolomite fields

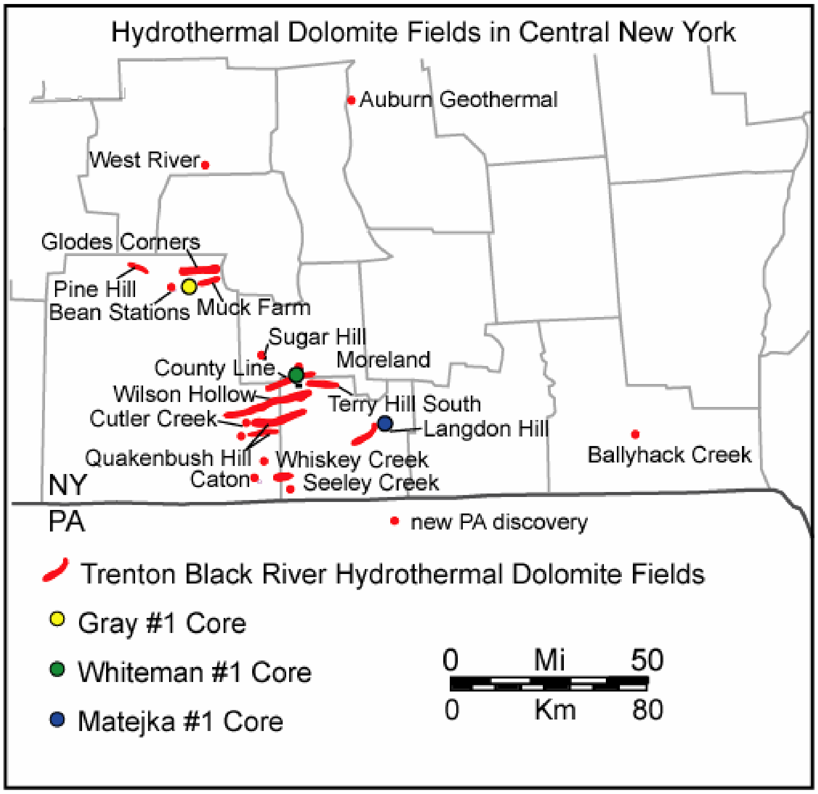


Figure 46. Field map and core locations for south central New York

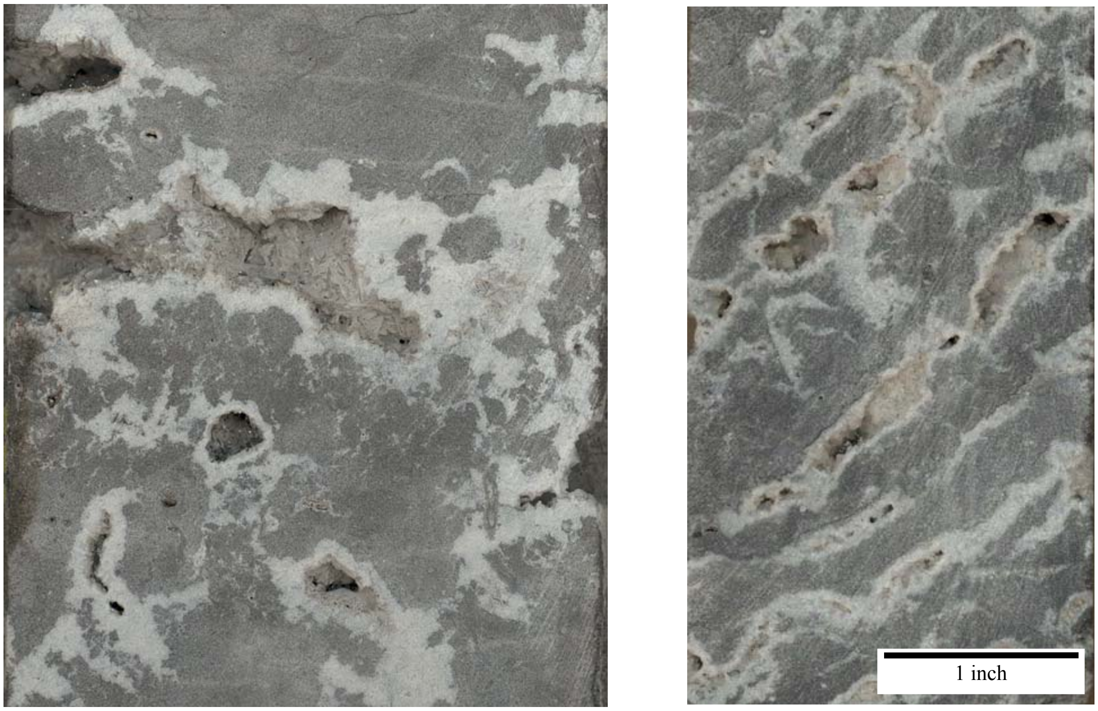


Figure 47. Dolomite from the Gray (left) and Whiteman cores in south central New York. The gray groundmass is the matrix dolomite and the white pore lining mineral is saddle dolomite.

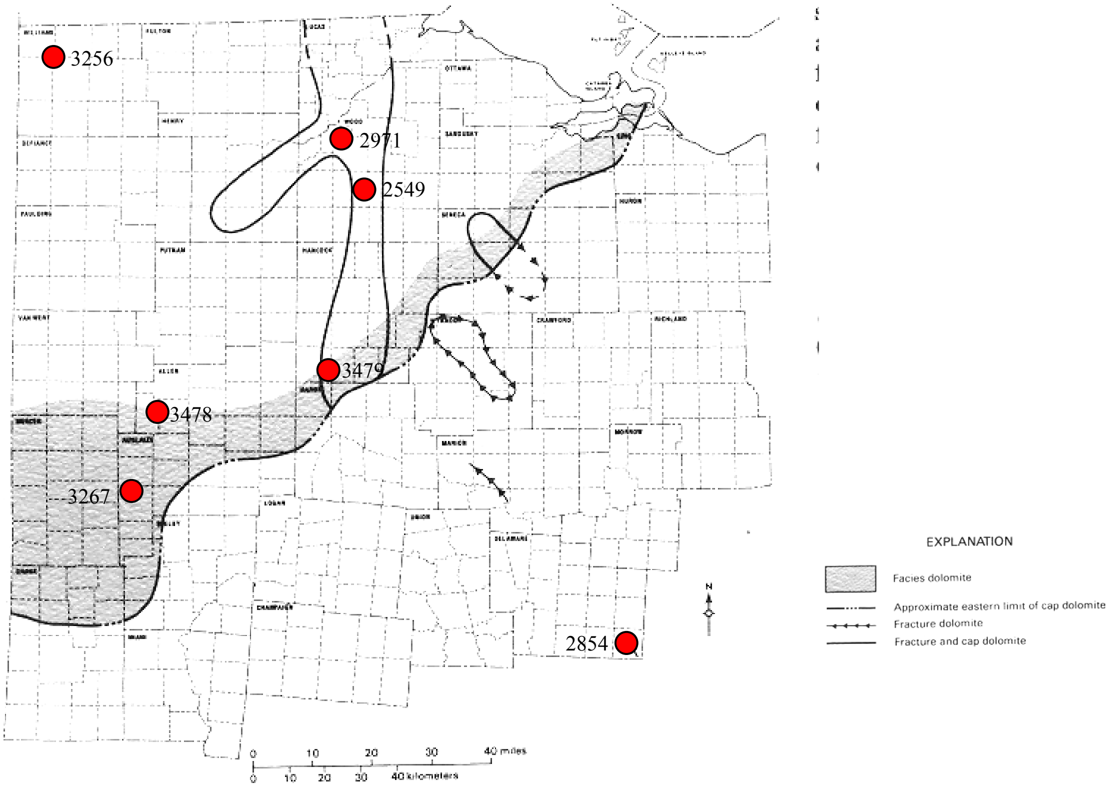
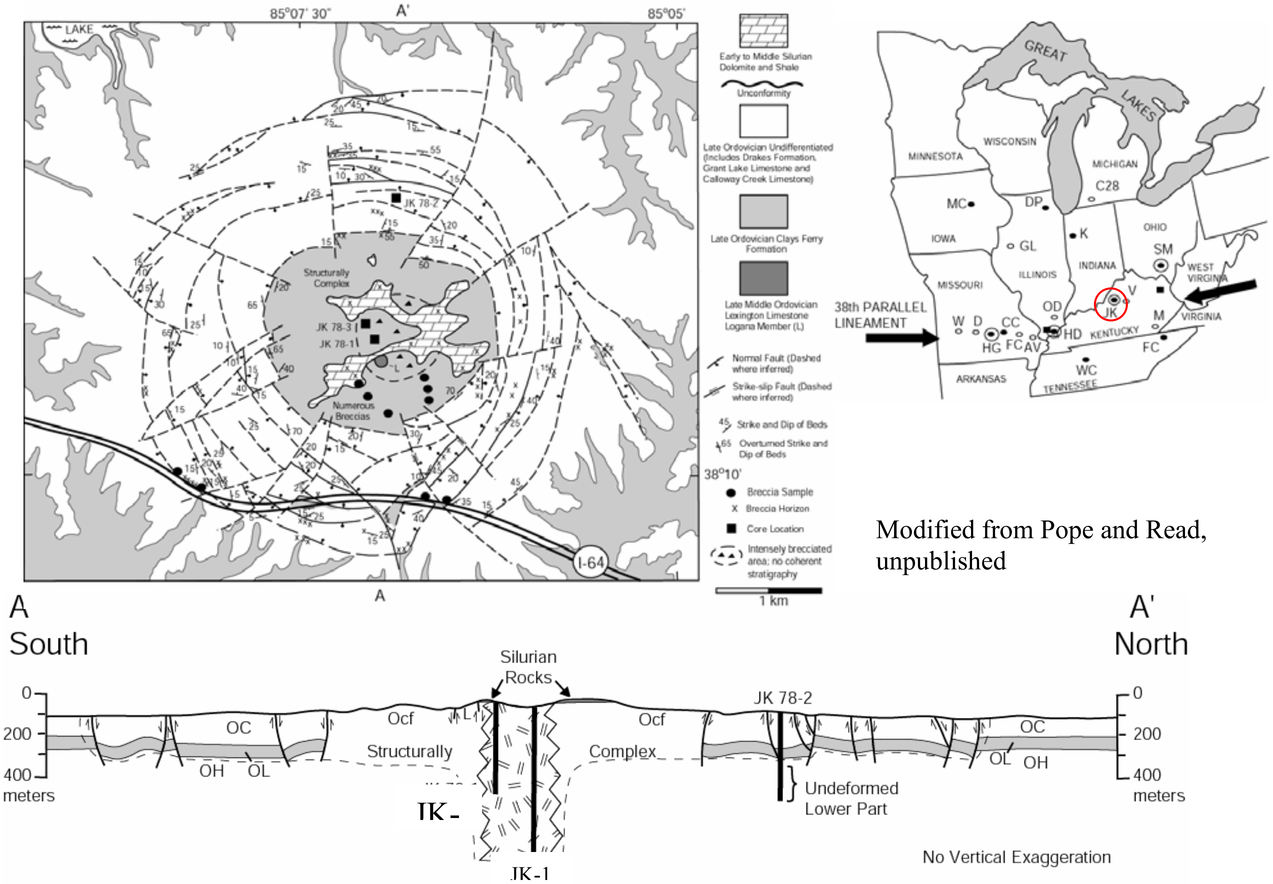


