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

Semi-Annual Report

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Principal Authors:

Douglas G. Patchen, Taury Smith, Ron Riley, Mark Baranoski, David Harris, John Hickman, John Bocan and Michael Hohn

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West Virginia University Research Corporation
P.O. Box 6845, Morgantown, WV 26506-6845

University of Kentucky Research Foundation
109 Kinkead Hall, Lexington, KY 40506-0057

New York State Museum Institute
Room 3140 CEC, Albany, NY 12230

Ohio Division of Geological Survey
4383 Fountain Square, Columbus, OH 43224

Pennsylvania Geological & Topographic Survey
400 Waterfront Drive, Pittsburgh, PA 15222-4745

West Virginia Geological & Economic Survey
1 Mont Chateau Road, Morgantown, WV 26508-8079

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ABSTRACT

Preliminary isopach and facies maps, combined with a literature review, were used to develop a sequence of basin geometry, architecture and facies development during Cambrian and Ordovician time. The main architectural features – basins, sub-basins and platforms – were identified and mapped as their positions shifted with time. This is significant because a better understanding of the control of basin geometry and architecture on the distribution of key facies and on subsequent reservoir development in Ordovician carbonates within the Trenton and Black River is essential for future exploration planning. Good exploration potential is thought to exist along the entire platform margin, where clean grainstones were deposited in skeletal shoals from Indiana thorough Ohio and Ontario into Pennsylvania. The best reservoir facies for the development of hydrothermal dolomites appears to be these clean carbonates. This conclusion is supported by observations taken in existing fields in Indiana, Ontario, Ohio and New York. In contrast, Trenton-Black River production in Kentucky and West Virginia has been from fractured, but non-dolomitized, limestone reservoirs. Facies maps indicate that these limestones were deposited under conditions that led to a higher argillaceous content than the cleaner limestones deposited in higher-energy environments along platform margins. However, even in the broad area of argillaceous limestones, clean limestone buildups have been observed in eastern outcrops and, if present and dolomitized in the subsurface, may provide additional exploration targets.

Structure and isopach maps developed as part of the structural and seismic study supported the basin architecture and geometry conclusions, and from them some structural control on the location of architectural features may be inferred. This portion of the study eventually will lead to a determination of the timing relative to fracturing, dolomitization and hydrocarbon charging of reservoirs in the Trenton and Black River carbonates. The focus of this effort will shift in the next few months from regional to more detailed structural analyses. This new effort will include topics such as the determination of the source of the hot, dolomitizing fluids that created hydrothermal dolomite reservoirs in the Black River, and the probable migration paths of these fluids. Faults of suitable age, orientation and location to be relevant for hydrothermal dolomite creation in the Trenton-Black River play will be isolated and mapped, and potential fairways delineated.

A detailed study of hydrothermal alteration of carbonate reservoirs was completed and is discussed at length in this report. New ideas that were developed from this research were combined with a literature review and existing concepts to develop a model for the development of hydrothermal dolomite reservoirs in the study area. Fault-related hydrothermal alteration is a key component of this model. Hydrothermal alteration produces a spectrum of features in reservoirs, ranging from leached limestone and microporosity to matrix dolomite, saddle dolomite-lined breccias, zebra fabrics and fractures. Mineralization probably occurred during the pressure drop associated with the rise of fluids up the fault system, and is due to the mixing of hydrothermal fluids with cooler, *in situ* fluids. Once they began to cool themselves, the hydrothermal fluids, which had a lower pH and higher salinity than formation fluids, were capable of leaching the

host limestones. Microporosity is common in leached limestones, and it is likely that it was formed, in some cases, during hydrothermal alteration. Dolomite leaching occurs near the end of the paragenetic sequence, and may significantly enhance porosity. However, leaching of dolomite typically is followed by the precipitation of calcite or anhydrite, which reduces porosity. A final conclusion is that hydrothermal alteration may be more common than previously thought, and some features previously attributed to other processes may be in fact be hydrothermal in origin.

Production data are being collected from all project partners. These data will be used to predict ultimate production from existing fields for which a complete production history is known, and for remaining reserves in fields for which the complete production history is unavailable. A plan to estimate the gas resource in the entire play area is being developed.

Enhancement of the project database, GIS and website was emphasized during the report period. The website, like the database, remains a work in progress, and can only grow when the database grows. Recent improvements to the website included how we serve well log files. An effort is being made to add all logs - approximately 1800 - that have been scanned in Tiff format, and another 500 logs that have been converted to vector (LAS) format, to the database and website. Tables for production data, log data, core data and cross sections, all linked to the well header information, were created.

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EXECUTIVE SUMMARY

The Trenton-Black River Appalachian Basin Research Consortium is rapidly approaching 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. Fairways are being identified, based on the structural, stratigraphic, petrographic, geochemical and production studies, and a final model for the origin of hydrothermal dolomites in the Trenton-Black River interval is nearly complete. The petrographic study was completed during the reporting period.

This effort of the Appalachian Oil and Natural Gas Research Consortium (AONGRC) is being conducted by a Trenton-Black River Research Team consisting of recognized experts employed by the state geological surveys in Kentucky, Ohio, Pennsylvania and West Virginia, and the New York State Museum Institute. The AONGRC organized this team and recruited seventeen gas production and exploration companies to form an industry-government-academic partnership, the "Trenton-Black River Appalachian Basin Exploration Consortium," that agreed to co-fund and conduct the research effort.

During this reporting period, geologists on the Stratigraphy Task Team finalized the regional cross section network, completed the interpretation of geophysical logs for regional mapping, generated preliminary regional isopach maps for selected intervals, and constructed generalized facies maps for the Black River and Trenton/Point Pleasant intervals. These geophysical log data were integrated with core and sample descriptions and published outcrop and subsurface studies of the Middle and Upper Ordovician. A network of 19 regional cross sections was generated to illustrate the regional stratigraphy of this interval. All logs for the 222 wells used in these cross sections were converted to LAS (Log ASCII Standard) format. Approximately 1800 geophysical logs that were used in constructing the various isopach and facies maps were scanned (Tiff format) and 500 of these also were converted to vector (LAS) format. These maps were used to develop a better understanding of the basin architecture and facies distribution during Middle and Upper Ordovician time. Core descriptions and detailed log analysis defined clean carbonate intervals within this basin architecture and facies distribution pattern that have good potential for hydrothermal dolomite (HTD) reservoir development. The facies distribution patterns also may explain why HTD reservoirs were not developed in other areas.

Data acquisition for the Seismic and Structural Geology task has been completed. Digitized geophysical well logs for 402 wells and stratigraphic tops from 1797 wells were used for seismic correlation and structural analysis. All raw data have been loaded into software packages: digital seismic data (SEGY files) into Seismic-Micro Technology's Kingdom Suite software, and raster images (Tiff files) into the PetraSeis module of Geoplus Petra software; and digital geophysical log data into Petra and Kingdom Suite software. Sonic logs for 114 wells were used to create synthetic seismograms and velocity models, which were then used to transform known well top depths in feet subsea to depths in time for seismic correlations. In addition, fault trend mapping is nearing completion. Once complete, this mapping effort will identify structural fairways that may be more prone to the development of fault-related hydrothermal dolomites. Seismic and structural data, combined with stratigraphic and facies data, and petrographic and geochemical analyses, were used to develop the model of HTD reservoir development.

This report contains an extensive discussion of the hydrothermal alteration of carbonate reservoirs based on current research results and a literature search of previous studies that are applicable to this effort. First-order controls on hydrothermal alteration include the composition, thickness, porosity and permeability of the limestone host rock; the pressure, temperature and chemistry of the hydrothermal fluid; the effectiveness of an overlying sealing unit; the distance between the basement and basal sandstone aquifer up to the host limestone; and the type and timing of faulting. Structural settings where hydrothermally-altered carbonates commonly are found include margin-bounding faults, newly-rifted basement and active normal faults, fault intersections, and around wrench faults that are activated during mountain building events. Fault-related hydrothermal alteration occurs when high-pressure, high-temperature fluids flow up active faults and then move laterally into permeable formations when upward movement is restricted by an overlying seal, such as an impermeable shale, argillaceous limestone or evaporate unit. Alteration of the original limestone host rock proceeds due to the episodic influx of fluid up a fault, the mixing of the deeper fluids with fluid in the host rock, and subsequent equilibration with formation conditions. These hydrothermal fluids not only create dolomite, but as they cool they also have the capacity to leach limestone and, in some cases, dolomite that had been created when the fluids were warmer. Microporosity is common in these leached limestones, and leached dolomites also may significantly enhance porosity.

Production data are still being collected from the various state agencies in the play area. As up-to-date-as-possible data are necessary to achieve the maximum results, so this data collection effort will continue for the next several months. These data will be used to predict the estimate ultimate recovery of existing Trenton-Black River fields for which a complete production history can be collected; remaining production from fields for which the early production history is unknown; and for estimating gas resources in the entire play area. A plan is being prepared to estimate gas resources. The decision has been made to work with outside industry and government experts to accomplish this task.

The project website continues to be a work in progress. In its current configuration, growth is limited by the amount of information in the database. Efforts were made to increase the amount of project data that are now considered to be final and, therefore, appropriate to be included in the database and on the website. As an example, progress was made on the number of LAS and Tiff files for well logs that were added to the database and website. During the recent meeting of research team members with company consortium members, the industry representatives requested access to all header information and expressed satisfaction with the format and contents of the database and website.

This technical report does not contain a section on results of the petrology task. However, a separate topical report that summarizes the final results of this task will be submitted as a companion to this semi-annual technical report.

RESULTS AND DISCUSSION

Regional Stratigraphy of the Trenton-Black River Interval

The primary focus of the stratigraphy task is to define Trenton, Black River, Utica and equivalent lithostratigraphic units within a regional framework; model the depositional environment and basin architecture; and integrate these results with the results from other project tasks to delineate potential areas of exploration interest. The stratigraphic framework will establish regionally-consistent formation/interval boundaries and nomenclature, which will be used in structure, isopach and facies mapping. A regionally-consistent stratigraphic framework also will provide a better understanding of the complexly interwoven geologic parameters controlling Trenton-Black River reservoirs. Once a consistent framework is developed one 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 develop the regional stratigraphic framework, which then will be integrated with results from other tasks to develop a stratigraphic-structural-diagenetic model for the origin of Trenton-Black River reservoirs and delineation of potential areas of exploration interest.

Methods

During the past semiannual report period, geologists in the Stratigraphy Group finalized the regional stratigraphic cross section network, completed the interpretation of geophysical logs for regional mapping, generated preliminary regional isopach maps for selected intervals of the Cambrian-Ordovician section, and constructed preliminary, generalized facies maps for the Black River and Trenton/Point Pleasant intervals. Geophysical log data were integrated with core and sample descriptions and published work on Middle and Upper Ordovician outcrop and subsurface studies. Core data 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. Geographix software was used for constructing the cross sections and maps.

A network of 19 cross sections has been generated across the Appalachian basin to illustrate the regional stratigraphy of the Middle and Upper Ordovician succession of strata (Figure 1). All logs for the 222 wells used in constructing these cross sections have been converted to LAS (Log ASCII Standard) format for construction of the final cross sections. Throughout the basin, approximately 1,800 geophysical logs for unique wells containing the Trenton-Black River interval have been scanned (Tiff format) and approximately 500 well logs have been converted to vector (LAS) format.

A depositional-strike direction of approximately northeast-southwest for the Trenton interval was established using a preliminary isopach map and other published maps. It generally is assumed that parallel isopach contour lines showing thick to thin areas define a regional deposition strike direction. Seven cross section lines were oriented parallel (strike) and 12 cross section lines were oriented 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 used in these cross sections 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, the assumption being that the dolomites are fault related.

The Stratigraphy Group completed the interpretation of geophysical logs and picked tops for all wells that will be used in the regional isopach maps. Units that were interpreted on geophysical logs (using Ohio and Kentucky nomenclature) include the top of the Knox Dolomite, Wells Creek Formation, "Gull River," Black River Limestone, Lexington Limestone (with its Curdsville Member, Logana Member and Lexington Undifferentiated Member), Trenton Limestone, Point Pleasant Formation, Utica Shale, Kope Formation, and top of the Ordovician. Equivalent units and nomenclature for the entire Appalachian basin can be seen in the regional stratigraphic correlation chart (Figure 2). As with the wells used in the cross sections, geophysical log tops were correlated to cores and sample descriptions to better refine the stratigraphic interpretation.

Preliminary thickness maps of the Precambrian to base of Knox, base of Knox to top of Knox, Knox to Black River, Black River to Trenton, Trenton to Kope, and Kope to top of Ordovician intervals were generated based on formation tops interpreted from approximately 1000 well logs, cores, and sample descriptions. Digital locations of Trenton–Black River oil and gas fields were obtained from Appalachian, Illinois and Michigan Basin states (including Ontario, Canada) and a Trenton-Black River oil and gas fields map was generated to assist in relating stratigraphy to producing trends (Figure 3).

Preliminary facies maps illustrating late Black River time and late Trenton-Point Pleasant time were constructed to develop a better understanding of the paleogeography and facies distribution of these units. Preliminary maps illustrating the regional distribution of the Logana Member of the Lexington Limestone, the Point Pleasant Formation and the Utica Shale also were constructed. These maps were all generated using the regional cross sections, core and sample descriptions, and published references. Regional facies maps will be refined for the final report as data from all states are further integrated into the regional stratigraphic picture.

Stratigraphic Nomenclature

Again, the focus for this study is to develop a regionally-consistent stratigraphic framework for the Trenton/Black River-Utica interval and coeval units. Numerous stratigraphic names have been applied to the Ordovician succession of rocks across the Appalachian basin. To simplify the use of stratigraphic nomenclature in this report, Ohio and Kentucky nomenclature will be used in the stratigraphy discussion. Stratigraphic equivalents of these units across the basin can be seen in the regional stratigraphic correlation chart (Figure 2). A correlation chart based on the formal nomenclature of each state geological survey was subdivided into the northwestern basin and arches, the Rome Trough, and the eastern basin. The Cambrian and Ordovician units that were mapped are discussed in ascending stratigraphic order.

Preliminary Summary of Central Appalachian Basin Geometry and Architecture During Ordovician Trenton Time

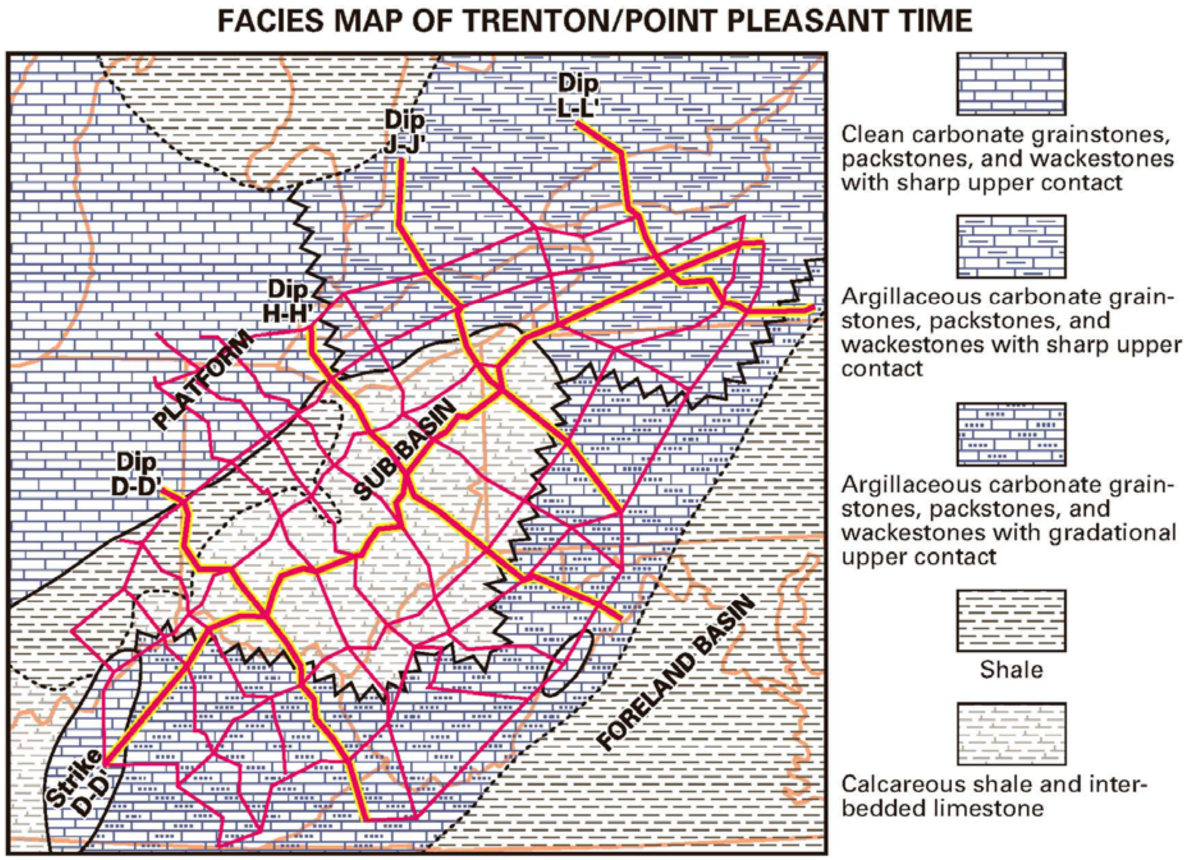


Figure 1

Figure 1. Map showing location of cross section lines (red lines) used in study and a facies map of late Trenton/Point Pleasant time. Cross sections presented within this report are highlighted and labeled.

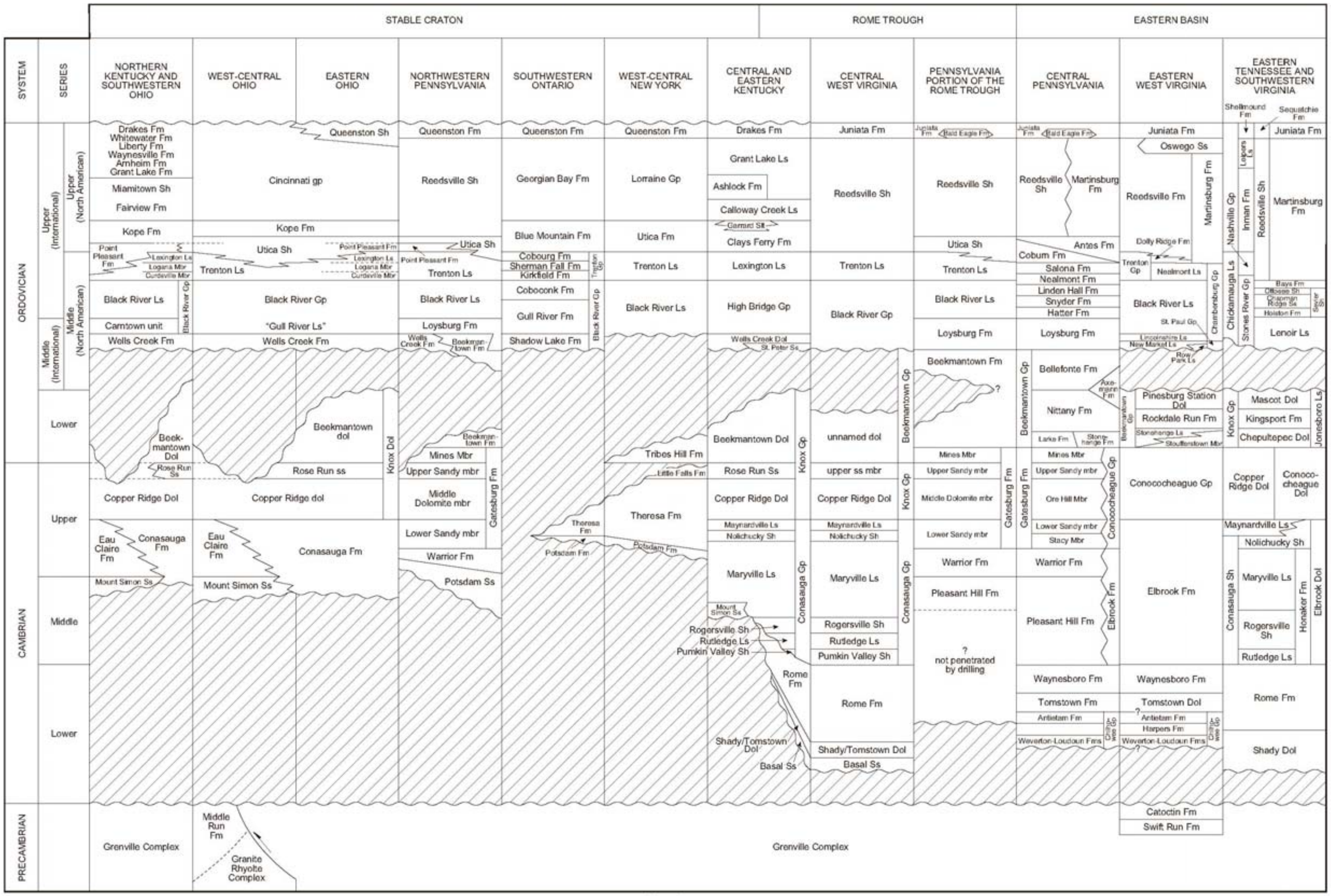


Figure 2

Figure 2. Correlation chart for Cambrian-Ordovician rocks in the northern Appalachian basin.

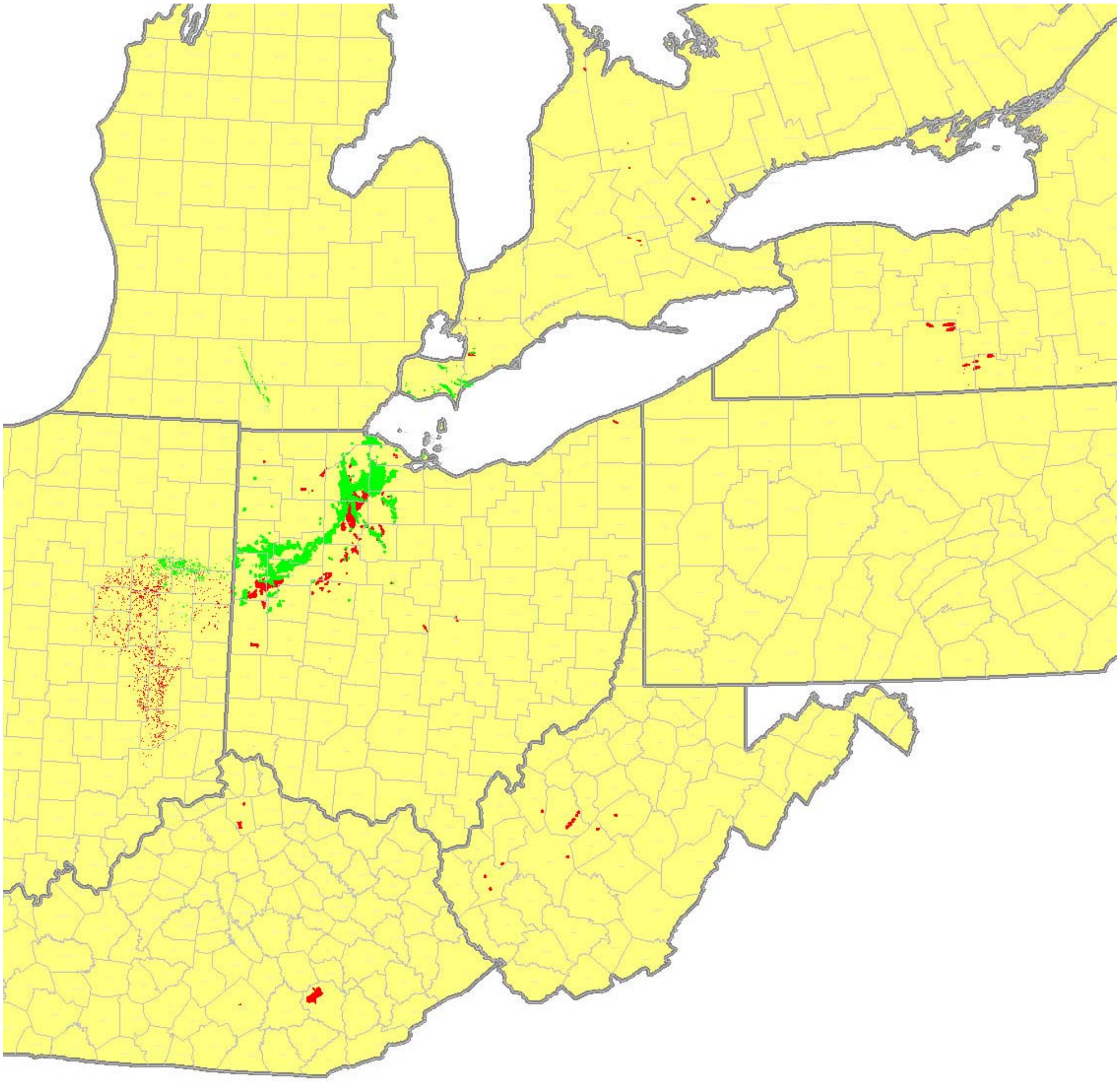


Figure 3. Map of producing Trenton-Black River oil and gas fields in the project area.

The discussion in this section is based in part on literature that will be synthesized, where appropriate, and cited in the final report, following the merge of these findings and conclusions with those of other state geological survey project team members. Not all references used in developing the following discussion have been cited in this preliminary report.

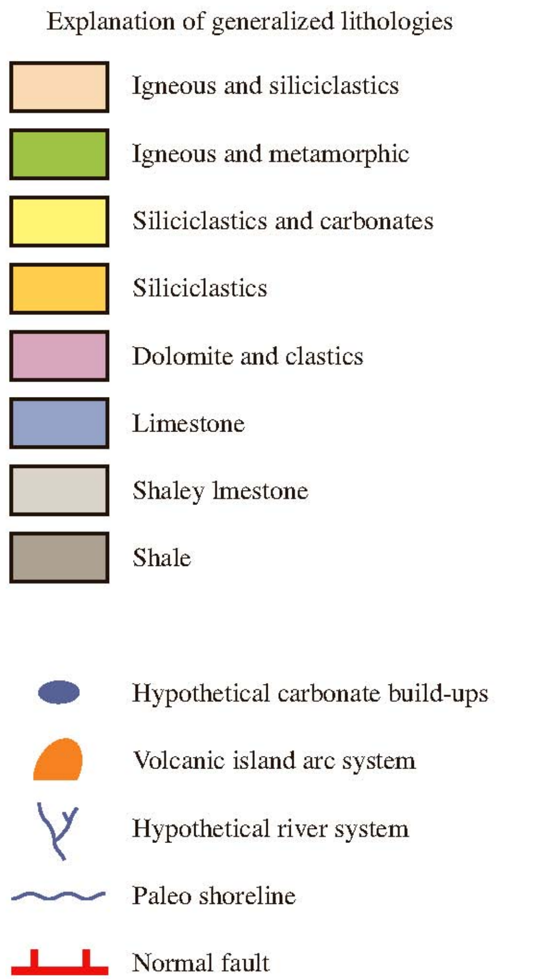
Paleozoic basin geometries and depositional patterns of the eastern U.S. are directly related to the underpinning Precambrian features of the region and indirectly to far-field stresses and crustal-loading during geologic time. The geometric shapes of the basins evolved over time as the sedimentary sequences were deposited and compacted. The effects of paleo-climate, paleo-oceanic circulation, and variable compaction of sediments also affected depositional setting as well as basin geometry, but are not addressed in this discussion. A preliminary analysis of the central Appalachian basin geometry and architecture was performed using subsurface well control data tied to an extensive cross section network, which establishes regional depositional strike and dip azimuths during Trenton time. Selected machine-contoured Cambrian and Ordovician intervals, including the Trenton, were evaluated for this preliminary analysis.

Tectonic features affecting geometry and architecture during Cambrian and Ordovician time included these Precambrian provinces: Eastern Granite Rhyolite (EGR), East Continent Rift Basin (ECRB), and Grenville Province (GP) Domains and the Cambrian Rome Trough (RT) (Figure 4). Within the central Appalachian basin region these underpinning structural features controlled areas of exposed craton, platforms and depo-centers. Platform and depo-center locations shifted laterally with time, thus affecting subsequent thickness patterns. Subsidence rates, variable sediment supply and accumulation and eustatic sea level variations are considered to be the dominant mechanisms for the basin geometries and architecture in the region. Major tectonic uplifts, aside from the Taconic Orogeny, following Early Black River time and remaining Ordovician time are absent in the region. The Cincinnati Arch is a post-Ordovician structural feature.

Precambrian to Middle Cambrian Rome Formation Interval

Following several hundred million years of erosion on the Precambrian surface, the Rome Trough became the first major Paleozoic regional structural feature that affected the geometry and architecture of the central and northern Appalachians (Figure 5). The Rome Trough was a rifted basin system adjacent to the exposed Precambrian craton during Early and Middle Cambrian time. The Rome Trough is bounded on the west by a series of en echelon normal faults and to the east by a positive magnetic anomaly interpreted to be a horst block by various researchers. The continental margin and open marine conditions extended southeastward away from the craton. These open marine conditions would prevail throughout the Cambrian and Ordovician. Significant volumes of exposed Precambrian craton were eroded and deposited as transgressive siliciclastics southeast of the boundary fault system of the Rome Trough. Extensive carbonates as well as marine shales also were deposited during this time. The northwestern boundary of the Rome Trough would remain active but with diminishing effects into Ordovician Black River time.

Precambrian to Middle Cambrian Mount Simon Sandstone/Conasauga Formation Interval



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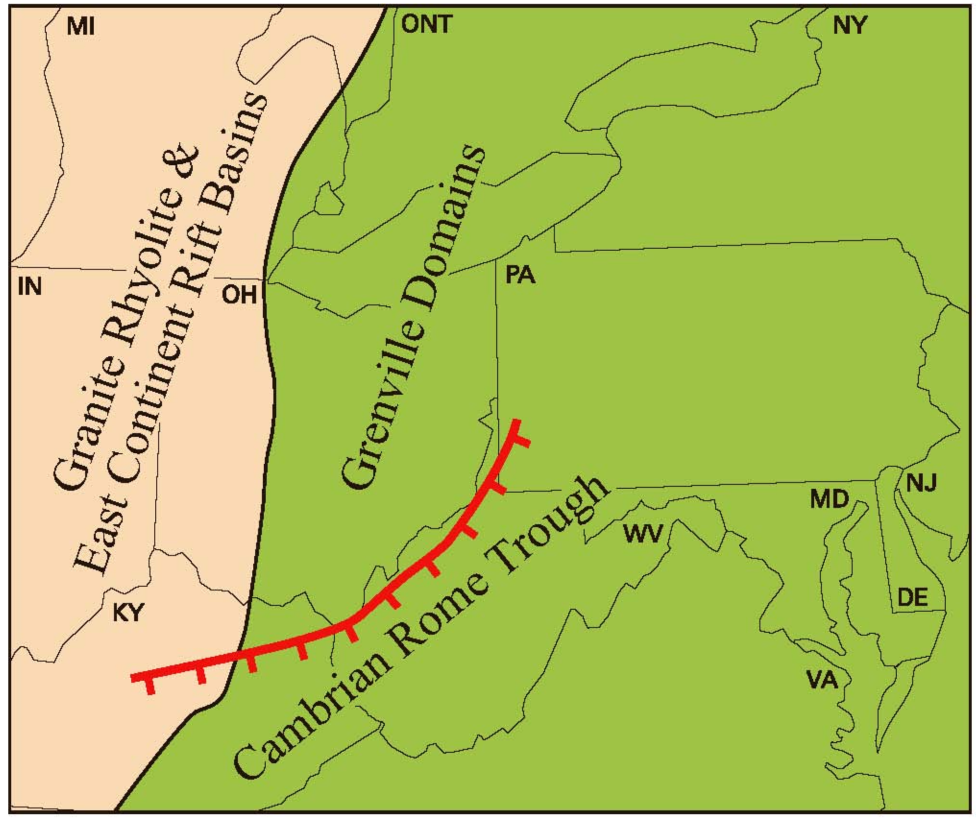
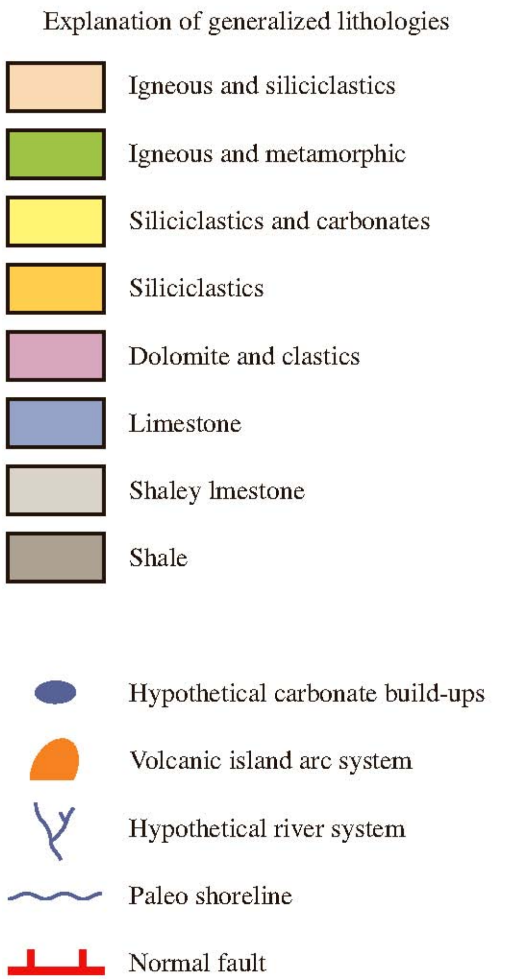


Figure 4

Figure 4. Map of major tectonic features affecting geometry and architecture during Cambrian and Ordovician time.



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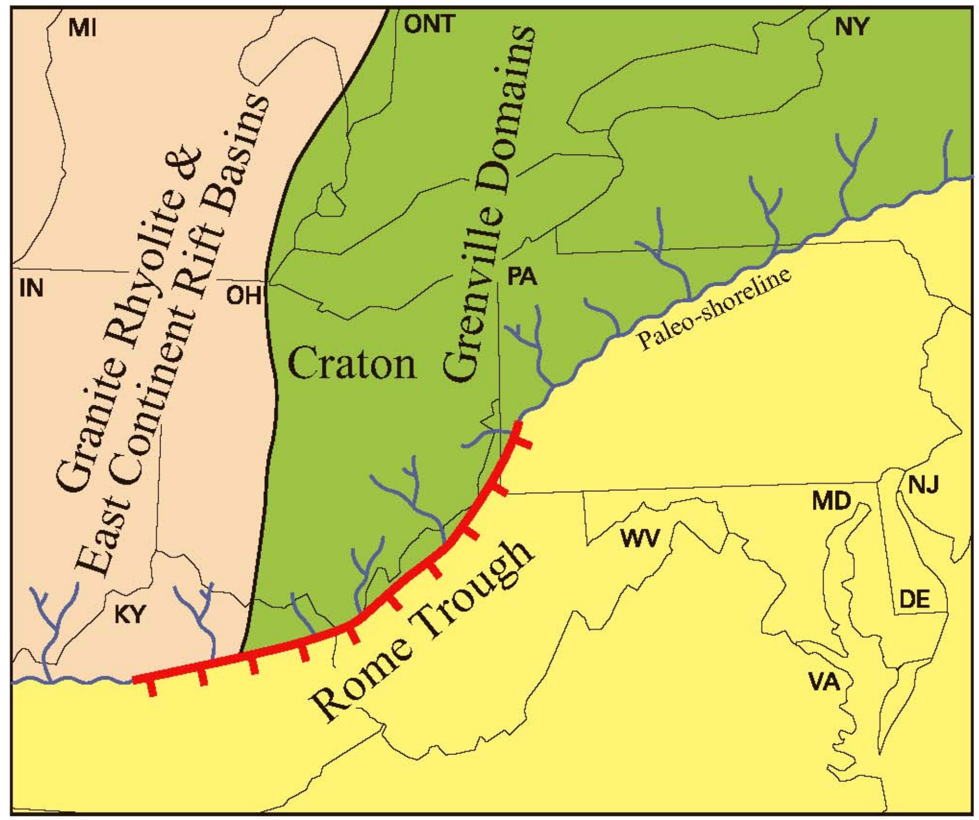


Figure 5

Figure 5. Map showing basin architecture during Precambrian to Middle Cambrian Rome Formation time.

Erosion of the Precambrian craton continued during Middle Cambrian Mount Simon/Conasauga Formation time, concurrent with regional transgressive deposits and the newly formed Proto-Appalachian and Proto-Illinois/Michigan basins (Figure 6). The overall shape of the depo-centers for the Proto-Appalachian and Proto-Illinois/Michigan basins followed geometric axes trending northeast and north-south respectively. These extensive depositional sags were separated by the Ohio Platform (Baranoski, in preparation), which was largely a surface of exposed Grenville Province Domains and relatively thin Middle Cambrian siliciclastics and carbonates. The northwest boundary fault system of the Rome Trough continued to control subsidence during deposition of transgressive sediments, but without the structural break observed in the Rome Formation to Precambrian interval.