Figure 48. Locations of wells studied and various dolomite types in NW Ohio (from Wickstrom et al., 1992)

Figure 49. Facies dolomite core from NW Ohio with coarse, porous matrix dolomite that was probably a grainstone prior to dolomitization. Scale is in cm.

Figure 50. Left: Breccia with saddle dolomite (white) matrix dolomite (brown) and pyrite (gold) and right: saddle dolomite from cores in obviously fracture related dolomite areas in NW Ohio (sensu Wickstrom et al., 1992).



Modified from Pope and Read, unpublished

Figure 51. Map and cross section of Jeptha Knob, Kentucky. Jeptha Knob is west of Lexington on I-64 and is one of many circular features along the 38th parallel lineament.

Figure 52. Porous dolomite from the Lexington (Trenton) and High Bridge (Black River) Groups in core JK-1 at Jeptha Knob in Kentucky.

Fluid Inclusions

We have conducted fluid inclusion analysis on dolomite samples from New York, Ohio and Kentucky (see sample fluid inclusion in Figure 53). Fluid inclusions were analyzed by Fluid Inclusion Technologies, Inc. for homogenization temperature and salinity. Minerals analyzed include matrix and saddle dolomite, quartz, calcite and anhydrite. The raw data from Fluid Inclusion Technologies will be placed on the project's ftp site (Table 2).

New York Data: Primary fluid inclusions from the saddle dolomite in New York wells have homogenization temperatures between 110 and 170° C with an average of 130°C (Figure 55). 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.

Ohio Data: Primary fluid inclusion data from Ohio shows that all of the dolomite formed at temperatures between 85 and 160°C and that most of it formed between 110 and 160°C (Figure 56). This includes the facies dolomite and the cap dolomite as well as the obviously fracture related matrix and saddle dolomite. Almost all of the dolomite occurred in the Trenton Group. Two facies dolomite wells were sampled and analyzed – Core numbers 3267 and 3479. The fluid inclusion homogenization temperatures for the dolomites from these two wells range from 120-155°C and the salinities range from 13-23 wt%. One cap dolomite well was analyzed (core 3256) and the dolomite there had primary fluid inclusion homogenization temperatures between 105 and 140°C and salinities from 19-23 wt%. Dolomite in the wells with obvious fractures, zebra fabrics and other features normally associated with fault-related hydrothermal dolomites had similar values. Fluid inclusion homogenization temperatures from the saddle dolomite in these wells (2549, 2854, 2971, 3479) had homogenization temperatures between 95 and 160°C and salinities ranging from 19-23 wt%. The average salinity for all the Ohio samples was around 20 wt%.

There was one well that had dolomitization near the base of the Black River around a fault that had very coarse veins of calcite plugging it (Well 3372). The dolomite was finer and there was no saddle dolomite present. The homogenization temperatures were generally lower ranging from 85-95°C. Salinities in the dolomite ranged from 21-23 wt%. The calcite that plugged the fault was very coarse and had common secondary inclusions that had homogenization temperatures that range from 55-75 °C and salinities ranging from 15-20 wt%.

Kentucky Data: Primary fluid inclusion data from Kentucky also suggest that the fluids that made the dolomite were hot and saline, although not as hot as the fluids in Ohio and New York. All of the dolomite fluid inclusion data comes from the Jeptha Knob cores (Figure 57). The dolomites were all matrix dolomite, some of which were quite coarse (some crystals >500 microns). Primary fluid inclusion homogenization temperatures range from 70 to 123°C (most 85 to 115°C). Salinities ranged from 3.5 to 24 wt% with most samples between 15 and 24 wt% (average 17.4 wt%).

The fluid inclusion data suggest that all of the dolomite types analyzed formed from hot saline brines. The dolomite in New York and Ohio formed from fluids that were, on average, hotter than the fluids that made the dolomites in Kentucky (Figure 58). The facies dolomite, cap dolomite and Jeptha Knob dolomite all had values that were similar to the saddle dolomite in New York and Ohio.

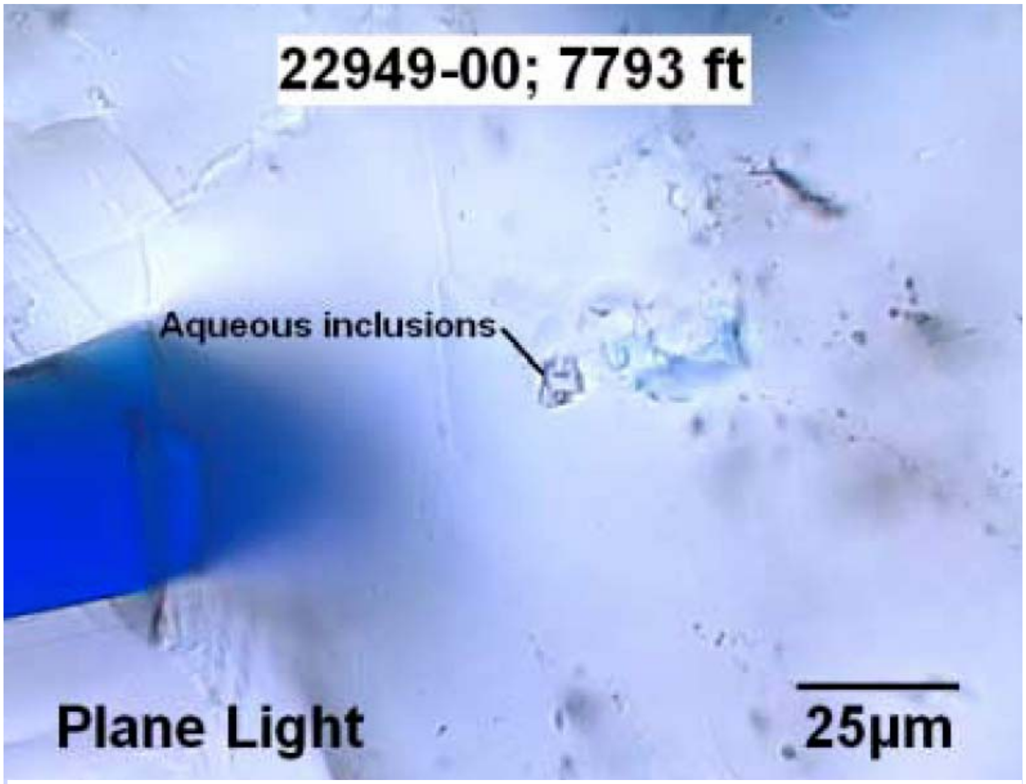


Figure 53. Photograph of fluid inclusion from Whiteman well in New York.

Table 11: Cisco #1-3267;1167 ft						
Population	**Fluor Color**	**Th hc (°C)**	**API hc (°)**	**Th aq (°C)**	**Tm aq (°C)**	**Sal (wt%)**
sec; outer zoned dol A	yellow-wht	110-120 (3)	N/A			
sec; outer zoned dol B	yellow-wht	105-120 (7)	N/A			
pr; dol transect pt1 C				149 (1)	-9.3	13.2
pr; dol transect pt2 C				142 (1)	-11.5	15.5
pr; dol transect pt3 C				138 (1)	-13.2	17.1
pr; outer zoned dol D				145-155 (3)	-11.0 to -12.0	15.0-16.0
pr; outer zoned dol E				150-160 (5)	-10.0 to -11.0	14.0-15.0
pr; outer zoned dol F				135-145 (3)	-14.0 to -15.0	17.8-18.6
pr; outer zoned dol G				145-155 (4)	-13.0 to -13.5	16.9-17.3
pr; outer zoned dol H				130-140 (4)	-14.0 to -15.0	17.8-18.6

Table 2. Sample of results of fluid inclusion analysis.

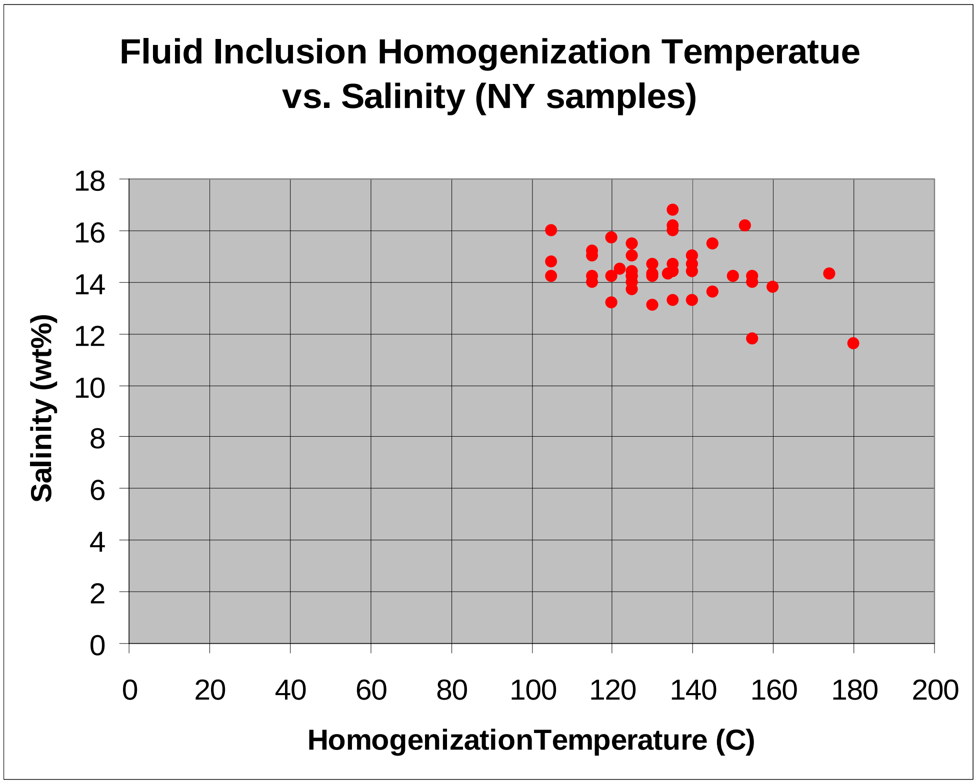


Figure 55. Results of fluid inclusion analysis for New York dolomites.

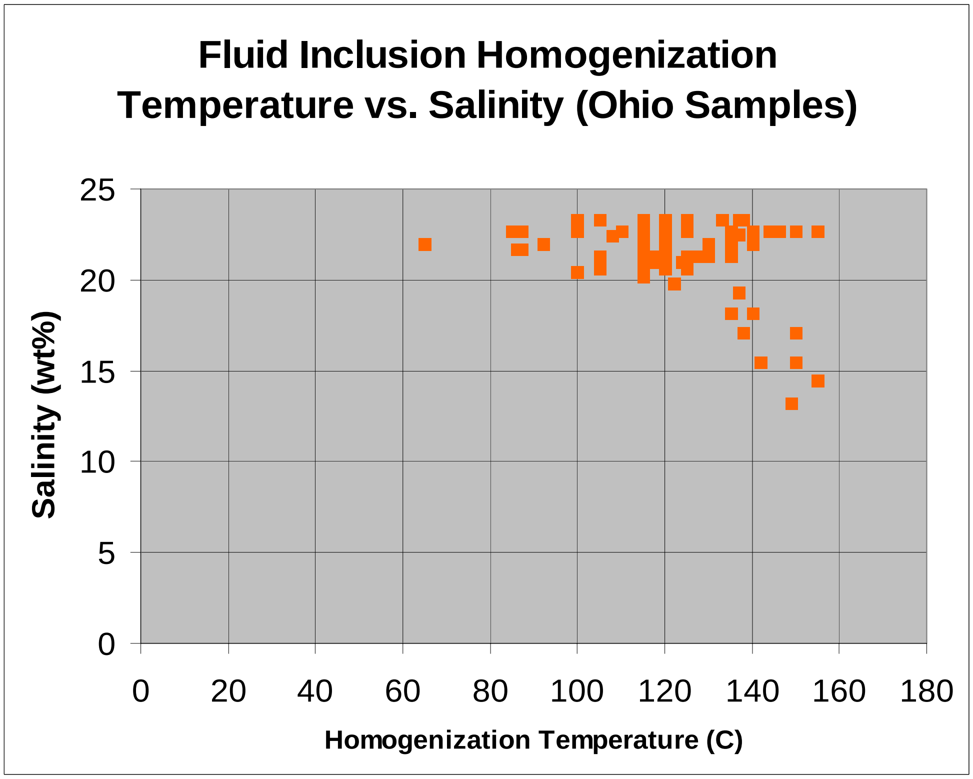


Figure 56. Results of fluid inclusion analysis for Ohio dolomites.

Stable Isotopes

More than 1200 samples have been analyzed for stable isotopes of carbon and oxygen. Steven Howe at the University of Albany did all analyses. Oxygen isotopes were used to help determine the origin of the dolomites. The limestones have $\delta^{18}O$ values between –4.5 and –7.5 ‰ in the Trenton and Black River Groups. Because of the fractionation factor, dolomites that formed from the same seawater should have oxygen isotope values between –1 and –4 ‰. Increased temperature drives stable isotope values toward more negative values, and most hydrothermal dolomites have $\delta^{18}O$ values that are "lighter" or more negative than the associated limestones. This does not always have to be the case, however, and the samples from Jeptha Knob are a prime example. The oxygen isotope value of dolomite is directly controlled by the isotopic composition of the fluid that made the dolomite. The heavier the fluid is, the heavier the $\delta^{18}O$ value will be at a given temperature. So it is possible that dolomites could plot in the range for expected seawater dolomites but still be hydrothermal in origin if the composition of the brine was significantly heavier than the composition of seawater during the time that the limestones were deposited.

New York Data: Stable isotopes of carbon and oxygen were analyzed on all three of the cores (Figure 59). The limestones in the Black River Group of New York 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 ‰. The matrix and saddle dolomites in the Black River have $\delta^{18}O$ values between –9 and –12.5‰.

Ohio Data: Stable isotope values were analyzed for all of the dolomite types in Ohio and they all plot fairly closely together (Figure 60). The cap dolomites had $\delta^{18}O$ values between –6.5 and –10‰. The facies dolomite had values between –7 and –9‰. The matrix dolomites associated with obvious fractures had values between –6.5 and –9‰ and the saddle dolomites had values between –8 and –9‰. These values are all significantly lighter than the expected values from seawater of –1 to -4 ‰.

Kentucky Data: The Jeptha Knob dolomites have $\delta^{18}O$ values between –2 and –7 ‰ with a significant percentage of the samples in the range where one would expect seawater dolomites (-1 to –4‰) (Figure 61). As noted earlier, this does not necessarily rule out a higher temperature origin for the dolomites. One must first learn the isotopic composition of the fluid before interpreting the origin of the dolomite.

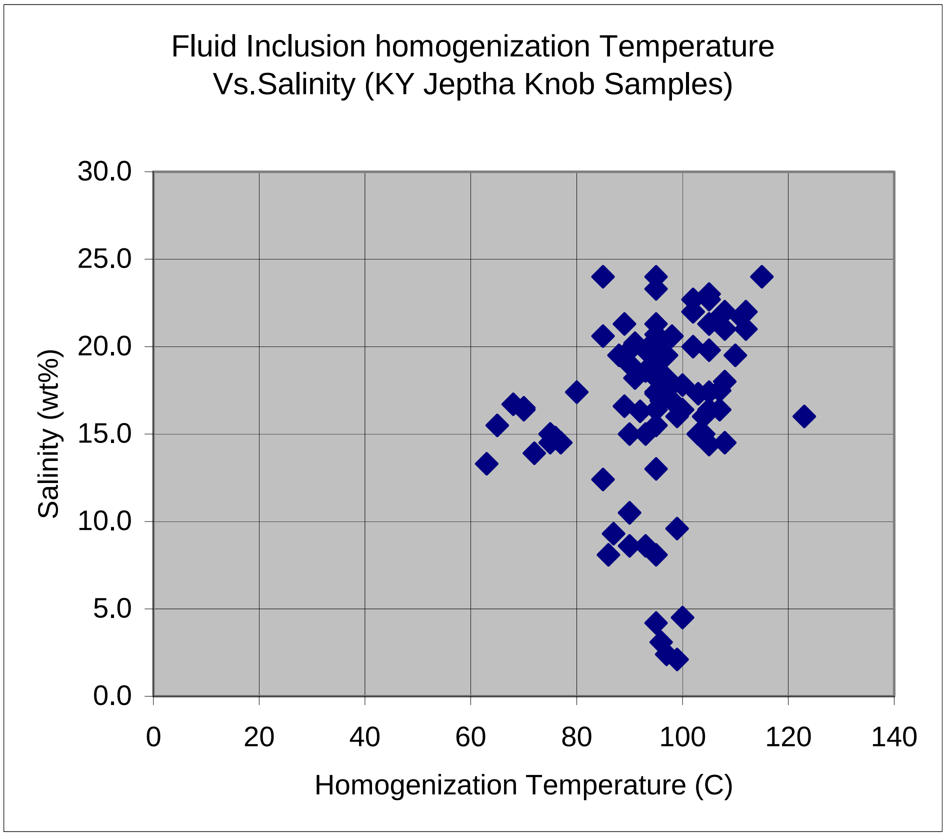


Figure 57. Results of Jeptha Knob dolomite fluid inclusion analysis.