Knox Group Interval

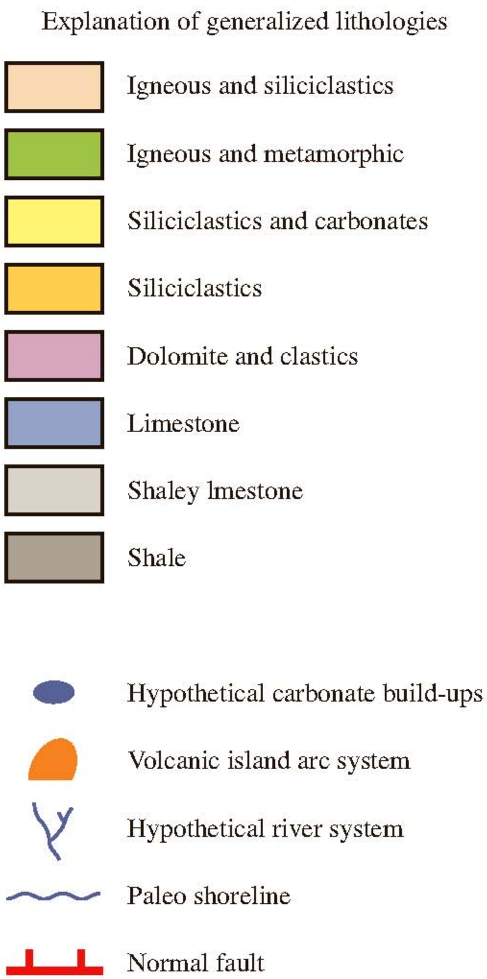
The Proto-Appalachian and Proto-Illinois/Michigan basin geometries were similar to the underlying interval as subsidence continued during Late Cambrian/Early Ordovician Knox time (Figure 7). Carbonate deposition dominated the region with a notable regressive/trangressive event with deposition of the Rose Run sandstone. The regional Knox unconformity exposed the craton and Ohio Platform, allowing extensive erosion of the platform. This regional unconformity, which is not recognized in the eastern depo-center, accentuated the shape and extent of these proto basins. The northwest boundary fault system of the Rome Trough continued to control subsidence during this time but with diminished effect on sedimentation and depositional patterns.

Knox Unconformity to Black River Interval

This time period marks an important departure from the underlying shape and extent of the Proto-Appalachian and Proto-Illinois/Michigan basins. An elongate-shaped geometry and architecture characteristic of the Appalachian basin came into existence during Middle Ordovician Black River time (Figure 8). The overall shape of the depo-center followed a north-northeastern-trending axis, which would continue throughout the Ordovician and remaining Paleozoic. The architecture was characterized by extensive Indiana/Ohio and Ontario/New York carbonate platforms, which developed across the region. Sediments controlling the architecture consisted of carbonate mudstones to the northwest of the Rome Trough, with shaley carbonates to the southeast and black and gray shales in the Sevier basin. Volcanic island arcs appeared further southeast of the Sevier basin, and would provide extensive ash beds across the region. The Michigan basin's oval-shaped geometry first came into existence during this time.

Trenton Interval

The elongate-shaped geometry and architecture of the region continued to evolve during Trenton time, marking an extensive marine transgression across the region. Maximum subsidence and sediment accumulation was maintained in the main depo-center to the east with increased clastic input, while carbonate platforms evolved into higher-energy accumulations of carbonates. Increased subsidence in the main depo-center had far-reaching effects westward onto the Indiana/Ohio Platform with development of the Ohio Sub-basin. The Indiana/Ohio Platform receded northwestward during encroachment of the Ohio Sub-basin, while the Ontario/New



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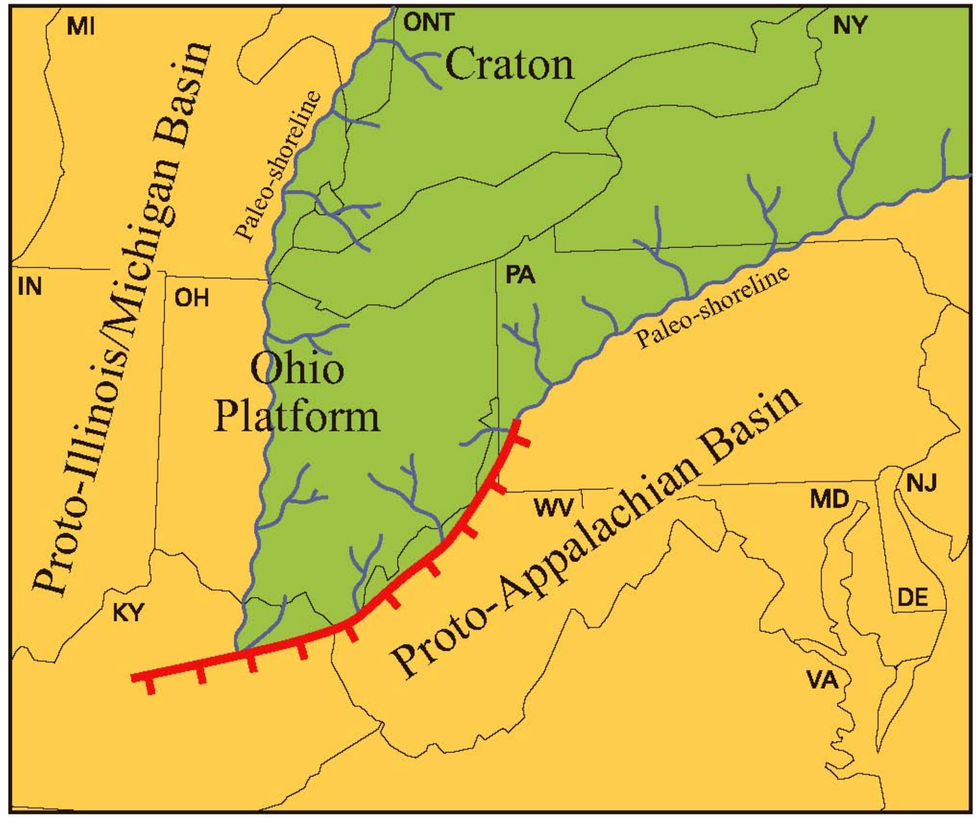
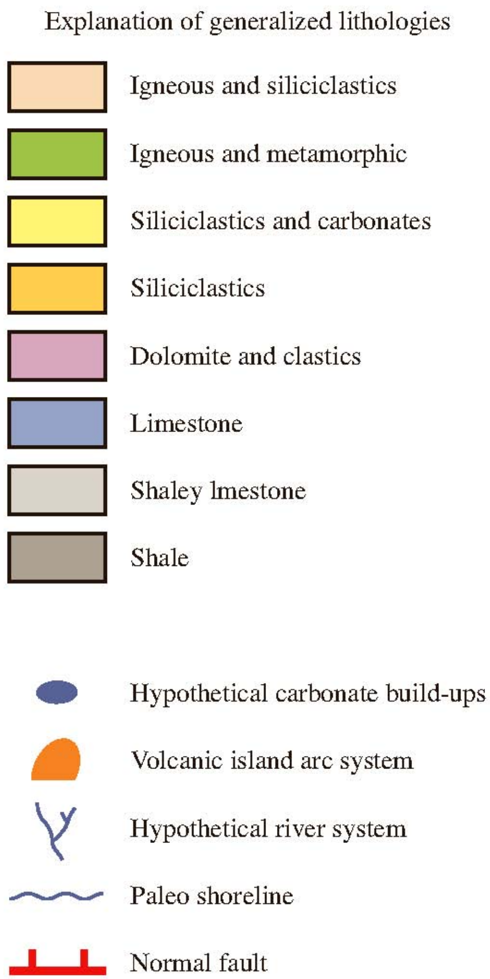


Figure 6

Figure 6. Map showing basin architecture during Precambrian to Middle Cambrian Mount Simon Sandstone/Conasauga Formation time.



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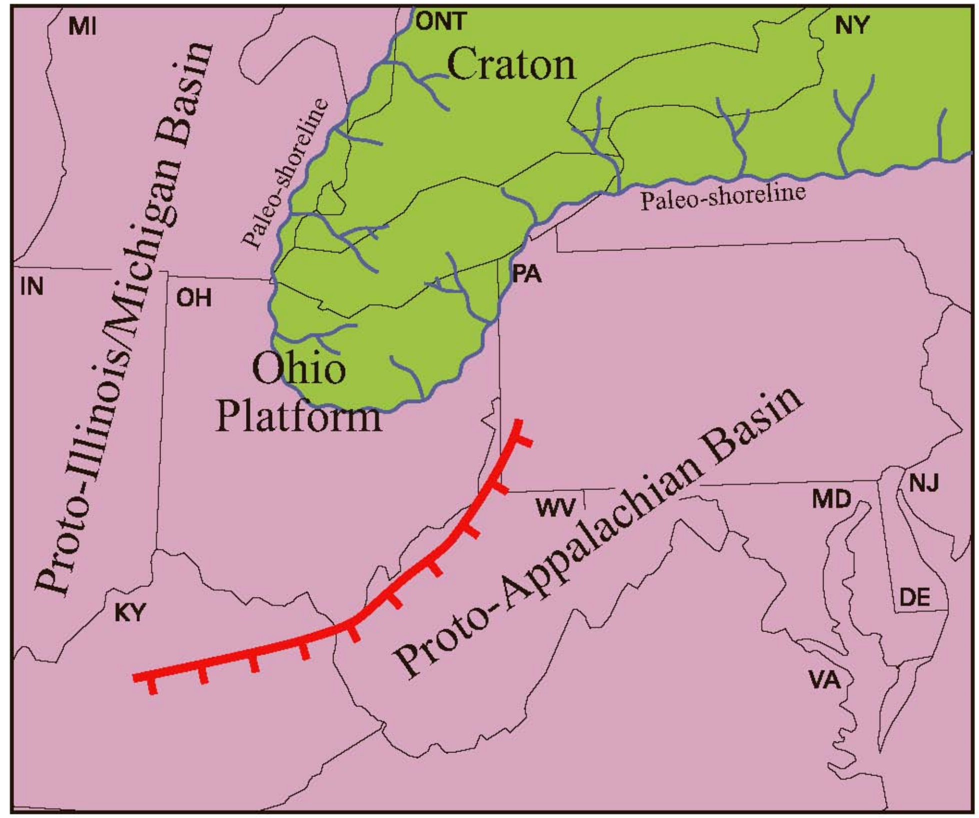
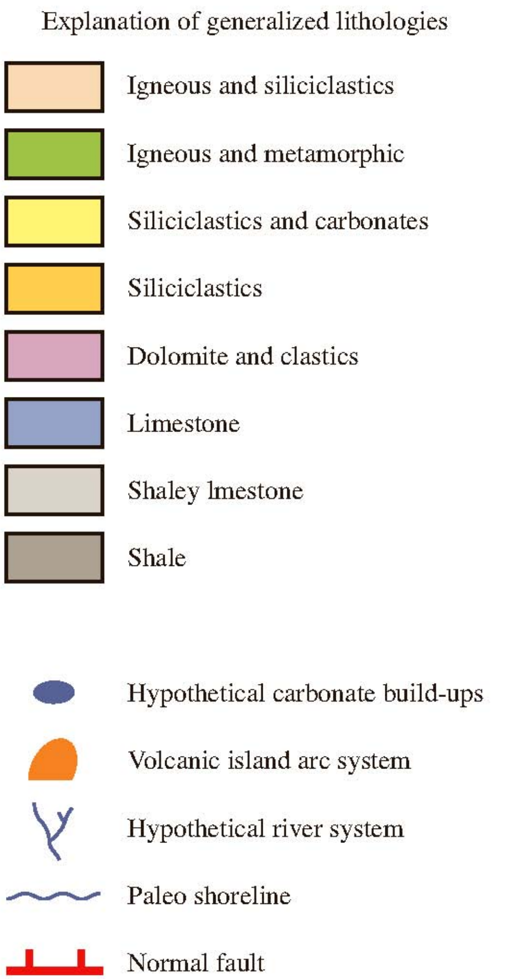


Figure 7

Figure 7. Map showing basin architecture during Late Cambrian/Early Ordovician Knox time.



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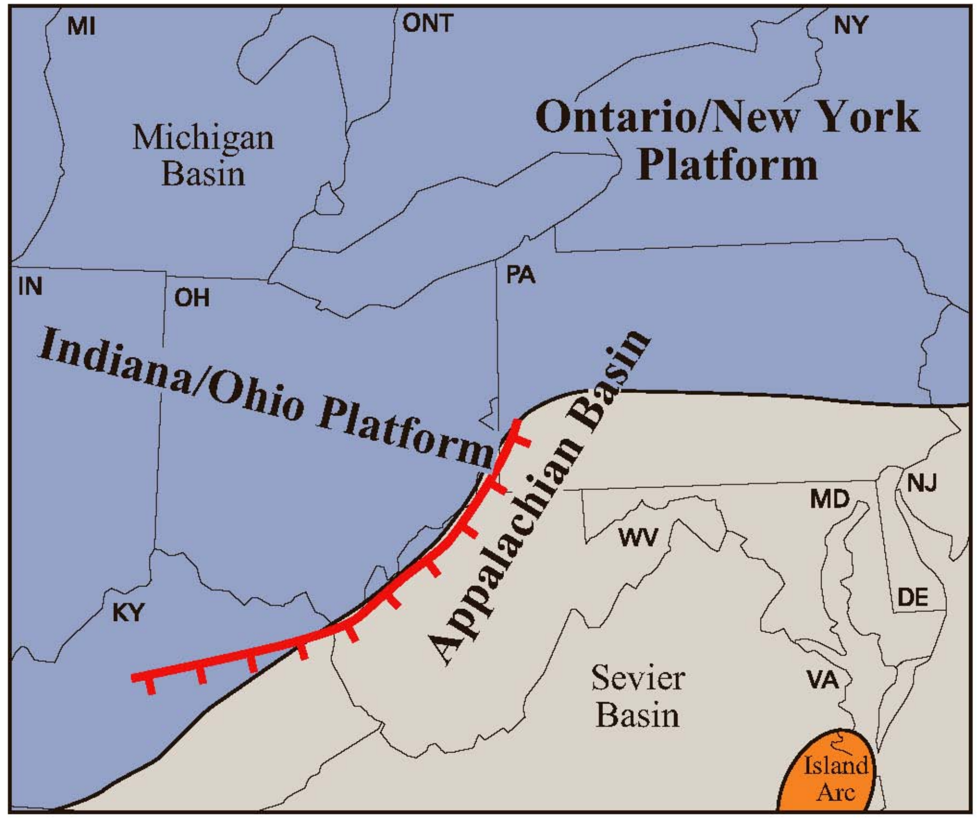


Figure 8

Figure 8. Map showing basin architecture during Middle Ordovician Knox to Black River time.

York Platform continued to grow with increased subsidence along the axis of the depo-center (Figure 9). The Lexington Platform came into existence at this time and was separated from the Indiana/Ohio Platform by shaley carbonates deposited within an arm of the Ohio Sub-basin. Localized carbonate build-ups appear to have accumulated along with overall thick shaley carbonates in the eastern depo-center. Volcanic island arcs migrated northeastward providing extensive ash and clastics to the region.

Trenton to Kope Interval

During Late Ordovician Kope time Appalachian basin geometry remained consistent with the Trenton depo-center and regionally extensive shale and lesser volumes of carbonate (Figure 10). The increase in volume of shale marks significant changes affecting basin architecture with reduced accumulation of carbonates across the region. Black, organic-rich shale volumes would decrease in significance by the end of Kope time. However, the overall increased volume of shale would continue throughout remaining Ordovician time, marking increased subsidence and expansion of the main depo-center onto the carbonate platforms. The Indiana/Ohio Platform receded further northwest and was buried by black and gray shale before the end of Kope time. The Lexington and Ontario/New York platforms were greatly diminished in size, becoming isolated areas of relatively clean carbonate deposition. These remaining, but isolated, carbonate platforms were buried by shale by the end of Kope time. The Ohio Sub-basin continued to subside and accumulate dominantly shale with significantly less carbonates.

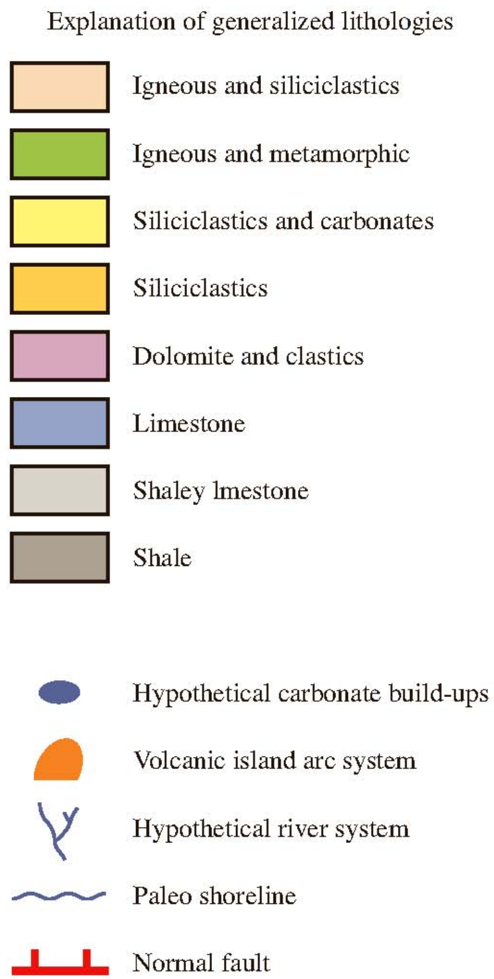
Kope to Ordovician Unconformity Interval

Following Kope time the Appalachian basin region continued to be dominated by marine shale deposition, followed by terrigenous shale deposition (Figure 11). The geometry and location of the depo-center was consistent with previous Kope deposits, but increased subsidence resulted in thicker and regionally extensive accumulations. Carbonate platforms deposits were very thin and poorly developed in the western areas and largely absent in the main depo-center, where deltaic siliciclastics and shales spread across the region.

Regional Facies Maps

Maps presented in this section represent a regional synthesis of broadly defined facies present during late Black River and late Trenton/Point Pleasant times. Regional facies for these time periods consist largely of clean carbonate mudstones, argillaceous carbonate mudstones, clean carbonate grainstones and packstones, argillaceous carbonate grainstones and packstones, calcareous shale and interbedded limestone, and shale. Regional facies patterns are important for understanding the location of the best potential reservoir rocks. Facies maps assist the explorationist in determining tectonic controls and potential areas for the best places for hydrothermal dolomite to form. Mapping the facies regionally may also help to better understand differences in seismic signature of the Trenton across the basin, which in turn may be useful as a potential exploration tool.