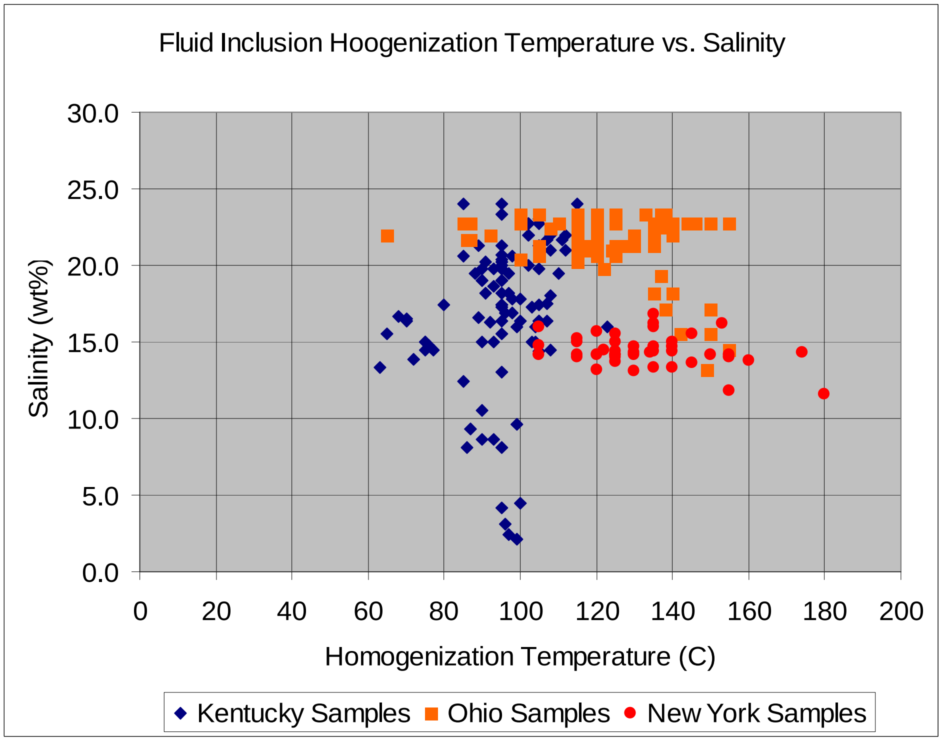


Figure 58. Results of all fluid inclusion analysis to date.

Isotopic Composition of Dolomitizing Brines: The isotopic composition of the dolomitizing brines can be determined by plotting $\delta^{18}O$ values and fluid inclusion homogenization temperatures from the same samples on a graph developed by Friedman and O'Neil (1977) (Figure 62). This shows that the fluids that made the dolomites in New York averaged around +2‰ and the fluids that made the dolomites in Ohio and Kentucky averaged around +4‰ (Figure 63). These values are typical of subsurface brines. Because the fluid that made the dolomite at Jeptha Knob was 10‰ heavier than Late Ordovician seawater from which the limestones were deposited, the dolomites plotted where one would expect seawater dolomites, even though they formed at elevated temperatures.

Trace Elements

Seawater has very little iron or manganese in it because these elements are readily oxidized. Therefore, the concentrations of each of these elements in seawater is less than .002 ppm. Dolomites that form from seawater should, therefore, have very low Fe and Mn concentrations. Subsurface brines, on the other hand, are commonly enriched in these elements. Consequently, dolomites that form in the subsurface commonly have high Fe and Mn concentrations.

The saddle dolomites in Ohio have Mn concentrations averaging 1200 ppm and Fe concentrations averaging around 8000 ppm. The matrix dolomites have Mn concentrations of around 450 ppm and Fe concentrations around 8000 ppm. The New York dolomites have Fe concentrations averaging around 4200 ppm and Mn concentrations of around 880 ppm (Figure 64). The Kentucky dolomites have average Fe concentrations of around 5000 ppm and Mn concentrations of around 550 ppm. The average values for the limestones are an order of magnitude lower (around 500 ppm for Fe and 50 ppm for Mn). This supports a subsurface origin for all of these dolomites.

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 seawater for the time that the Trenton and Black River formed is between 0.7078 and 0.7085 (Figure 65). So dolomites with values that are higher than 0.7085 are likely to have formed from fluids that passed through the basement or immature siliciclastics prior to making the dolomite. Limestones are generally more enriched in Sr than the dolomites, so some matrix dolomites may inherit seawater values for $^{87}Sr/^{86}Sr$ from the limestones they replace.

New York Data: 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 just above the range for Ordovician. 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

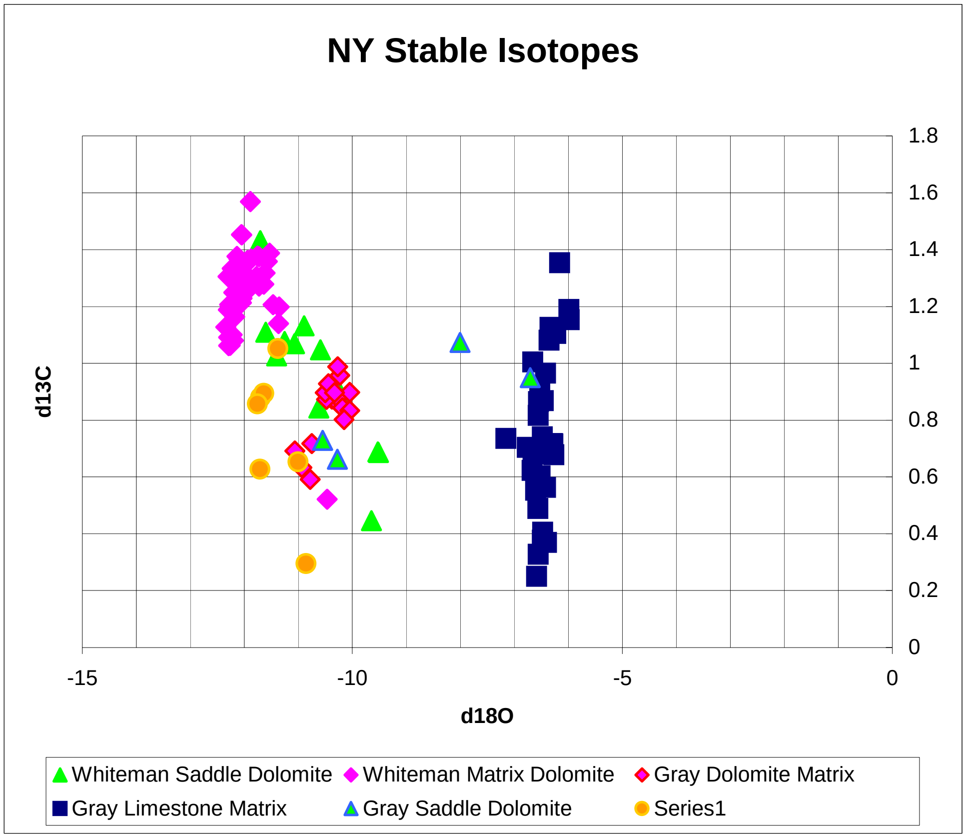


Figure 59. Stable isotope data from New York. Series 1 is matrix dolomite from the Matejka well.

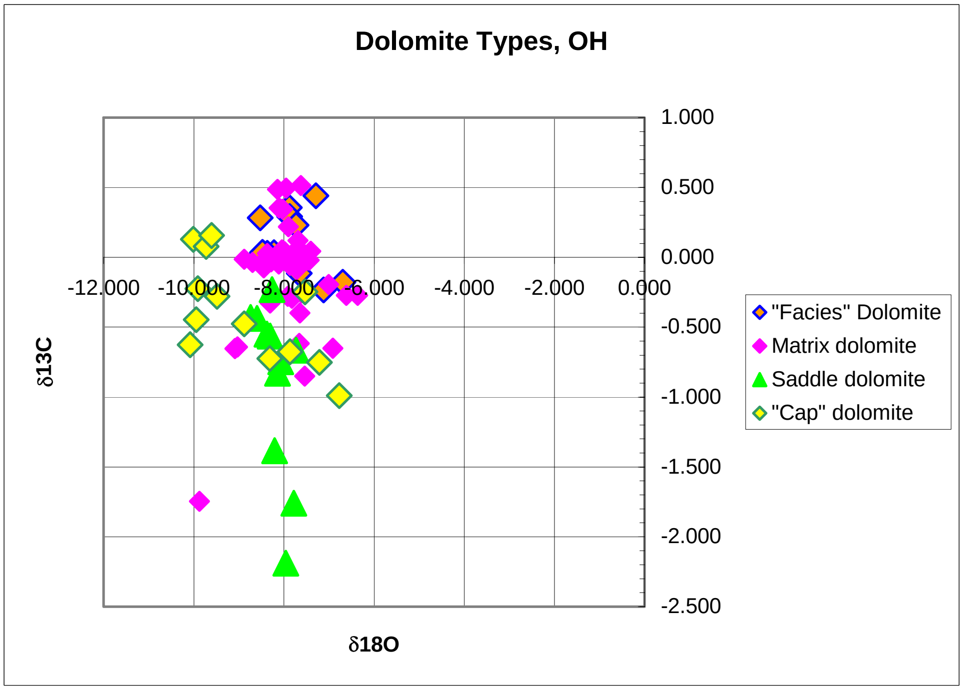


Figure 60. Stable isotope data from Ohio dolomites.

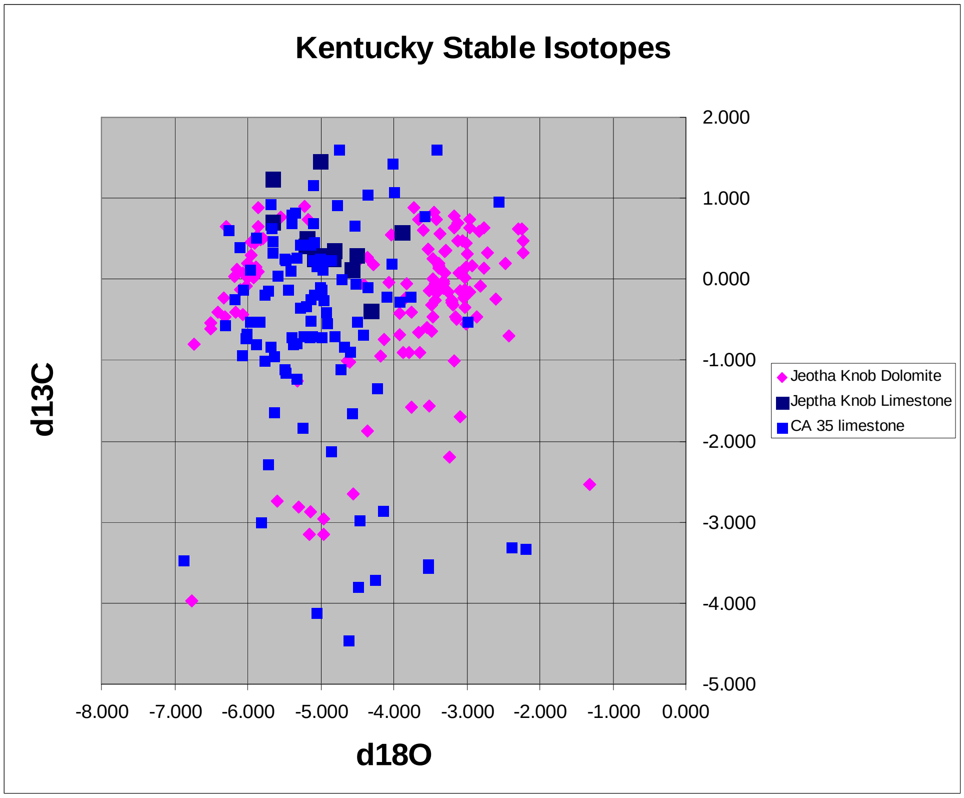


Figure 61. Stable isotope values from Kentucky Jeptha Knob dolomites and limestones.

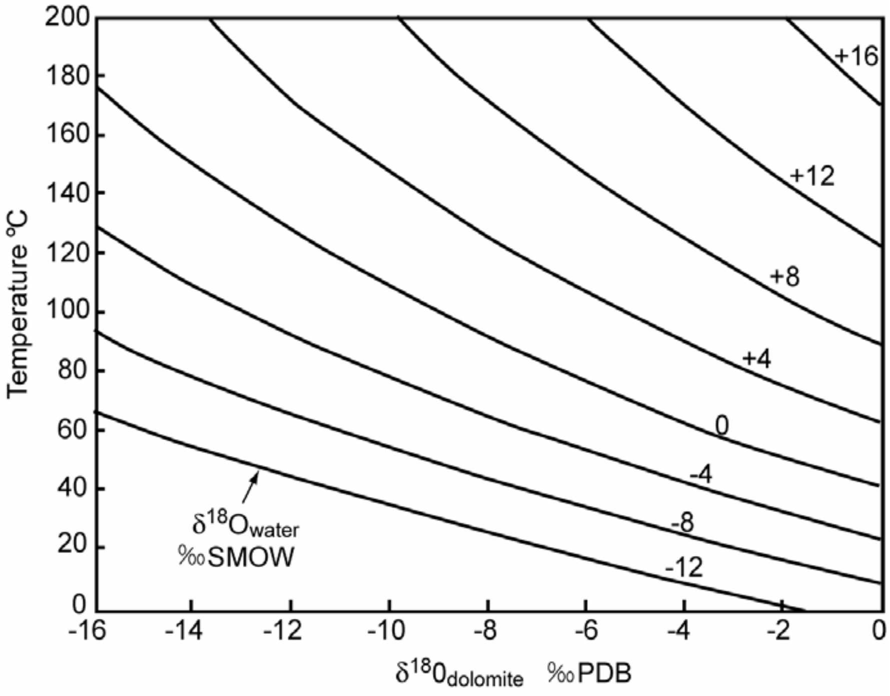


Figure 62. Chart used to determine fluid composition by plotting homogenization temperature and δ^{18}O values for same sample. Note how fluid composition can greatly alter δ^{18}O values of dolomites.

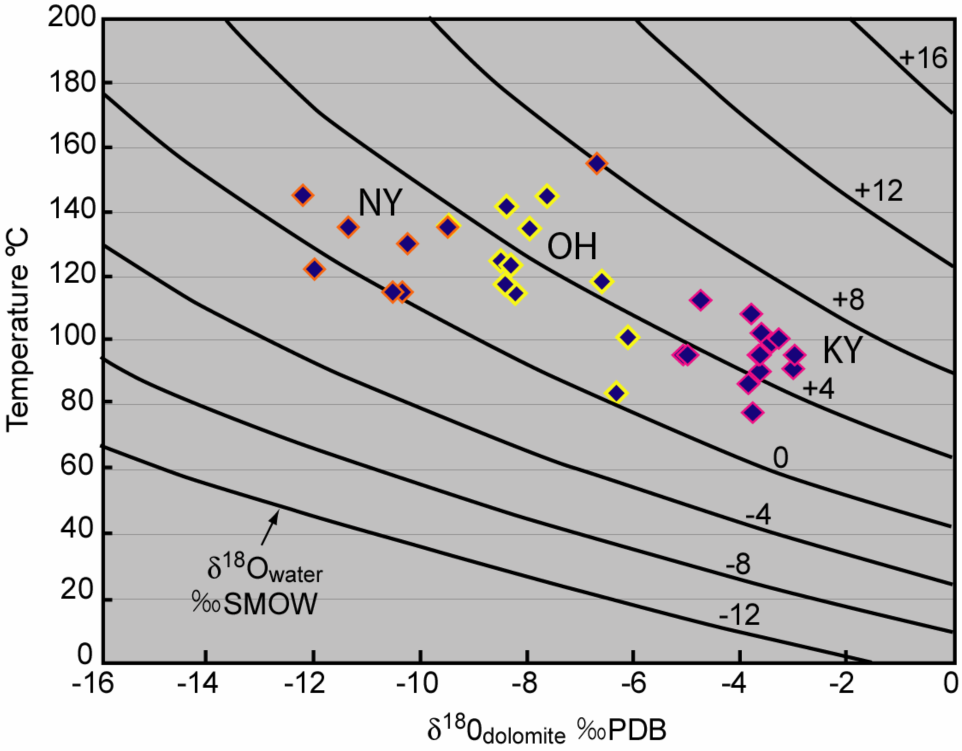


Figure 63. Data from New York, Ohio and Kentucky plotted on Figure 18. NY fluid looks like it was a bit lighter (~+2‰) than the fluid in KY and OH (around +4 or +5‰).

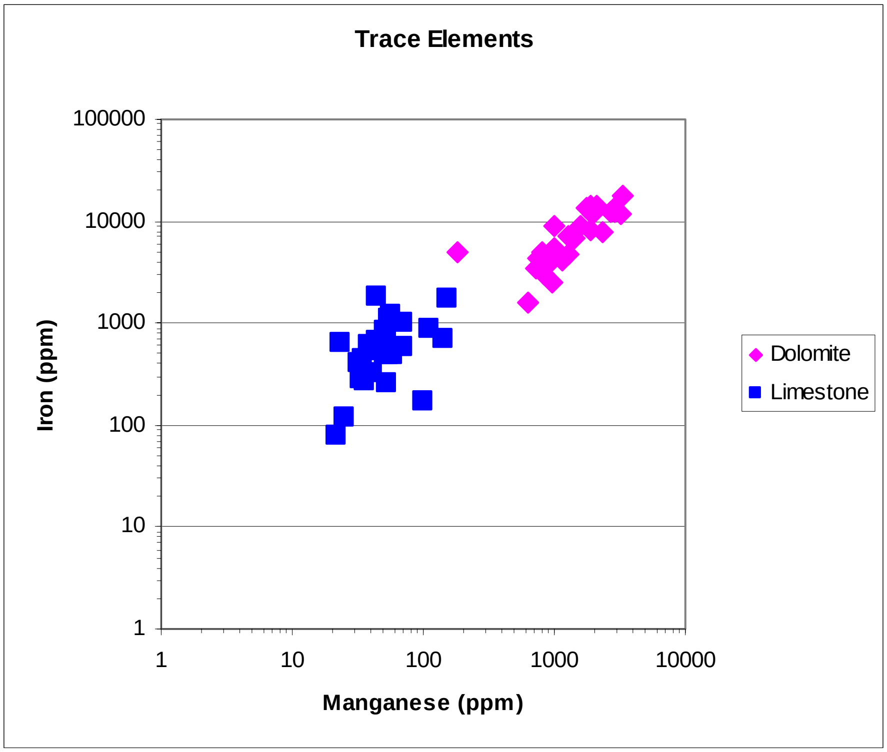


Figure 64. Trace element data from New York.