Late Black River Time



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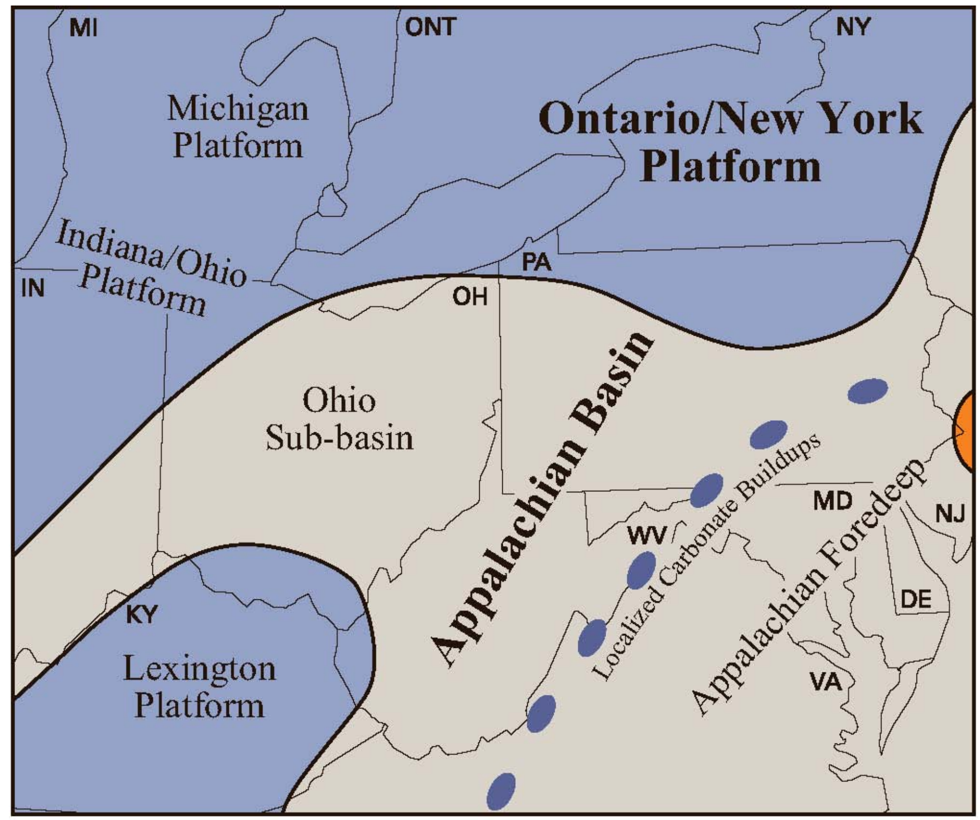
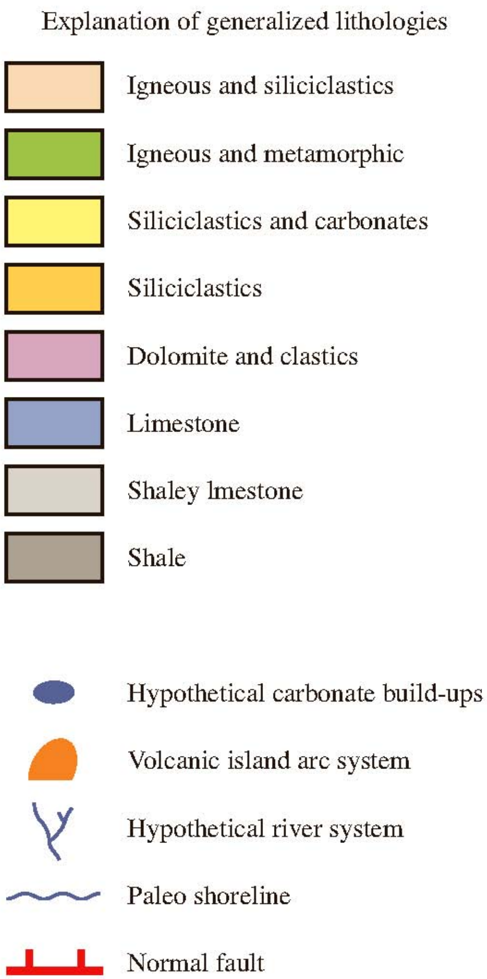


Figure 9

Figure 9. Map showing basin architecture during Middle Ordovician Trenton time.



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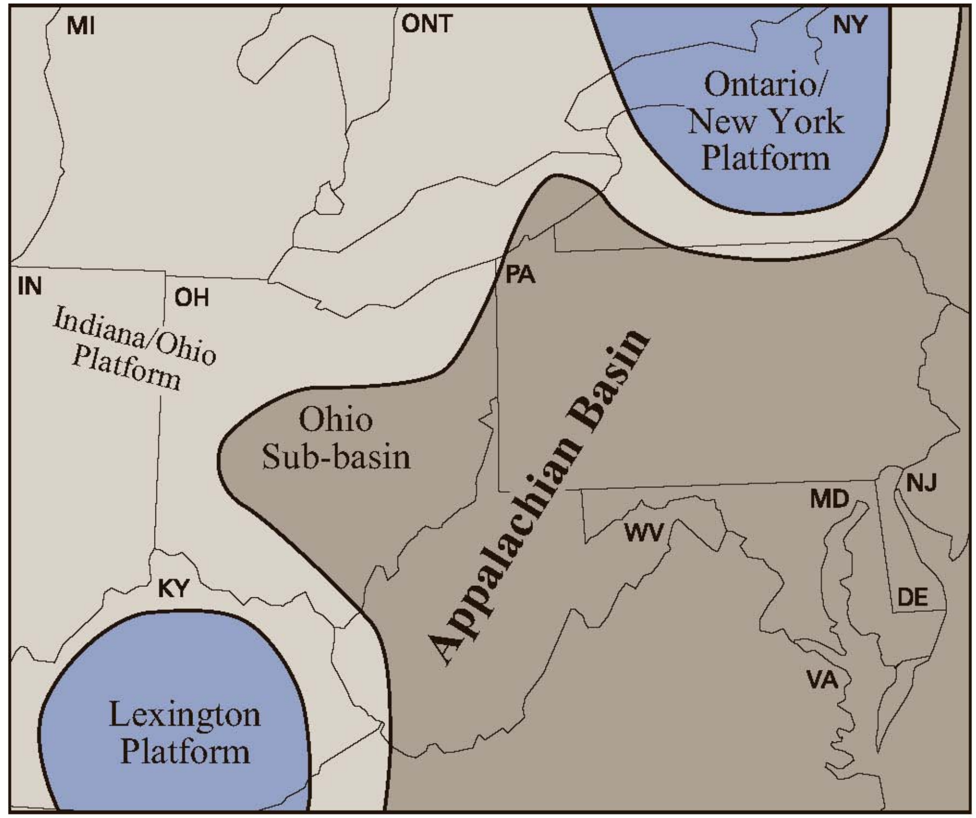
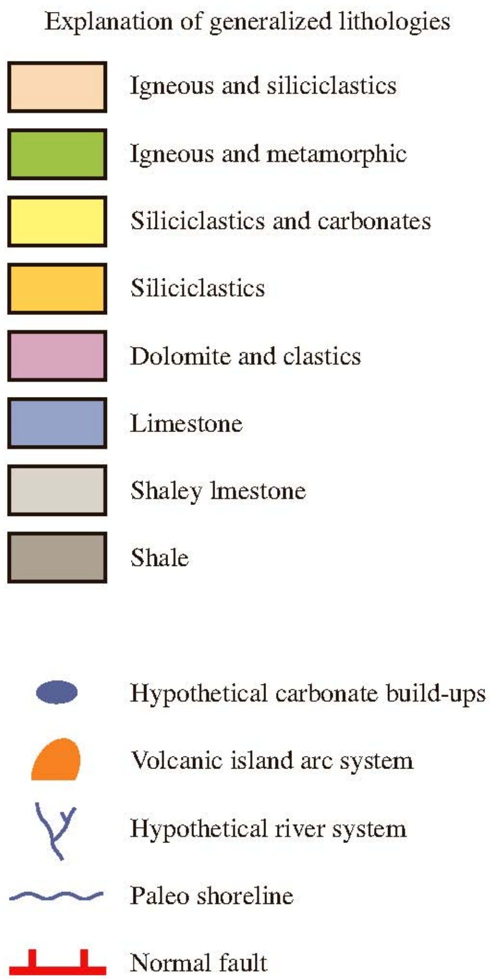


Figure 10

Figure 10. Map showing basin architecture during Middle Ordovician Trenton to Late Ordovician Kope time.



Explanation for Figures 4 through 11

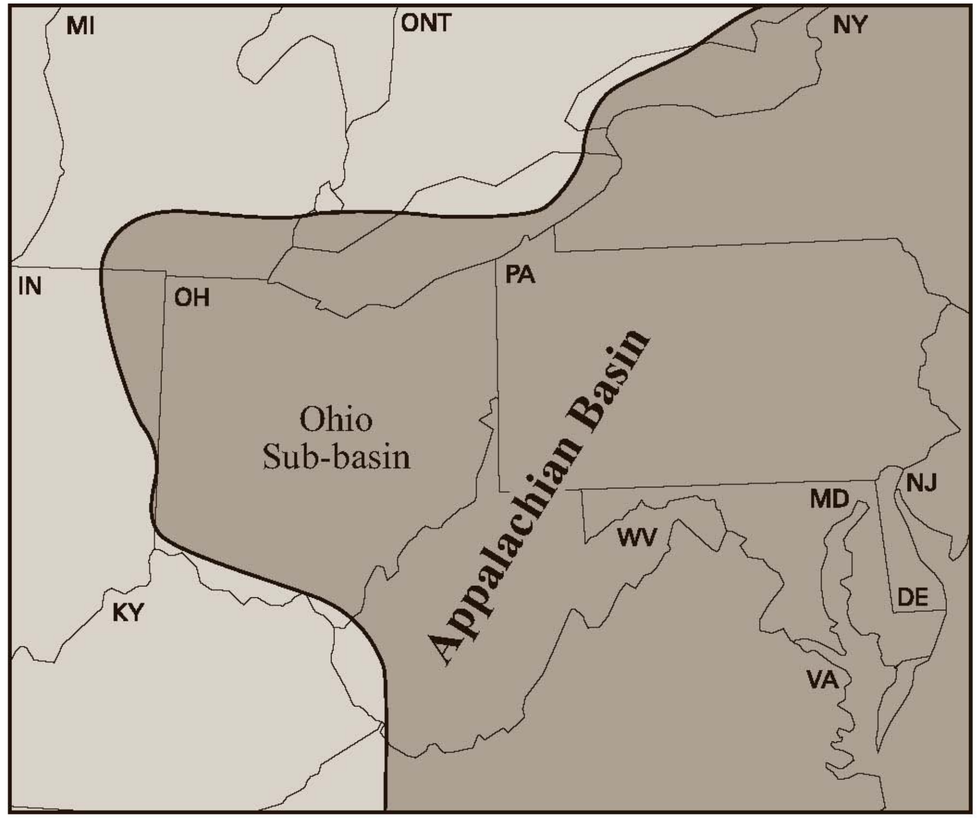


Figure 11

Figure 11. Map showing basin architecture during Late Ordovician Kope to Ordovician Unconformity time.

Black River facies consist of shallow subtidal to peritidal carbonates that were deposited across a very low relief carbonate ramp (Keith, 1989; Pope and Read, 1997). The Black River directly overlies the Wells Creek Formation, or the Knox Group on paleotopographic highs where the Wells Creek is absent. As examined in core and outcrop this unit is lithologically consistent and uniform across the region (Figure 12). It consists dominantly of a light-medium brown to gray, burrow-mottled, stylolitic mudstone. 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. Approaching the foreland basin to the southeast, a facies change occurs where the cleaner mudstones recognized in core and geophysical logs become more argillaceous in the deeper water portion of the basin.

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 the outcrop and subsurface. In cores in western and southern Ohio, the Millbrig occurs near the top of the Black River and marks a change from a bioturbated mudstone Black River lithology to the overlying highly fossiliferous, grainstone-packstone lithology typical of the Trenton. The Black River-Trenton contact is generally a gradational zone in which Black River and Trenton lithologies are interlayered through a zone up to 10 feet thick, but 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 top of the Nealmont mudstone (Black River equivalent).

The Millbrig is used in this report to define this boundary because it is a reliable marker on geophysical logs for Black River subsurface correlations in much of Ohio, Indiana and Kentucky. Where the Millbrig is absent, however, one must use a correlation point on geophysical logs tied to cores or sample descriptions. The source for the volcanic ash of the bentonites was to the east and southeast, originating from active island-arc volcanism associated with the Taconic orogeny (Cisne and others, 1982; Kolata and others, 1996). The foreland basin developed in two phases named the Blountian and Taconic tectophases (Rodgers, 1971). According to Ettensohn and others (2002), there was a time-transgressive, northeastward shift of convergence during the Blountian and Taconic tectophases of the Taconic orogeny. The earlier Blountian tectophase was strongest at the Virginia Promontory and possibly the Alabama promontory and created the Sevier Basin turbidite deposition in Alabama, Georgia, Tennessee and Virginia. This initial collision during the Blountian tectophase created the portion of the island-arc system shown in Figure 12. The later Taconic tectophase generated the Martinsburg foreland basin in northern Virginia, Maryland and Pennsylvania (Etttensohn and others, 2002; Pope and Read 1997) and created the island-arc system to the northeast (not shown on this figure).

Logana Limit

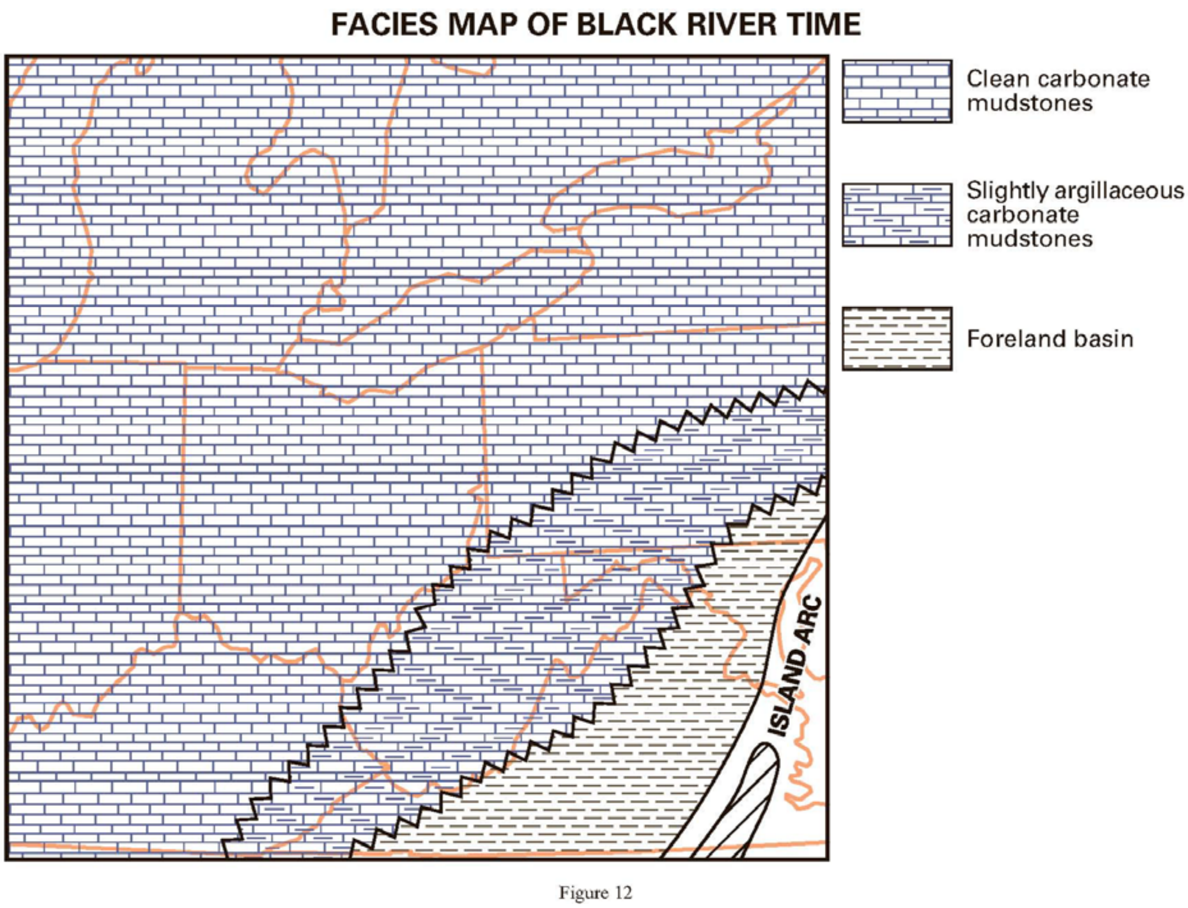


Figure 12. Facies map of late Black River time.

From the Trenton platform margin into the sub-basin one can correlate the sharp contact at the top of the Trenton to the gradational top of the Lexington Limestone. In the subsurface, the Lexington Limestone can be subdivided into the Curdsville Member, Logana Member and Lexington Undifferentiated Member, in ascending stratigraphic order (Figure 2). Both core and geophysical well logs indicate that the Logana Member and Lexington Undifferentiated Member are relatively higher in shale content than the Trenton Limestone on the platform and Curdsville Member of the Lexington Limestone. Pope and Read (1997) subdivide the late Middle to Late Ordovician supersequence into four large third-order sequences. The Curdsville Member represents the transgressive systems tract (TST) of sequence 1 and consists of medium-gray to brownish-gray, medium-to fine-crystalline wackestone to grainstone. The Curdsville Member is a cleaner carbonate represented by a lower gamma-ray response similar to the Trenton and has a gradational contact with the overlying Logana Member. The Logana Member is thought to represent a maximum flooding surface (MFS) of sequence 1 (Pope and Read, 1997). It consists of deeper water 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. The distinct lithology of this unit can be identified and correlated on geophysical logs by its higher gamma and increased neutron response. Source rock analyses of samples from Ohio wells show this unit to have total organic carbon (TOC) values up to 3, indicative of potential source rock.

Figure 13 illustrates the limit of the Logana Member as it has been correlated in cores and on geophysical logs. It is present throughout most of Ohio in the sub-basin region, and extends into Kentucky and western West Virginia. The southern limit of the Logana Member is controlled by the Lexington Platform. Preliminary work based on regional cross sections indicates that the Logana Member may be time equivalent to part of the Trenton and possibly the base of the Utica Shale to the southwest. Preliminary correlations also indicate that the Logana Member may correlate with the Salona to the east. Results of the isotope geochemistry task in correlating the Guttenberg Isotope Carbon Excursion (GICE) may help to resolve some of these time lines.

Trenton/Point Pleasant Time

Figure 14 illustrates facies distribution during late Trenton/Point Pleasant time. It should be noted that this is an interpretation for an approximate time marker. The Trenton top mapped for this region is a diachronous surface, and thus is not time equivalent throughout the basin. The upper portion of the thick Trenton platform development in New York, for example, is younger than the thinner Trenton platform development in northwest Ohio. Also, the relationship of the Point Pleasant with the Trenton is not well understood because of a lack of good biostratigraphic time markers. The Point Pleasant appears to have been deposited in part contemporaneously with the Trenton in northwest Ohio, but also appears to have been deposited above the Trenton along portions of the platform margin to the southwest.