f

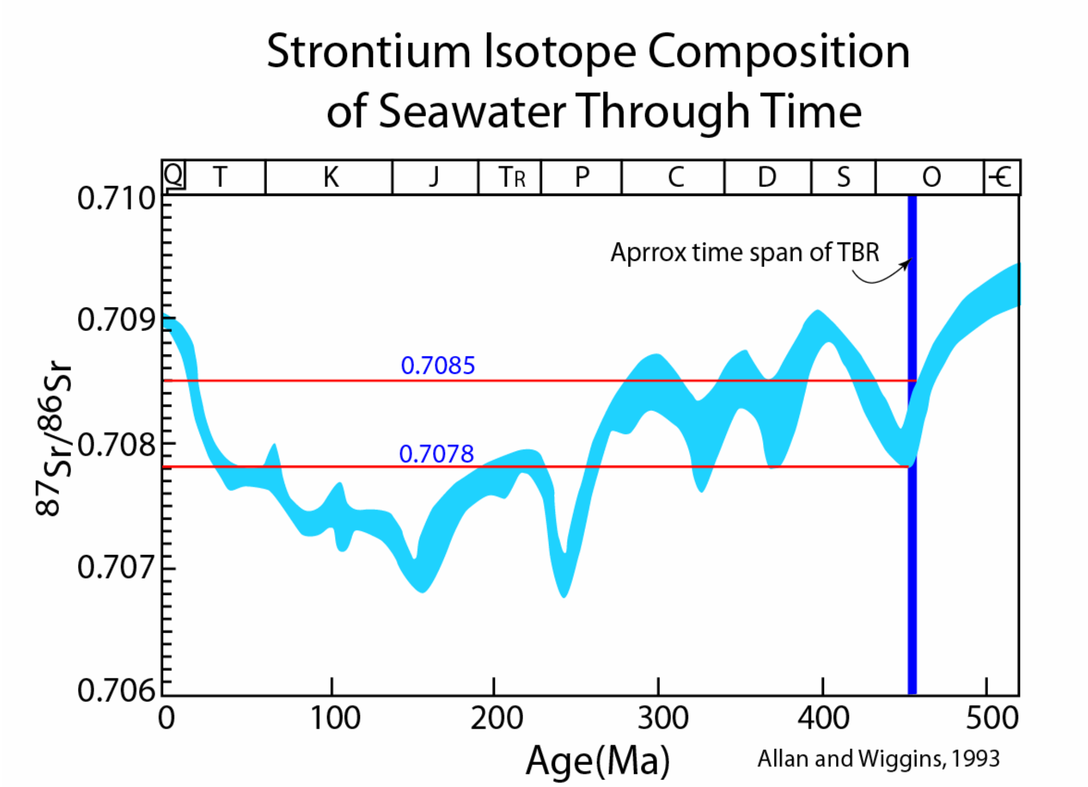


Figure 65. Strontium isotope ratio curve for seawater through time with range for Trenton and Black River seawater highlighted. The ratio decreased with time from the Black River to the Trenton.

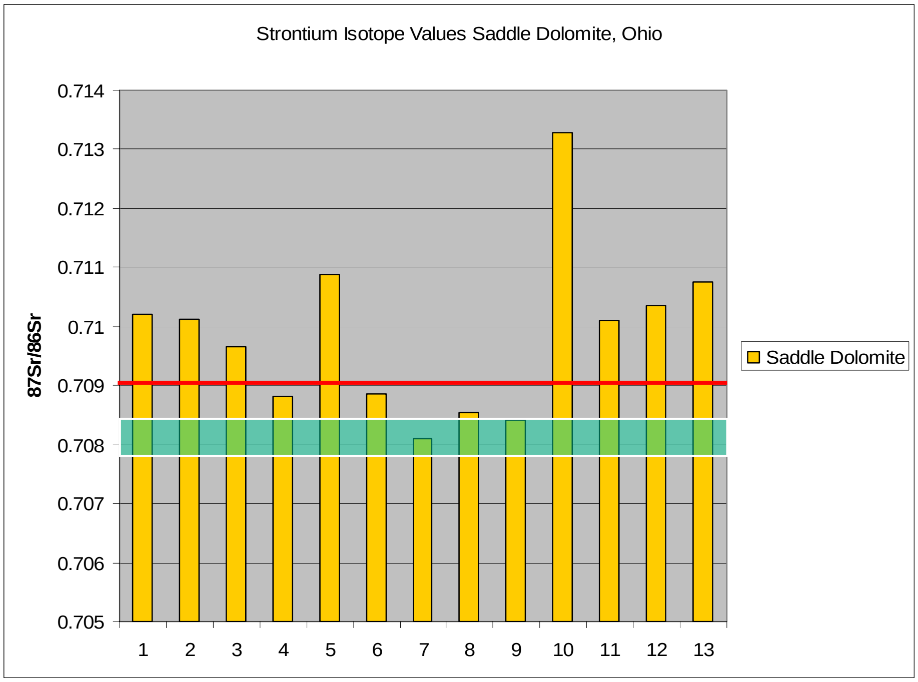


Figure 66. Strontium isotope ratios for saddle dolomite in Ohio samples. All but one sample exceeds the seawater ratio (shaded in green) for Trenton Black River time. Many exceed the all time maximum ratio for seawater (red line).

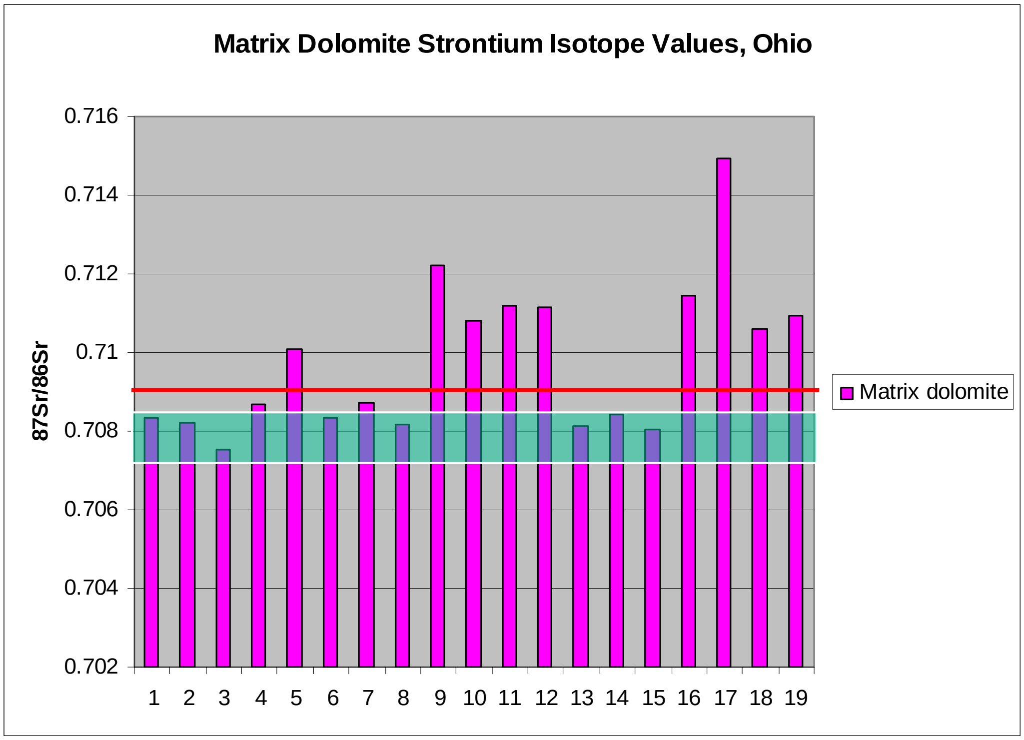


Figure 67. Strontium isotope ratios for matrix dolomite in Ohio samples. About half the samples fall within the seawater range and half exceed it.

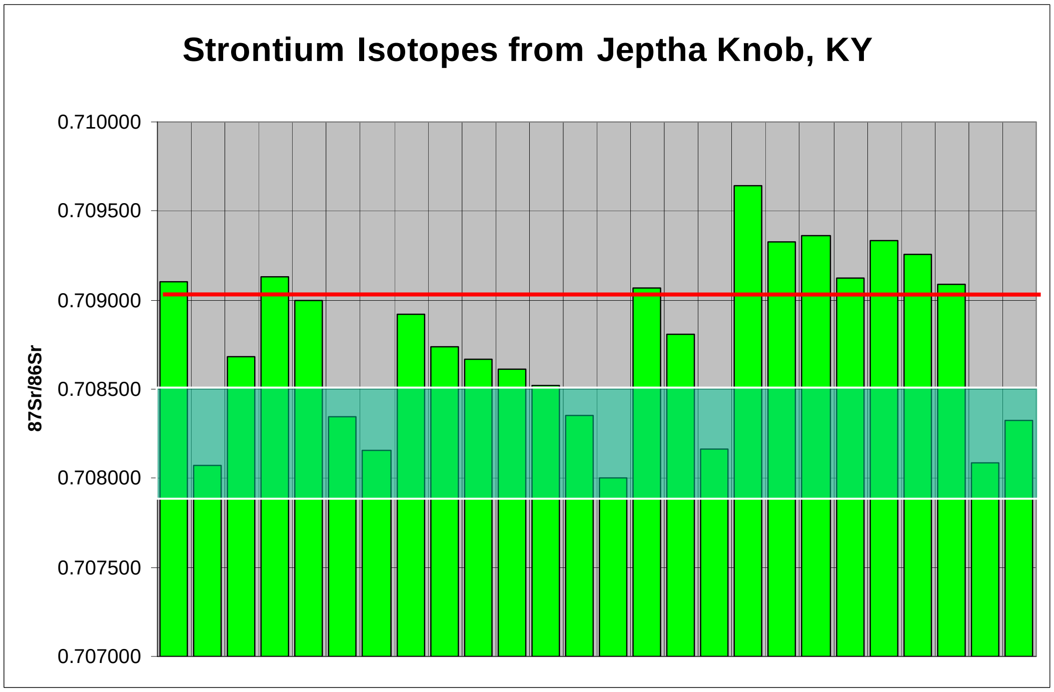


Figure 68. Strontium isotope ratios for Jeptha Knob dolomite in Kentucky. Eight of 26 samples occur within the seawater range and the rest are higher.

feldspar-rich siliciclastics prior to making the dolomite. Again, this analysis supports a subsurface origin for the dolomites where the fluid that made them flowed up from the basement or underlying immature siliciclastics.

Ohio Data: The saddle dolomites range from 0.7083 to 0.714 with all but one sample plotting above the upper limit for Trenton Black River seawater (Figure 66). The matrix dolomites from Ohio have ^{87}Sr/^{86}Sr ratios ranging from 0.708 to 0.715 (Figure 67). About half of the samples have values within the range of Late Ordovician seawater. The generally lower values for the matrix dolomites suggests that they may have reused much of the strontium from the limestones while the saddle dolomites precipitated directly from the fluids flowing up the faults and more accurately reflect the composition of the dolomitizing brine.

Kentucky Values: The Jeptha Knob samples have ^{87}Sr/^{86}Sr ratios between 0.708 and 0.7096 with 8 of 26 measurements plotting in the seawater range and the rest above the seawater range (Figure 68). Again, since these dolomites are all matrix dolomites, some strontium from the limestones may get reused.

The strontium isotopes suggest that the fluids that made the dolomite passed through continental basement rocks or immature feldspar-rich siliciclastics prior to making the dolomite. This supports a bottom-up fluid flow path and a likely hydrothermal origin. The fact that the matrix dolomites generally have lower values suggests that they may reuse some of the strontium from the limestones they replace.

Summary of Preliminary Geochemistry Results

The fluid inclusion and geochemistry results to date support a hydrothermal origin for all of the dolomite types that occur in the Trenton and Black River Groups across the study area. The fluid inclusion homogenization temperatures suggest that the dolomite formed at temperatures between 85 and 160°C with generally higher temperatures in New York and Ohio and slightly lower temperatures at Jeptha Knob in Kentucky. The fluid that made the dolomite was a saline brine. The salinity of the fluid inclusions averaged around 14.5 wt% in New York, 17 wt% in Kentucky and about 20 wt% in Ohio. These values are 4 to 6 times the salinity of normal seawater. The oxygen isotope composition of the brine was about +2‰ in New York, and +4 ‰ in Ohio and Kentucky. The dolomite is enriched in iron and manganese supporting a subsurface origin for the dolomitizing brine. The dolomite also commonly has radiogenic ^{87}Sr/^{86}Sr values, which suggests that the fluid passed through basement rocks or immature siliciclastics prior to making the dolomite. All of these support a hot subsurface origin for the dolomites.

Hydrothermal or Geothermal?

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 given 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 efficient 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 confined 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 laterally through the formation (Deming, 1992).

Hydrothermal alteration is thought to occur when relatively high-pressure, high-temperature fluids flow up active faults and into permeable formations that underlie sealing shales, evaporites 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). When fluids first enter the formation from the faults they may have significantly different pressure, temperature and composition than the fluids in the host rock. Because the fluids are introduced geologically instantaneously, they can overcome rock buffering and are capable of producing significant diagenesis in short periods of time. With time, the fault-derived fluids mix with fluids in the formation and eventually equilibrate with the ambient conditions. Further diagenesis is likely to occur during these periods of fluid mixing and equilibration. Hydrothermal dolomitization would most likely occur during periods of pressure drop by highly supersaturated fluids. The curved shape of saddle dolomite crystals is probably a result of precipitation from *highly* supersaturated fluids (Davies, 2001; Machel, 2004). The most efficient way to introduce a fluid that is highly supersaturated with respect to dolomite into a regional limestone is via faults and fractures.

Machel and Lonee (2002) suggested that hydrothermal dolomite needs to be distinguished from “geothermal” dolomite, which forms from fluids that are the same temperature as the surrounding rocks. Geothermal dolomite is thought to form from fluids that flow laterally or very slowly in a vertical sense.

Demonstration of a hydrothermal vs. geothermal origin for dolomites and other minerals can be done in different ways. As a first pass, field relations can strongly suggest a hydrothermal origin. 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, 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. Although compelling, this evidence is still viewed as equivocal support for a hydrothermal origin because the fluids could theoretically have flowed very slowly up the faults and dolomitized the limestone at near ambient temperatures.

The most convincing 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). 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 51). This does not mean that the dolomites in New York are not hydrothermal in origin, just that the formation was buried to a temperature that exceeded the temperature at which the dolomites formed. If the dolomitization was during early burial when the ambient temperature was still <100°C the dolomite would still be considered to be hydrothermal in origin.

Confirmation of hydrothermal origin for similar Trenton-Black River hydrothermal dolomites comes from Ontario, Michigan and northwest Ohio (Figure 67). In most respects, the dolomitized zones 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 was never buried more than a kilometer (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 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 meters in this area (fluid inclusions analyzed for this report and CAI data from Rowan et al., 2004 – Figure 70). Therefore, the Trenton-Black River dolomites are unequivocally hydrothermal in Ohio, Michigan and Ontario. The Kentucky dolomites are also likely to be hydrothermal. If one extends the trendlines from the Rowan et al. data across the Kentucky border it appears that Jeptha Knob also was probably never buried more than a kilometer yet has fluid inclusion homogenization temperatures in excess of 100°C. The dolomites from those fields 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.

It appears that all of the dolomite types in Kentucky and Ohio (including Jeptha Knob, the facies and cap dolomite types) are hydrothermal in origin. Their fluid inclusion temperatures for all those dolomite types exceed the established local maximum burial temperatures. Even though saddle dolomite is not present, these dolomites are still hydrothermal in origin. This work will have lasting scientific value because it is demonstrating that dolomite can be hydrothermal in origin yet have no obvious saddle dolomite or vugs. It is interpreted that the fluids are still sourced from faults, but that the matrix was more permeable at the time of dolomitization so fluids flowed farther from the fault source, dolomitizing the limestone without significant pressure related features such as zebra fabrics or breccias forming in abundance.

Implications for Oil and Gas Exploration

This work shows that hydrothermal dolomite occurs in three of the five states included in the study. Outcrop observations and recent drilling success show that it occurs in Pennsylvania as well. Data limitations in West Virginia do not allow an interpretation at this time.

This work also suggests that hydrothermal dolomite reservoirs may be found in other structural settings besides negative flower structures or sags. The "facies" dolomite in northwest Ohio occurs along a carbonate margin likely to be controlled by a NE-SW trending normal fault that is down to the southeast. Jeptha Knob is a positive feature (that is also likely to be related to strike-slip faulting) that has great porosity and would make an excellent reservoir given the right burial depth/charge/trap scenario.

Future Work –Geochemistry

We are still sampling and analyzing samples from Kentucky, Pennsylvania and Ohio. Data also have been culled from the literature for dolomites in Michigan and Ontario. All of these data will be integrated and presented in both raw form and in more polished formats. We also have analyzed 6 wells for 13C stratigraphy. The early work has demonstrated great potential with this method. A full presentation and analysis of this method will be included in the final report.

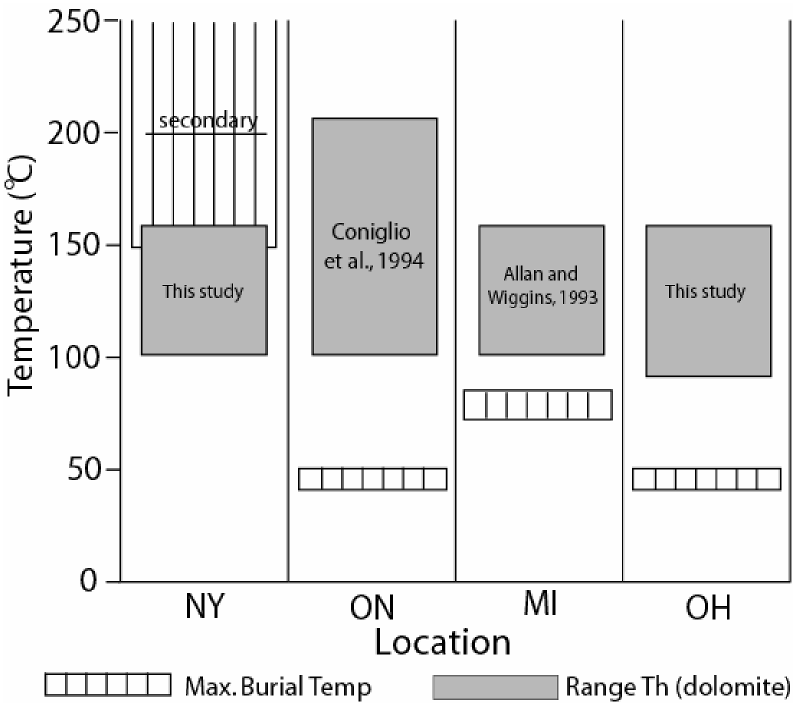


Figure 69. Maximum burial temperatures and fluid inclusion homogenization temperatures from saddle dolomites in Trenton Black River reservoirs. Dolomites in OH, MI and ON are unequivocally hydrothermal, NY experienced higher burial temperatures than are recorded in the fluid inclusions.