The major facies interpreted to be present during Trenton-Point Pleasant time are shown in Figure 14. On the platform in northwestern Ohio, Indiana and Michigan the Trenton consists of a clean carbonate comprised primarily of a grainstone-packstone texture, and has a sharp upper contact with the overlying Utica Shale. The type well for this facies is the cored Ohio

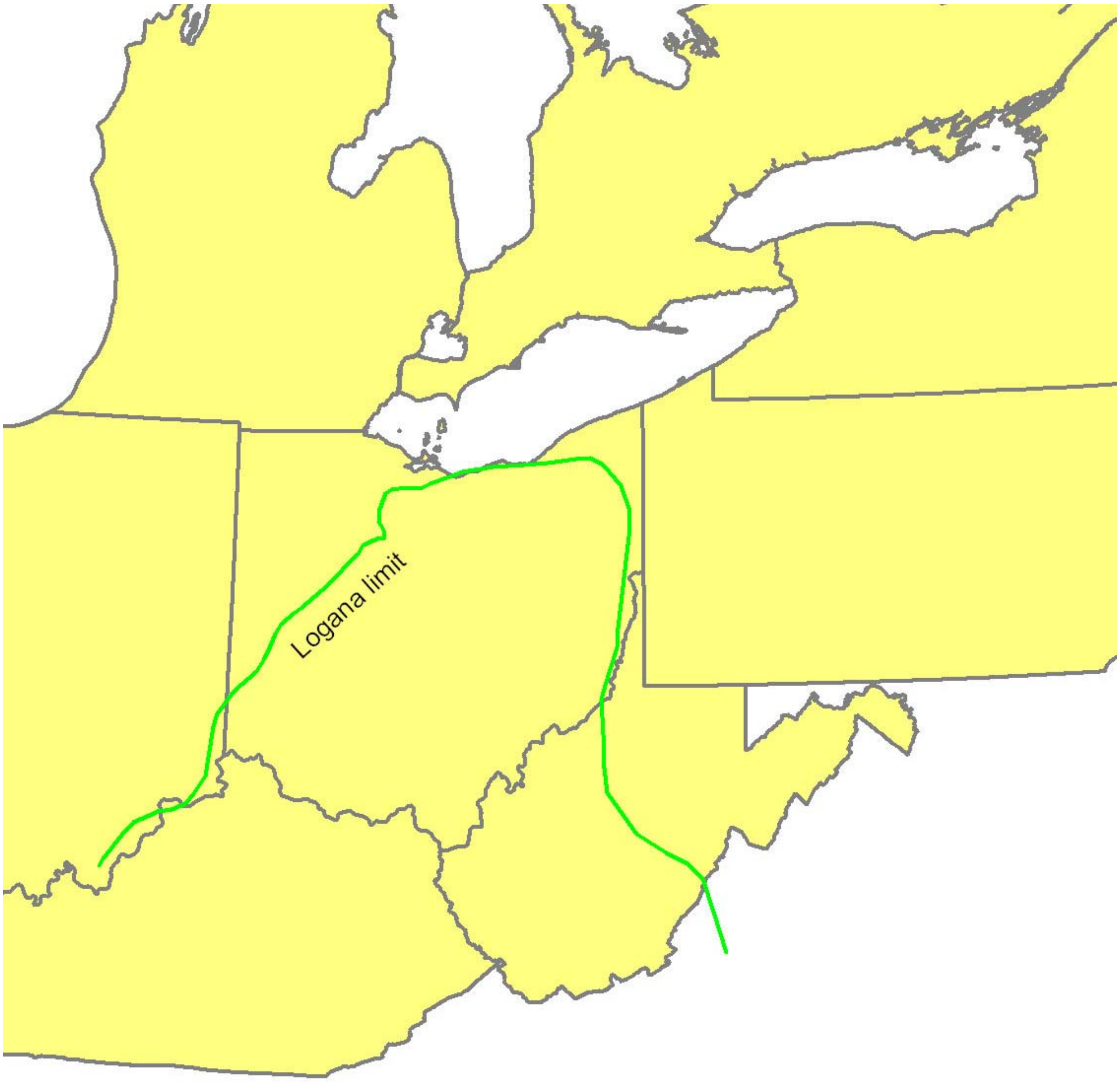


Figure 13. Map showing the limit of the Logana Member of the Lexington Limestone.

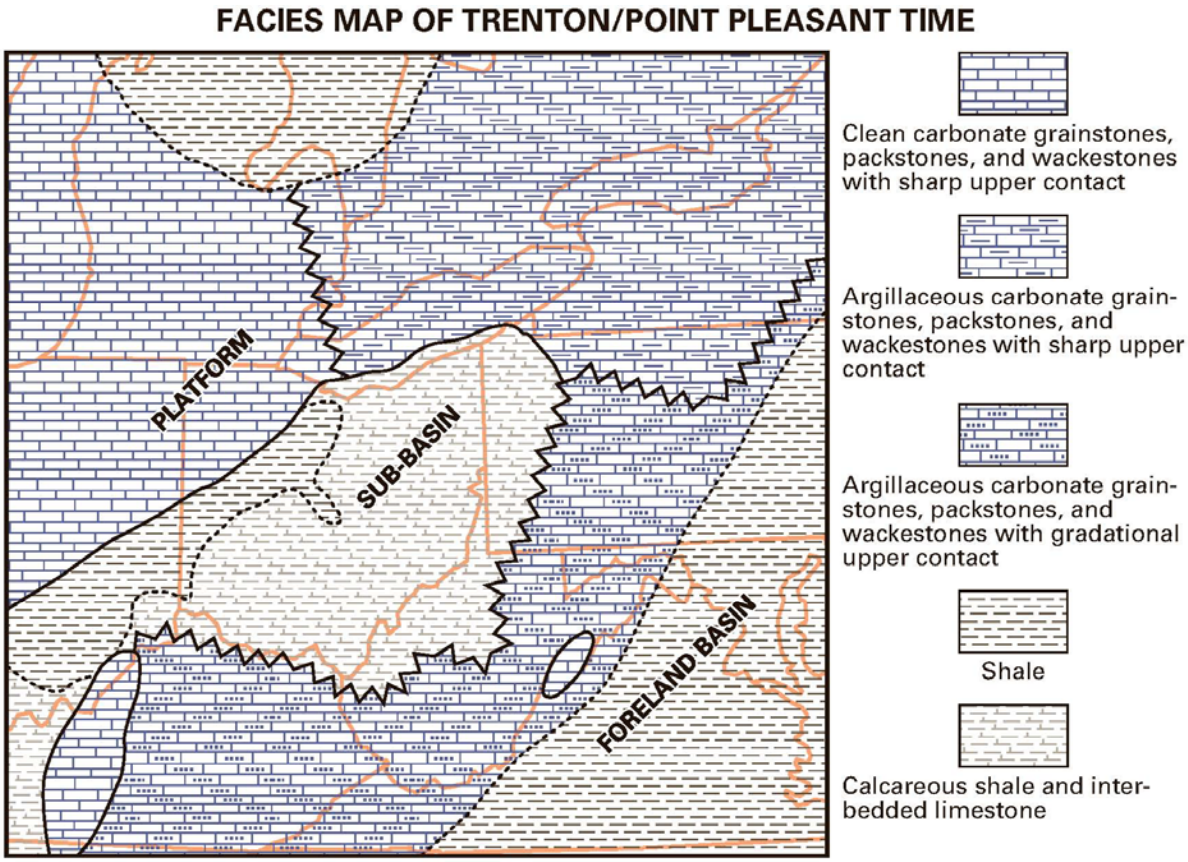


Figure 14

Figure 14. Facies map of late Trenton/Point Pleasant time.

Geological Survey Stone Company well (APINO 3417160004) in Williams County, Ohio (Figure 15). Approximately 230 feet of Trenton are present below the sharp upper contact with the overlying Utica Shale. The Millbrig k-bentonite marks the contact with the underlying mudstone of the Black River. In southwestern Ontario, the Trenton Group (Cobourg, Sherman Fall, and Kirkfield formations) thickens and consists primarily of grainstones and wackestones (Coniglio and others, 1994).

A facies change to a more argillaceous carbonate occurs in western Ontario (Figure 14) and extends to New York. Previous researchers have shown a facies change in western Ontario indicating this eastward transition from a clean carbonate to a more argillaceous carbonate (Keith, 1985; Wickstrom and others, 1992). In this facies, the Trenton consists of an argillaceous carbonate with a grainstone-packstone texture and a sharp upper contact with the overlying Utica Shale. As shown in a type well (Belden and Blake 1 Huber; APINO 3110122859) in Steuben County, New York (Figure 16), the Trenton is much thicker here, approximately 700 feet, compared to the 230 feet present in the Williams County, Ohio well. The upper 100 feet of Trenton in this well contains a clean carbonate, which may have exploration potential for hydrothermal dolomite reservoirs.

To the south of these platform carbonate facies is a deeper water sub-basin where the deeper-water Utica Shale and calcareous shales of the Point Pleasant were being deposited, contemporaneously, in part, with the clean Trenton carbonates. Well-developed Trenton carbonate grainstones-packstones on the Trenton platform margin become thin to the southeast into a sub-basin of increasing shale content. Within this sub-basin the overlying dark Utica shales are thickest where the Trenton is the thinnest. Representative wells of this facies include the Chevron Prudential well (APINO 3410120196) in Marion County, Ohio (Figure 17) and the Ohio Geological Survey American Aggregates well (3416560005) in Warren County, Ohio (Figure 18). In both of these cored wells the cores and geophysical logs indicate the Trenton can be subdivided into the Curdsville Member, Logana Member and Lexington Undifferentiated Member. The top of the Trenton/Lexington is an argillaceous carbonate with a gradational contact with the overlying Utica Shale and Point Pleasant, as compared to the Trenton carbonates on the platform to the north. The Warren County well illustrates the interfingering facies relationship of the Utica Shale with the Point Pleasant as shown by a tongue of typical Utica lithology being present below the Point Pleasant. Hydrothermal dolomites are present in a fractured zone near the base of the Black River in the Marion County well.

South of the sub-basin is the development of the Lexington Platform where carbonate packstones and wackestones were deposited, in part, contemporaneously with the Utica and Point Pleasant clastics of the sub-basin (Figure 14). The Lexington Platform is a deeper water platform than the Trenton platform in northwestern Ohio, as indicated by more argillaceous material and a more gradational upper contact with the overlying Point Pleasant. A representative well for this facies is illustrated by the Signal Oil and Gas Henry Stratton well (APINO 1619524577) in Pike County, Kentucky (Figure 19). The Trenton interval in this well is approximately 550 feet thick and has tentatively been subdivided into the Curdsville Member, Logana Member, and Lexington Undifferentiated Member. A thin (20 feet) Point Pleasant was deposited above the Trenton/Lexington and grades upward into the overlying Kope Formation.

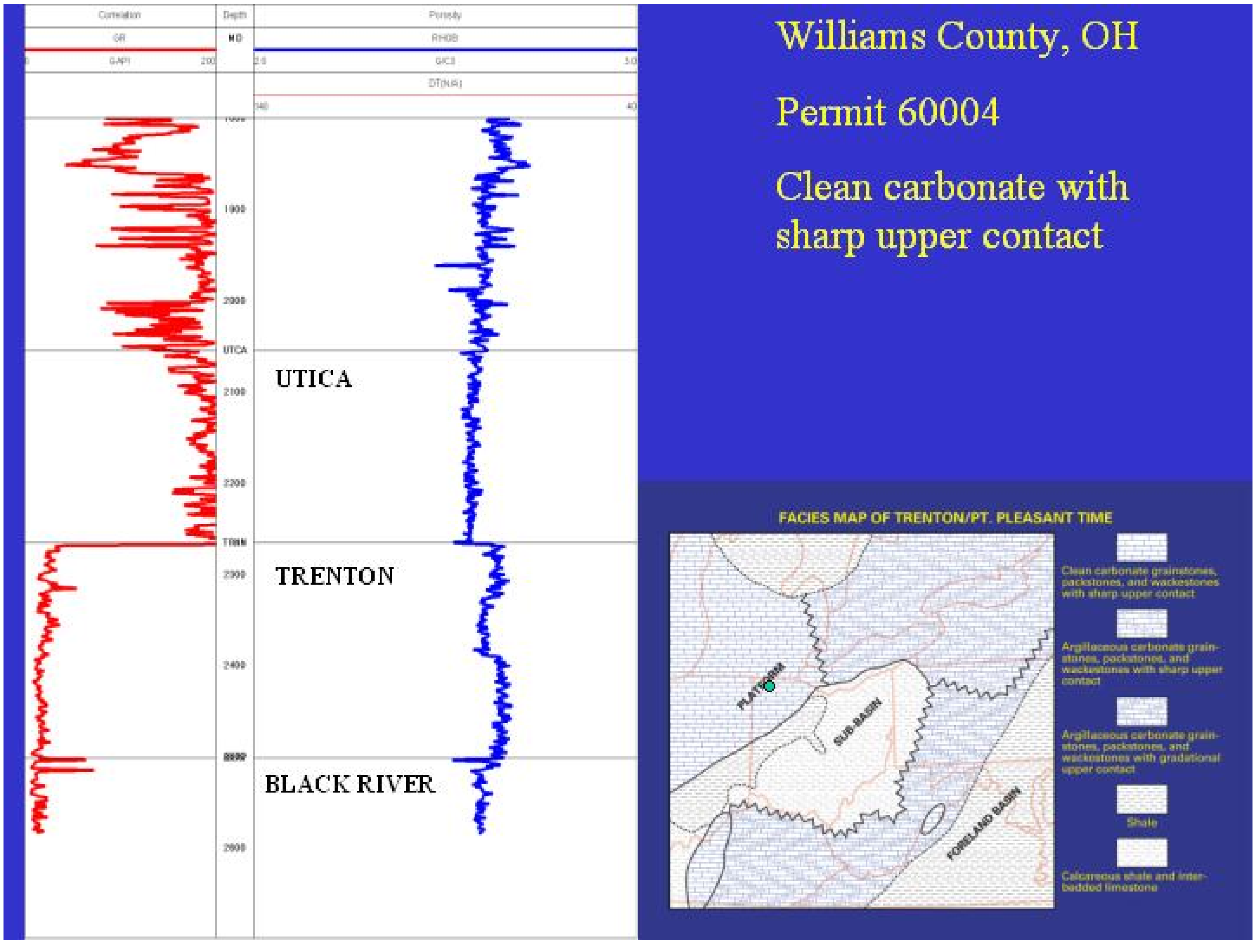


Figure 15. Representative well on the Trenton Platform for the clean carbonate with sharp upper contact facies. Ohio Geological Survey Stone Company well (APINO 3417160004) in Williams County, Ohio.

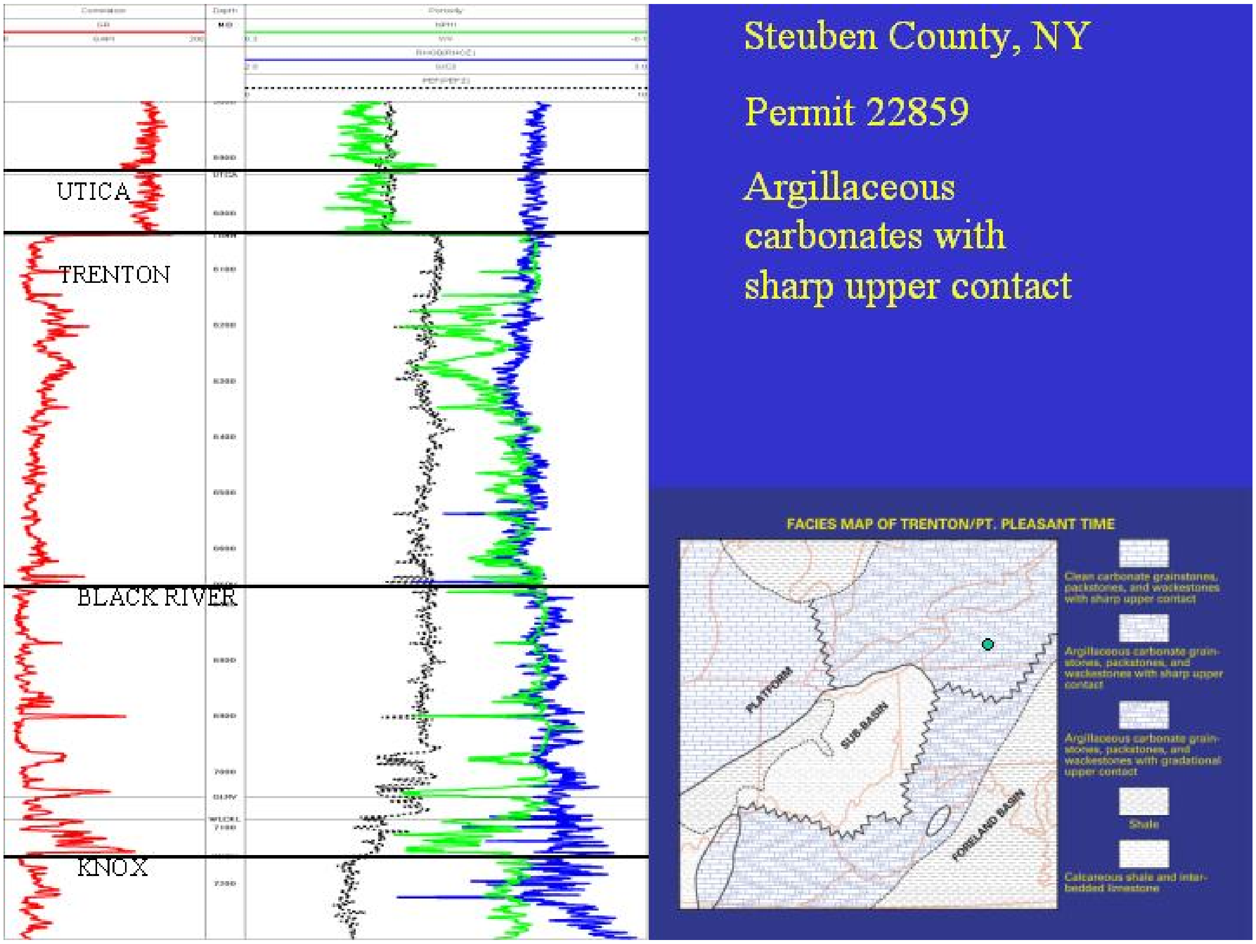


Figure 16. Representative well from the New York Platform for an argillaceous carbonate with a sharp upper contact. Belden and Blake 1 Huber (APINO 3110122859) in Steuben County, New York.

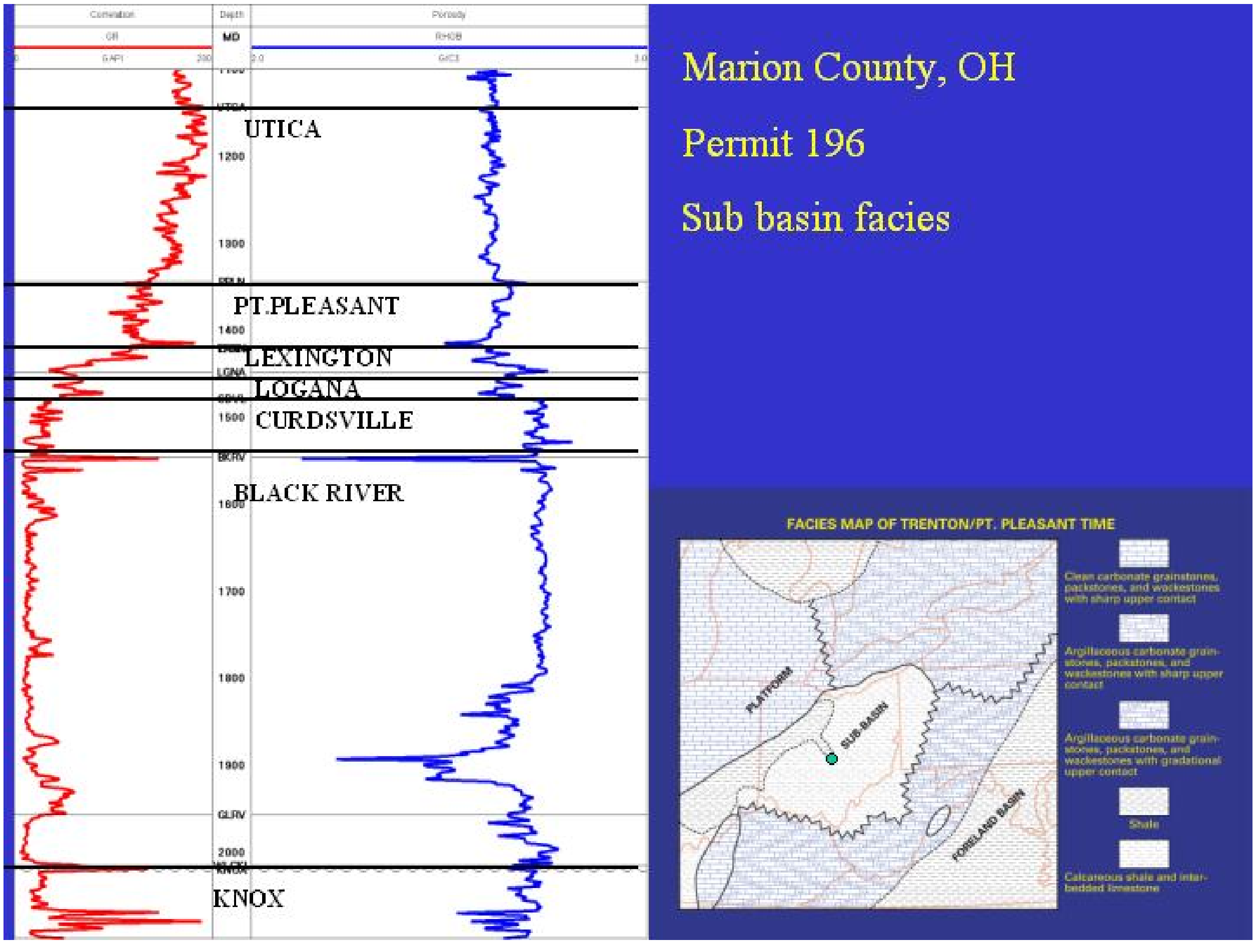


Figure 17. Representative well of the sub-basin facies. Chevron Prudential well (APINO 3410120196) in Marion County, Ohio.

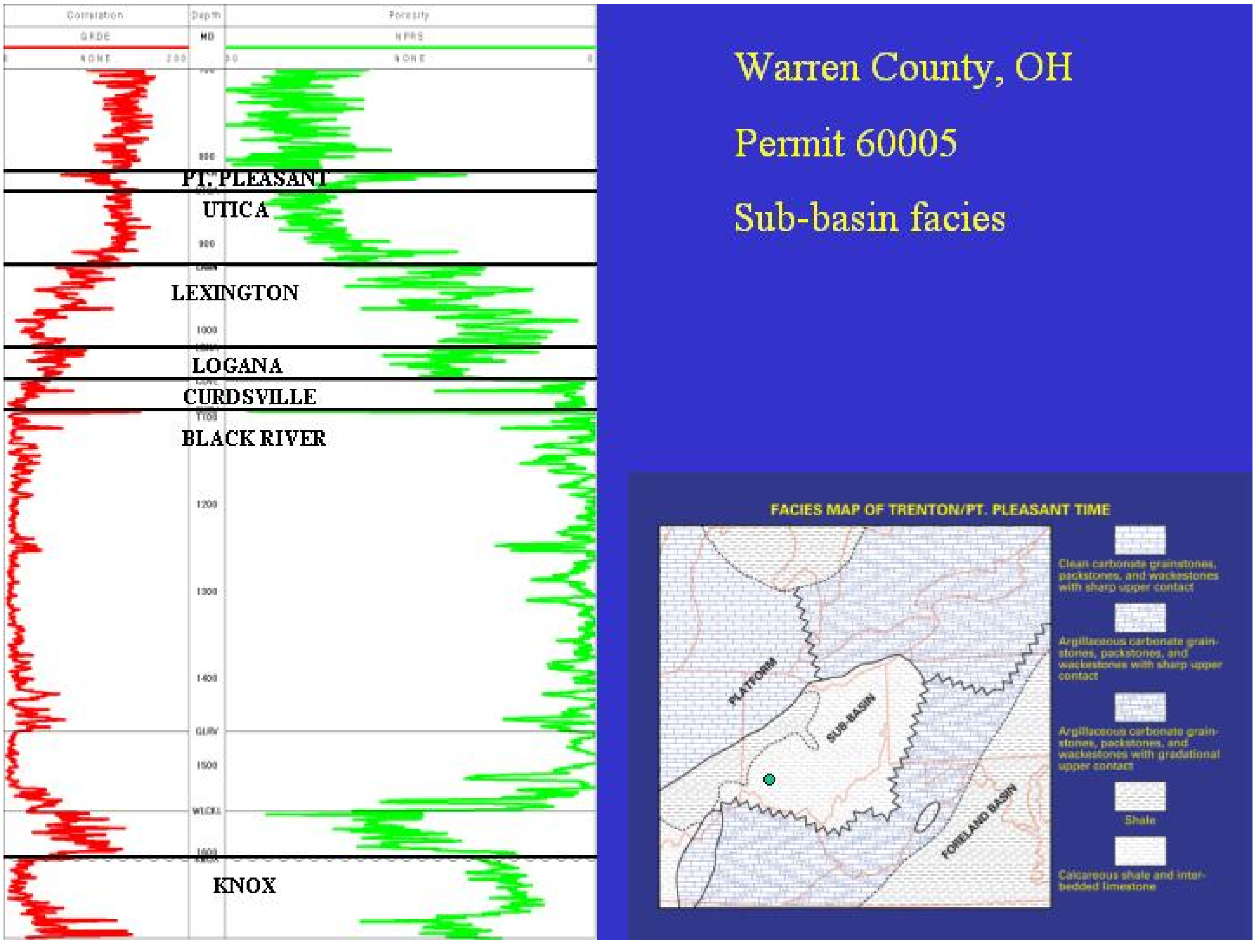


Figure 18. Representative well of the sub-basin facies. Ohio Geological Survey American Aggregates well (APINO 3416560005) in Warren County, Ohio.

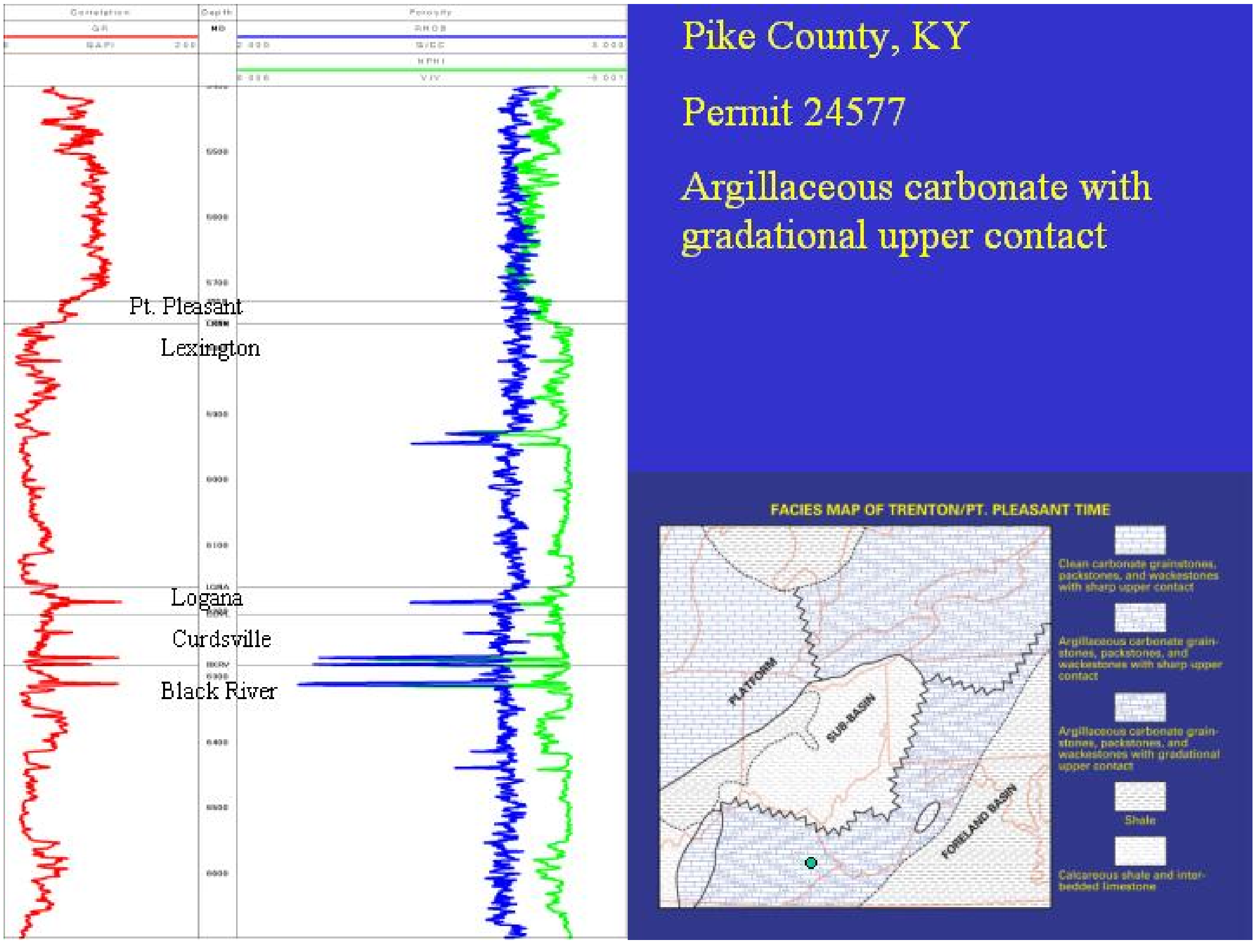


Figure 19. Representative well on the Lexington Platform. Signal Oil and Gas Henry Stratton well (APINO 1619524577) in Pike County, Kentucky.

Based on sample and core data, the dark black, organic-rich shale characteristic of the Utica Shale is absent in this well.

Localized areas of clean carbonate buildups have been identified in the deeper basinal areas where the Trenton is typically an argillaceous carbonate. One of these clean carbonate buildups is illustrated by the United Fuel Gas 1 Sponaugle well (APINO 4707100006) in Pendleton County, West Virginia (Figure 20). This well contains a clean Trenton carbonate with a sharp contact with the overlying Utica Shale. This upper Trenton interval is located at the top of an overthrusted well and a repeated Trenton section (entire interval not displayed). Clean carbonate buildups in this deeper portion of the basin have been described in outcrop work in Kentucky and Virginia by Pope and Read (1997), and also suggested by Keith (1989) in a facies map of Shermanian time.

Point Pleasant and Utica Shale

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 top of the Point Pleasant is placed at the occurrence of thin, interbedded limestone in the shale interval overlying the Trenton. Figure 21 illustrates the limit of Point Pleasant deposition, as interpreted from core, sample descriptions and geophysical logs. North of the line showing the limit of Point Pleasant, the Trenton is overlain by a sharp contact with the overlying Utica Shale. South of this line, the contact of the Trenton with the overlying Point Pleasant is a gradational contact.

The Utica Shale is defined as a dark brown to black, organic-rich shale. Based on examination of core, sample descriptions and geophysical logs, the Utica Shale is absent in south-central Ohio, Kentucky and southern West Virginia (Figure 22). The Utica Shale appears partially coeval with the Trenton of the platform and entirely coeval, as well as overlapping with the Point Pleasant of the sub-basin area. The Utica Shale is absent over most of the Lexington Platform due to facies transition with overlying gray shale of the Kope Formation.

Cross Sections Illustrating Middle and Upper Ordovician Stratigraphic Relationships

A network of cross sections (Figure 1) was developed to unravel the regional stratigraphy and facies relationships, which are necessary for understanding the productive Trenton-Black River reservoirs. Five of those cross sections are discussed and shown within this report. Cross sections are tied to open-file reports, published reports, continuous core and geophysical well logs, and geolog sample descriptions. For all cross sections in this report, the top of the Black River Group is used for the datum and a vertical exaggeration of 200 is used.

Cross section Dip D-D' is oriented northwest to southeast from Jay County, Indiana to Russell County, Virginia (Figure 23). This cross section illustrates subsurface lithostratigraphic correlations of the producing Trenton platform margin area across the sub-basin area to the Lexington platform region. Well-developed Trenton carbonate grainstones on the Trenton

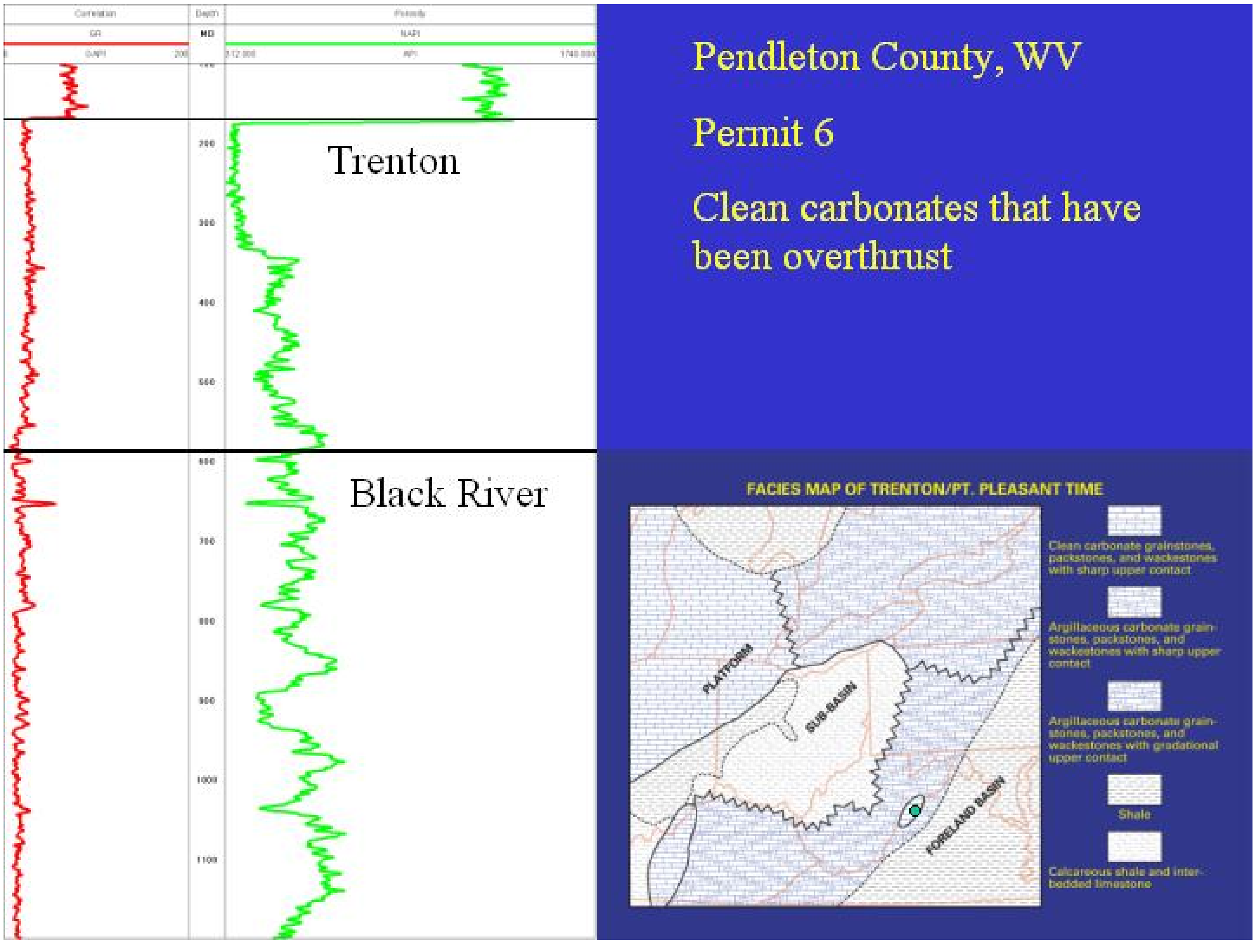


Figure 20. Representative well of a clean Trenton carbonate in the deeper basinal area. United Fuel Gas 1 Sponaugle well (APINO 4707100006) in Pendleton County, West Virginia.

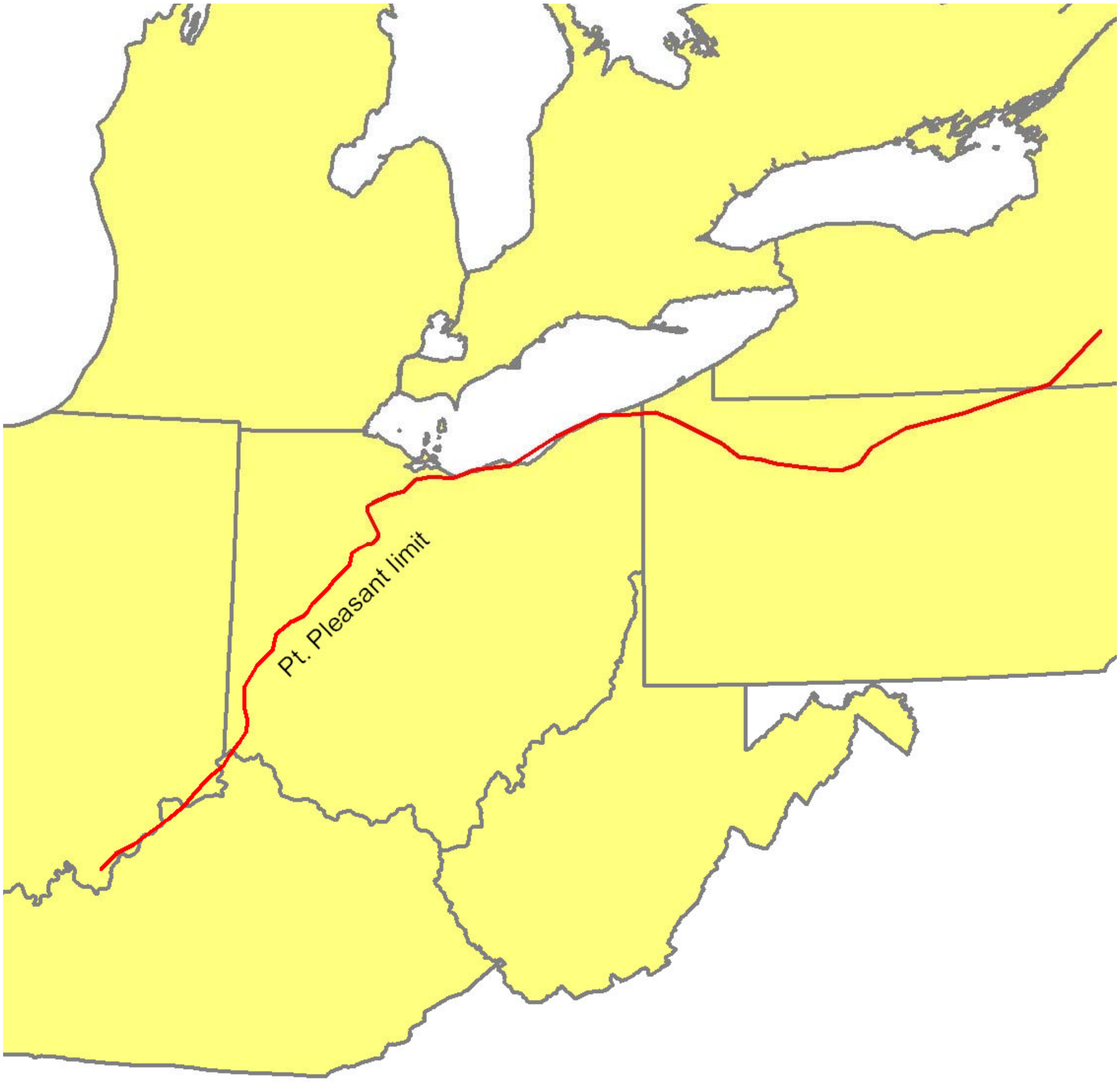


Figure 21. Map showing the limit of the Point Pleasant Formation (present to the south of the line).