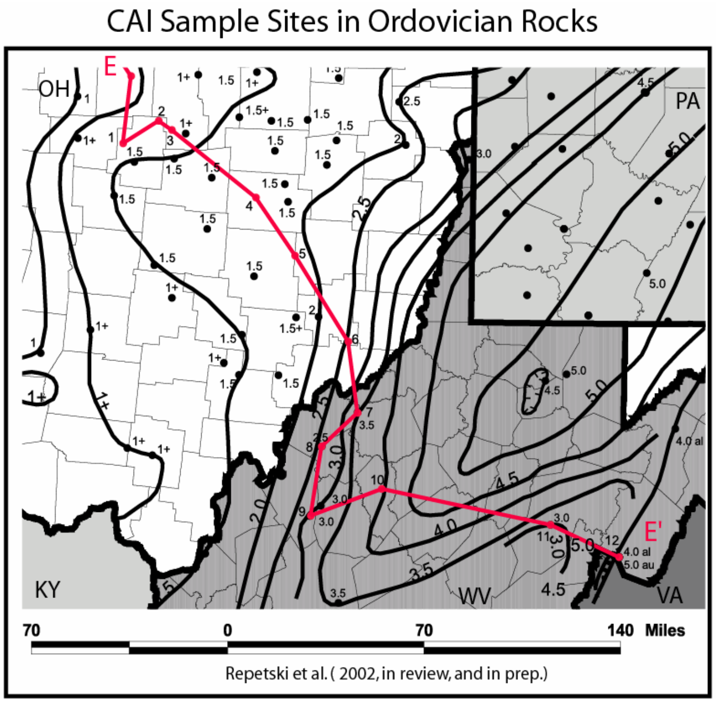


Figure 70. CAI values for Utica Shale in OH, western PA and WV. CAI values of 1-1.5 in NW Ohio and probably in northern KY suggest very low burial temps.

Analysis of Production Data and Histories, and Horizontal Well Technology

Data were gathered from the Ohio and West Virginia Geological Survey databases in preparation for analysis and mapping in the next calendar quarter. Key fields are being selected for comparison of reservoir character and production performance.

Database, GIS and Website Management

During this reporting period, a new development PC and flat screen monitor were purchased, because the previous system was becoming inadequate for growing project needs. In addition, an upgraded version of the database package was purchased and will be installed in the near future.

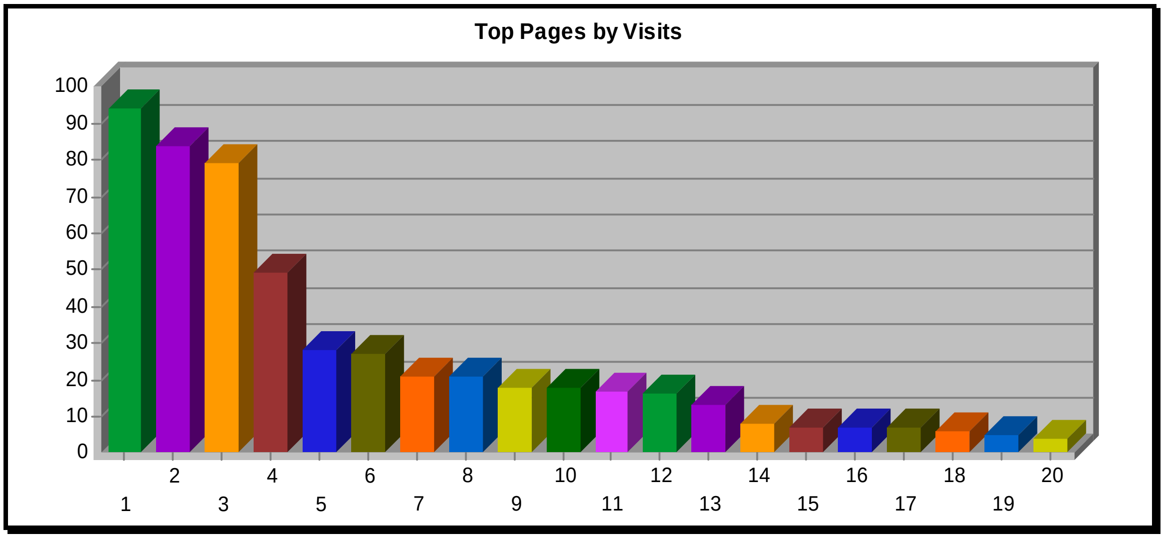
Current technical issues for this period are centered on database development and deployment. Some redesign of the original model was necessary as new data became available. Deployment within an interactive web framework (non-IMS) will occur within the second quarter of CY 2005. Log files (LAS and log images) will be the first in this implementation. Well production data, as received to-date, are being reformatted for standard relational database management system requirements.

The user/password authenticated website has a total of 55 activated members to date: 34 individuals from our industry partners and 21 survey research team individuals—an increase of 16 and 1, respectively, since the last reporting period. General statistics of use and top pages viewed are provided in the tables below.

Table 3. General Statistics of Trenton Project Website Visits Over Time by Visitors Outside WVGES – 1st Quarter, 2005

General Statistics	
Hits	
Successful Hits For Entire Site	1,155
Average Hits Per Day	12
Home Page Hits	6
Pages	
Page Views (Impressions)	411
Average Per Day	4
Dynamic Pages and Forms Views	65
Document Views	346
Visits	
Visits	81
Average Per Day	0
Average Visit Length	00:10:11
Visits of Unknown Origin (e.g., domain name undetermined)	58.02%
Visitors	
Unique Visitors	45
Visitors Who Visited Once	33
Visitors Who Visited More Than Once	12

Table 4. Top Pages by Visits Outside WVGES – 1st Quarter, 2005



Top Pages by Visits – January to March 2005				
	Visited Pages	**Visits**	**%**	**Avg Time Viewed**
1.	Default Login Page (default.asp)	94	17.15%	00:00:27
2.	Home Page (welcome.asp)	84	15.33%	00:00:24
3.	Trenton Gateway Page (index.html)	79	14.42%	00:00:11
4.	Logout Page (logout.asp)	49	8.94%	00:01:43
5.	LAS Files Page (las.asp)	28	5.11%	00:01:55
6.	Default non-Trenton index page for server (index.html)	27	4.93%	00:00:08
7.	Basemap Introduction Page (basemapintro.asp)	21	3.83%	00:00:30
8.	Technical Presentations from Meetings (technical_presentations.asp)	21	3.83%	00:03:29
9.	Basemap Page (basemap.asp)	18	3.28%	00:00:01
10.	Contents Frame for Basemap Page (contents.asp)	18	3.28%	00:04:44
11.	March 29th Meeting Page (05/050329meeting.asp)	17	3.10%	00:01:56
12.	Trenton Members Listing (members.asp)	16	2.92%	00:02:16
13.	Default for Erroneous Login *(accessdenied.asp)*	13	2.37%	00:00:11
14.	Default Trenton Index for server via internal suffix only	8	1.46%	00:00:05
15.	Default non-Trenton Index for server via internal suffix only	7	1.28%	00:00:04
16.	Default non-Trenton Index for server via IP only	7	1.28%	00:00:00
17.	Semi-Annual Report, October 2004 (41856R02.asp)	7	1.28%	00:07:50
18.	Semi-Annual Report, April 2004 (41856R01.asp)	6	1.09%	00:02:42

Top Pages by Visits – January to March 2005				
	Visited Pages	**Visits**	**%**	**Avg Time Viewed**
19.	Trenton Technical Proposal (technical_proposal.asp)	5	0.91%	00:02:17
20.	Bibliography of Trenton Related Documents (bibliography.asp)	4	0.73%	00:00:53
	Subtotal	**529**	**96.53%**	**00:00:48**
	Other	**19**	**3.47%**	**00:02:19**
	Total	**548**	**100.00%**	**00:00:50**

CONCLUSIONS

From the Structural and Seismic Task:

- Basement faulting (often with a wrench component), structural sags and hydrothermal dolomite within the Trenton-Black River carbonates can indicate possible traps and reservoirs.
- The nature of the basement differs in New York as compared to the southern part of the basin. No evidence of Cambrian syntectonic sedimentation in New York has been observed. In contrast, Cambrian syntectonic sedimentation is apparent in Pennsylvania, West Virginia and Kentucky.
- The seismic character of the Trenton-Black River interval as observed in wavelet form and amplitude change across the basin. This change reflects lithologic changes shown on the stratigraphic maps being prepared.

From the Stratigraphy Task:

- Basin architecture appears to control deposition of carbonates and shales and may be structurally controlled.
- Fault-related structural control along platform margins influenced the formation of hydrothermal dolomite reservoirs in original limestone facies deposited in high energy environments.
- The use of the term "Sebree Trough" is not recommended.

From the Petrology and Geochemistry Tasks:

- Sufficient porosity and permeability leading to commercial quantities of petroleum accumulation appear to be restricted to areas where secondary porosity developed in association with hydrothermal fluid flow along faults related to basement tectonics.
- The geochemical and fluid inclusion analyses all support a hydrothermal origin for dolomites in the Trenton and Black River Groups.

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LIST OF ACRONYMS AND ABBREVIATIONS