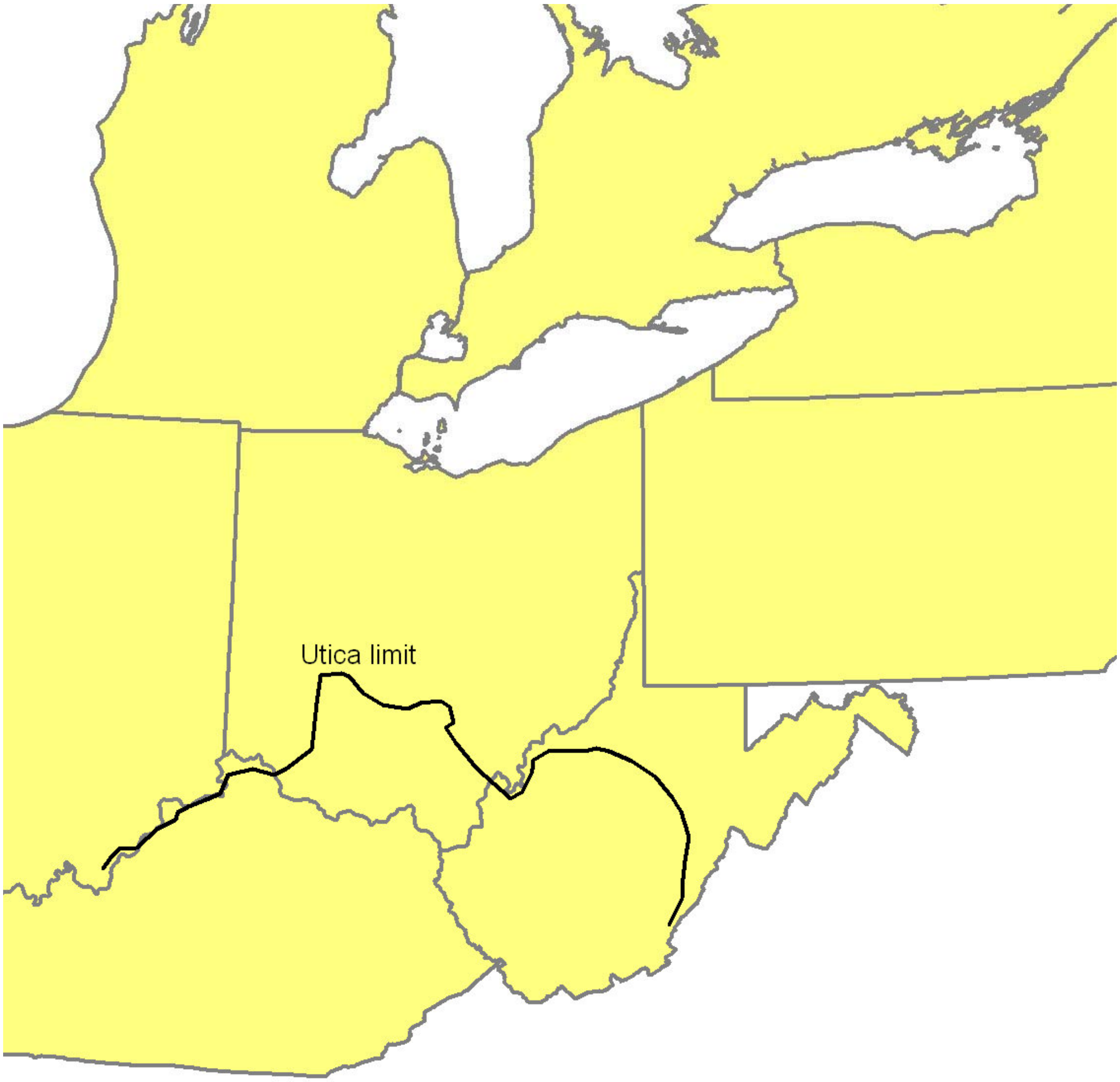


Figure 22. Map showing the limit of the Utica Shale (present to the north of the line).

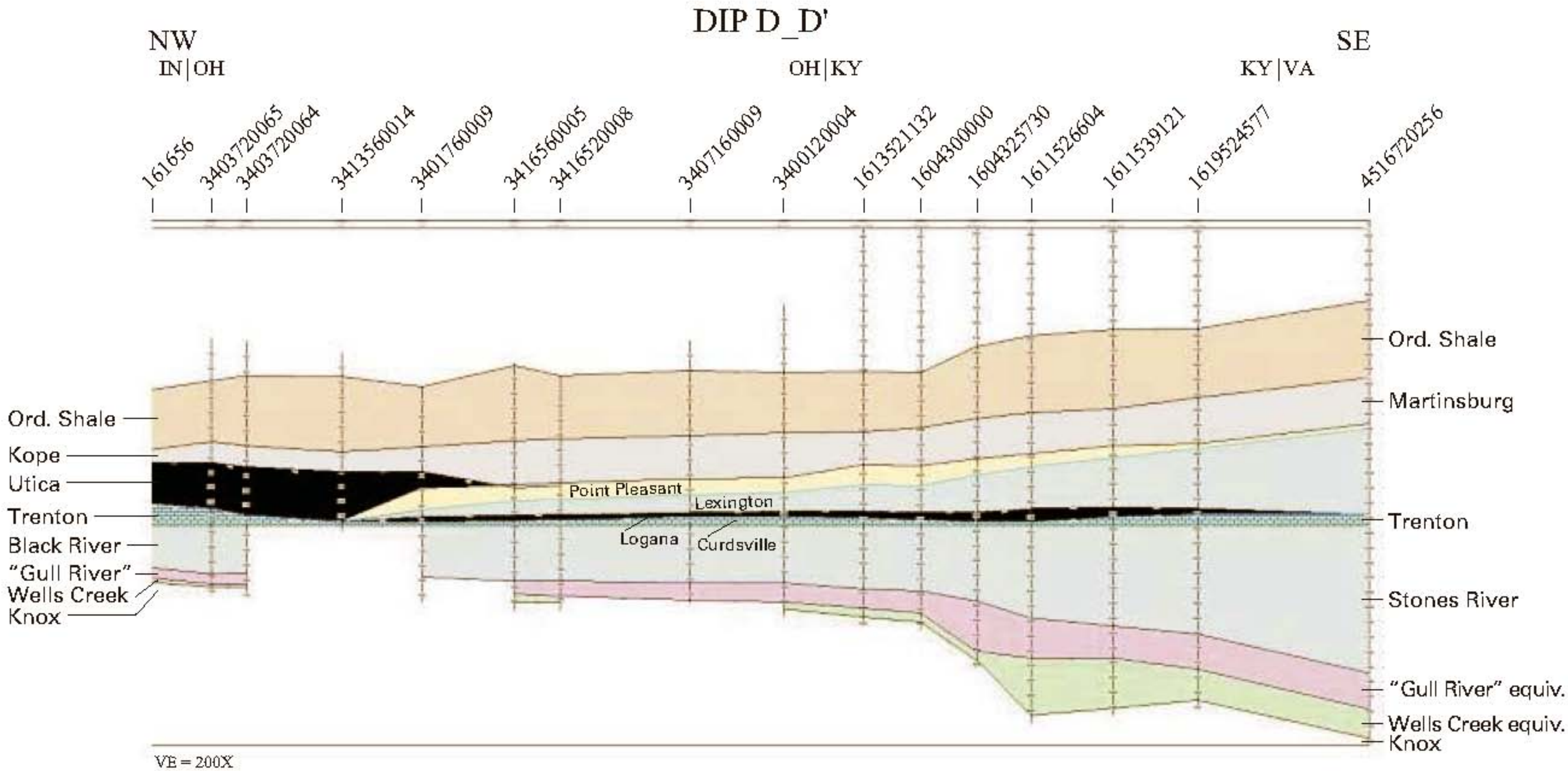


Figure 23

Figure 23. Regional cross section Dip D-D' extending from Jay County, Indiana to Russell County, Virginia. Datum is the top of the Black River. Wells are proportionately spaced and a vertical exaggeration of 200 is used. Location of cross section is seen on Figure 1.

platform margin are approximately 160 feet thick and thin to about 30 feet to the southeast into a sub-basin of deeper water Utica Shale and Point Pleasant calcareous shales. 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. The Lexington is subdivided in ascending order into: the Curdsville Member, the Logana Member and the Lexington Undifferentiated Member. The top of the Lexington is chosen on geophysical logs using the best-developed carbonate bed at the base of the Point Pleasant Formation.

Cross section Dip H-H'(Figure 24) trends northwest-southeast from Essex County, Ontario to Hardy County, West Virginia and roughly parallels the previous cross section. Similar facies relationships are evident to the previous cross section as shown by the Trenton Platform, the sub-basin and the thicker Trenton/Lexington development to the southeast. On the productive Trenton Platform, the Trenton carbonates obtain a thickness of 370 feet and thin to approximately 80 feet in the sub-basin. The upper portion of the Trenton appears to be, in part, coeval with the Point Pleasant strata of the deeper water sub-basin. Trenton equivalent strata (Lexington, Logana and Curdsville members) in the sub-basin thicken on to the deeper water carbonate platform where the unit reaches a maximum thickness of 640 feet. The overlying Ordovician shales and the underlying Black River both indicate basinward thickening to the east and southeast. The "Gull River" and Wells Creek Formation indicate thickening over the Rome Trough feature.

Cross section Dip J-J' (Figure 25) extends from Huron County, Ontario to Bedford County, Pennsylvania and also depicts the basin architecture discussed previously. The Trenton section reaches a maximum thickness of 480 feet on the Trenton platform and thins to 120 feet in the sub-basin where the Trenton is in facies transition with the Point Pleasant. In the eastern portion of this line, the more argillaceous Trenton equivalents obtain a thickness of 440 feet. As shown earlier, the overlying Ordovician shale section and underlying Black River both thicken basinward to the southeast.

Cross section Dip L-L' also trends northwest-southeast (Figure 26). This line of cross section illustrates the platform area from Durham Regional Municipality, Ontario to Broome County, New York. The Trenton platform carbonates reach a maximum thickness of 750 feet in Steuben County, New York, and thin to the southeast along the platform margin to approximately 230 feet. Point Pleasant-type rocks are present above the Trenton at the southeastern end of this line and display a similar relationship along the platform margin that is observed in northwestern Ohio.

Cross section Strike D-D' trends southwest-northeast along depositional strike from Hart County, Kentucky to Onondaga County, New York (Figure 27) and ties into the previous dip cross sections shown. The southwestern portion of the cross section illustrates the Lexington platform where the Trenton equivalents reach a thickness of 180 feet. This cross section then extends across the sub-basin in Ohio and Pennsylvania and onto the Trenton Platform of New York where the Trenton reaches a maximum thickness of 780 feet. As with the previous cross sections, the Trenton equivalent thins in the sub-basin where it is subdivided in to the Curdsville,

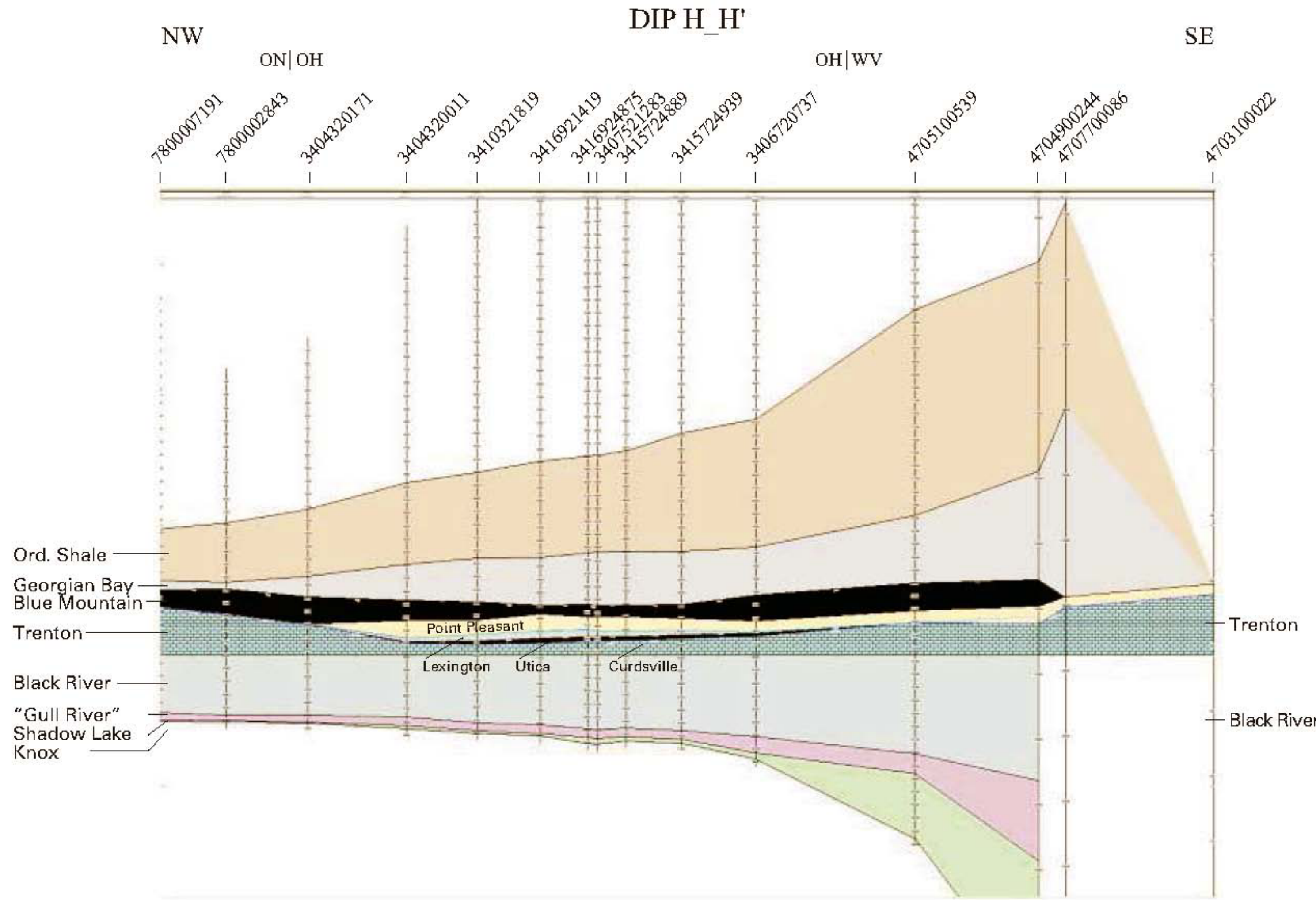


Figure 24

Figure 24. Regional cross section Dip H_H' extending from Essex County, Ontario to Hardy County, West Virginia. Datum is the top of the Black River. Wells are proportionately spaced and a vertical exaggeration of 200 is used. Cross section location is shown on Figure 1.

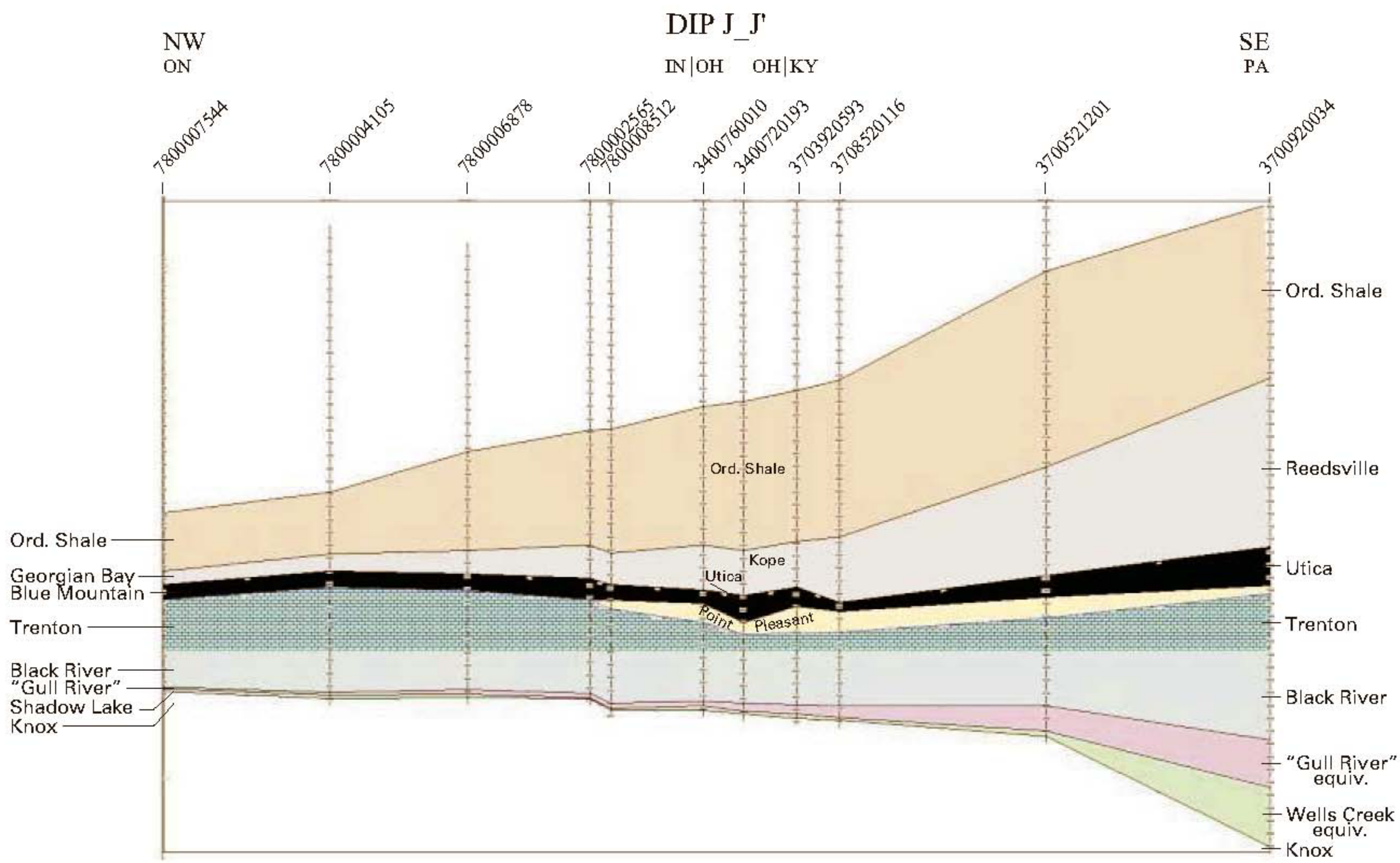


Figure 25

Figure 25. Regional cross section Dip J_J' extending from Huron County, Ontario to Bedford County, Pennsylvania. Datum is the top of the Black River. Wells are proportionately spaced and a vertical exaggeration of 200 is used. Cross-section location shown on Figure 1.

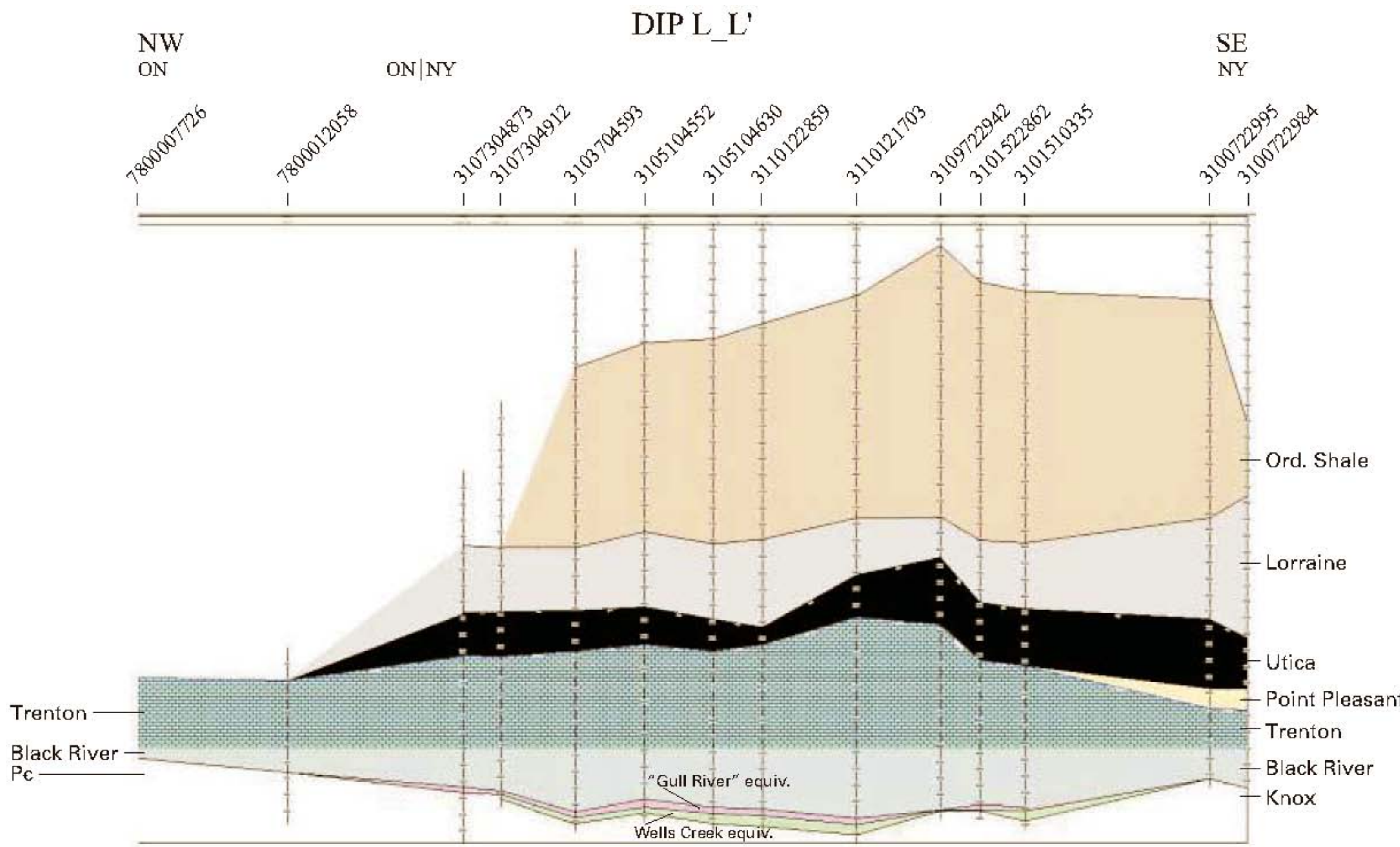


Figure 26

Figure 26. Regional cross section Dip L-L’ extending from Durhan, Ontario to Broome County, New York. Datum is the top of the Black River. Wells are proportionately spaced and a vertical exaggeration of 200 is used. Cross section location is shown on Figure 1.

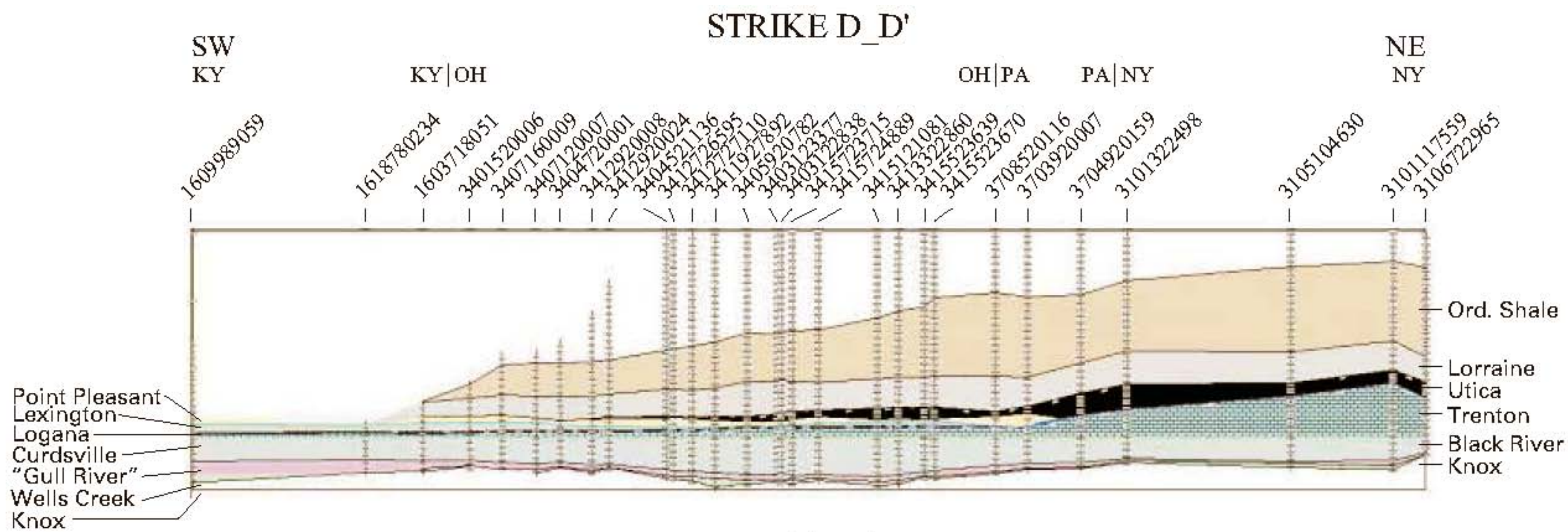


Figure 27

Figure 27. Regional cross section Strike D-D' extending from Hart County, Kentucky to Onondaga County, New York. Datum is the top of the Black River. Wells are proportionately spaced and a vertical exaggeration of 200 is used. Cross section location is shown on Figure 1.

Logana, and Lexington Undifferentiated members. Development of the Point Pleasant also is evident in the sub-basin region.

Stratigraphic Summary and Conclusions

Understanding the basin architecture and facies distribution has important implications for Trenton-Black River exploration. Preliminary isopach maps of the Trenton interval and preliminary facies maps representing Trenton/Point Pleasant time indicate that exploration potential exists along the entire platform margin. Grainstones in the skeletal shoals that developed along the platform margin extending from Indiana to northwest Ohio to Ontario and to northern Pennsylvania appear to be prime intervals where hydrothermal dolomite (HTD) reservoirs could be developed in the Trenton. Vast unexplored areas are present along the platform margin in the Ohio and Pennsylvania portion of Lake Erie that could yield large reserves.

The best reservoir facies for HTD appear to be developed in the clean Trenton and Black River carbonates. Comparison of the Trenton-Black River producing fields with the type of producing reservoir supports that idea. Producing HTD reservoirs in the historic Lima-Indiana producing trend in northwest Ohio and Indiana and in producing fields in Ontario indicate that the best reservoirs are from clean carbonates in the Trenton grainstones and packstones. Production in HTD reservoirs in New York, thus far, has been from the cleaner carbonate of the Black River and as yet has not been found extending up into the Trenton. Current thinking within this project is that the more argillaceous nature of the Trenton carbonates may inhibit the process of HTD reservoir development. There is, however, an upper, cleaner portion of the Trenton in western New York which may have potential for HTD reservoir development. Thus, this may be an unexplored area with potential Trenton hydrocarbons.

Trenton-Black River production in Kentucky and West Virginia, thus far, has been from fractured limestone reservoirs. This also seems to support the idea that the dirtier, more argillaceous carbonates in these deeper, basinal areas may not be as conducive to HTD reservoir development as the cleaner carbonates on the northern Trenton platforms. However, there do exist in this deeper portion of the basin, localized areas of cleaner carbonate buildups in the Trenton that may be more conducive to HTD reservoir development. If these localized areas of cleaner carbonates with a sharp upper contact could be imaged with seismic reflection data, it could assist in identifying potential exploration trends for Trenton-Black River production where the seismic signature can be mapped. Seismic modeling is required to lend credence to this idea.

Geologic Structure & Seismic Analysis

Structural and seismic analyses are being carried out to characterize the major geologic structures of the study area. The objective is to evaluate the regional structures of the study area and determine as closely as possible the fault timing relative to the fracturing, dolomitization and hydrocarbon charging of reservoirs in the Trenton-Black River interval.

As part of the Geologic Structure and Seismic Analysis Task, structure and isopach maps will be created for the five-state study area for the following horizons and intervals: top and base of the Devonian Shale; top of the Ordovician, Kope Formation, Utica Shale, Trenton Formation and Black River Limestone; top and base of the Knox Supergroup, Rome Formation and basal sandstone; and top of the Precambrian igneous/metamorphic basement. Horizon elevations from well data will provide the bulk of the data for these maps. However, data points from wells are inherently 1-dimensional points. The addition of horizon elevations from 2-D seismic lines adds not only to the overall data density, but also adds information on regional dip trends, fault zone width and offset, and anticline/syncline axis magnitude and character.

Over the next three months, the workload will shift from regional stratigraphic mapping to more detailed structural analyses. This work will include topics such as determining the source of the heated dolomitizing fluids that altered portions of the Trenton and Black River units in the Appalachian Basin, and defining the probable migration paths of these fluids. Along with mapping the major structural features and evaluating the regional structural framework that emerged from the regional structure and isopach mapping, faults of suitable age, orientation and location to be relevant for HTD creation within the Trenton-Black River section will be isolated. From this, potential hydrothermal dolomite development fairways can be delineated.

Completed Tasks and Results

Data Acquisition

Data acquisition for this task has been completed. A considerable amount of 2-D seismic data, although less than anticipated, has been compiled for this project. Also, digitized geophysical well logs for 402 wells and preliminary stratigraphic well tops from 1797 wells have been used for seismic correlation and structural analysis.

Data Loading

Raw data loading for this task has been completed. Digital seismic data (SEGY files) have been loaded into Seismic-Micro Technology’s Kingdom Suite software, and raster images (Tiff files) have been loaded into the PetraSeis module of Geoplus Petra software platform. A total of 402 digital geophysical well logs (LAS files) have been loaded into Petra and Kingdom Suite software, including sonic logs for 114 wells. The preliminary set of formation tops that has been loaded includes 831 Kentucky wells, 103 Ohio wells, 644 New York wells, 101 Pennsylvania wells, and 22 West Virginia wells.

Correlate Stratigraphic Tops to Seismic Horizons

Sonic logs for 114 wells throughout the 5-state project area were used to create synthetic seismograms and velocity models. These velocity models were used to transform known well top depths in feet subsea to depths in time for seismic correlation. This additional step within the interpretation process worked both as a quality checking mechanism and in assisting the correlation of log tops to reflecting seismic horizons in areas with seismic data of poor quality. The correlation and velocity model creation have been completed.

Interpret Stratigraphy and Structure from Seismic

All seismic data available to the consortium have been examined and interpreted. Fault trend mapping is nearing completion. Because the mapped horizons are all offset at one point or another by faults, this is the final step before regional mapping and merging of the multifaceted research that has been done by the five member research consortium can begin.

Discussion

Determining the Source of the Dolomitizing Fluids

One of the unknowns about the development of the productive dolomitized zones within the Trenton and Black River (TBR) units of the Appalachian Basin is the source and timing of the dolomitizing fluids. Where did these magnesium-rich fluids come from, and how were they heated to “hydrothermal” levels?

Numerous lines of evidence suggest that these fluids migrated along basement-rooted faults. Because in many, if not most, cases these faults terminate in the strata just above the Trenton, these fluids probably did not migrate downward from a higher source. Instead, the high magnesium levels within the fluid that was needed to dolomitize large portions of the Ordovician limestone units must have come from a deeper source.

No evidence has been found that suggests extensive leaching of the dolomites within the Knox Supergroup. Therefore, the likely source of magnesium is even deeper, from the igneous and metamorphic rocks of the Precambrian Grenville “basement”. This also would explain the occurrence of other non-magnesium metal ions observed within the hydrothermal dolomites. Within a cored fault zone in central Kentucky, sphalerite, barite and pyrite were reported (Harris, et al., 2004) in the hydrothermal dolomites within the Upper Ordovician section. All of this suggests that the heated brines that formed the dolomite had spent a considerable time in close contact with either basement rocks, or within the relatively immaturely-weathered basal sandstones derived from the basement.

Determining the Source of the Elevated Temperatures

Stratigraphic and anecdotal data suggest that the Trenton was faulted and dolomitized by Late Ordovician time. At the end of the Ordovician, the depth to the Precambrian was roughly 1250m in New York, and 1600m in Kentucky. If we assume from the analysis above that the fluids came from the basement, they would have to have originated from at least this depth.

Because igneous and metamorphic rocks tend to have close to 0% porosity, it is reasonable to assume that the large volumes of fluid needed to create the amount of dolomite observed probably came from within the upper, weathered portion of the basement or within the overlying basal sandstones. It is unlikely that the aperture of the fault itself could contain sufficient volumes, especially with the increasing pressure at depth.

If we assume a high surface temperature of 28°C and a high geothermal gradient of 30°C/km, the expected ambient temperatures within the upper portion of the Precambrian during the Late Ordovician would be around 76°C for Kentucky and 65°C for New York. However, fluid inclusion data from TBR dolomites in central Kentucky and western New York indicate that the dolomitizing fluids were at much higher temperatures. The homogenization temperatures for these inclusions were 104°C for central Kentucky and 140°C for the New York samples. If a pressure correction is made to these values to account for the depth of burial, these values rise even further. The values rise to 110-122°C for Kentucky, depending on if you assume a hydrostatic or a lithostatic pressure gradient. The calculation of the pressure corrected values for the New York samples was not complete at the time of this writing.

What is the source of this extra 35-45°C for Kentucky and 75+°C (uncorrected) for New York Ordovician dolomites? Possible additional heat sources that have been suggested include deep-seated (upper mantle) fault fluids, volcanics or pluton emplacement, an anomalous "thermal pulse" from within the mantle, or co-seismic frictional heating.

If the assumption that dolomitization occurred during the Late Ordovician is correct, then excess heat from emplacement of igneous plutons is unlikely. Hydrothermal dolomites have been documented in an area that extends from eastern Tennessee to southern Ontario. The likelihood of a continent-scale volcanic event occurring over this broad area without having any igneous rocks observed above the Precambrian unconformity seems quite remote. Similar evidence of a mantle derived "thermal pulse" during this period has not been documented, either.

Using deep-seated fault fluids as both a source of excess heat and for magnesium content is an attractive option, but the ability of that type of hydrothermal system to generate the volumes of fluids needed is questionable, but not impossible.

The last hypothesis for a Late Ordovician heat source is co-seismic frictional heating. In this scenario, earthquake motions along wrench faults create frictional heat within and immediately adjacent to the fault zone. Pore fluid within this area is heated by conduction and expands, rising rapidly up newly-formed fault conduits (direction of lowest pressure). Repeated faulting episodes are needed to achieve the required fluid volume, but this scenario works well with the "fault-valve" model of Sibson, et al. In this model, fault conduits are periodically plugged by precipitated minerals from hydrothermal fluids. After being plugged, fluid pressures and temperatures rise below the fault blockage until another earthquake ruptures the fault-sealing plug of minerals. Once this is breached, fluids expand rapidly up the fault conduit which lowers the pressure (and therefore temperature) at depth. At these lower pressures and temperatures, minerals precipitate out of the fluids until the fault is plugged once again. Repeated episodes of this type create a "pump valve" affect for the hydrothermal fluids. More work is needed to evaluate this scenario to determine if it is applicable to the TBR dolomites.

Unfortunately, data suggesting Late Ordovician HTD emplacement are somewhat circumstantial. If fluid migration and dolomitization of these rocks occurred after the Ordovician Period, then other scenarios are possible. It is possible that the faulting occurred during the Taconic Orogeny, but that the dolomitizing fluids migrated to the Trenton-Black River later, during the Acadian Orogeny. With more sediments deposited on top of the Ordovician section, depth of burial of the Precambrian basement would be greater. This would in turn cause the ambient temperatures to be higher as well, reducing the need for an additional heat source. In addition, there is evidence of a Middle Devonian "thermal event" which has been interpreted from illite-based Rb/Sr data. This also may coincide with volcanic intrusives within New York, adding an additional possible heat source for the hydrothermal fluids.

Did the dolomites form during the Late Ordovician, or Middle Devonian, or sometime else? More work is needed and is ongoing within this research consortium to refine the timing of migration of these heated, high-Mg fluids. The dolomitizing event was needed to create the future reservoir volumes being exploited by the current TBR gas play. The discovery of this timing and method may prove crucial to understanding the play, and in forecasting where further accumulations of oil and gas will be found.

Hydrothermal Alteration of Carbonate Reservoirs

Hydrothermal dolomite reservoirs have received much recent attention in North America with the discovery of Ladyfern (~750 Bcf) in Western Canada and continued exploration success in the Trenton-Black River Play in the Appalachian basin (newly discovered reserves of up to 1 Tcf so far). Further investigation of these and other fields suggest that many carbonate reservoirs are either formed entirely by hydrothermal processes or significantly modified (both positively and negatively) by fluids flowing up active faults. The purpose of this discussion is to show petrographic and geochemical criteria for recognition of hydrothermally-altered carbonates, and to discuss the structural settings and seismic expression of some hydrothermally-altered carbonate reservoirs with the goal of developing exploration and development concepts. Hydrothermally-altered reservoirs may represent one of the largest untapped resources in mature basins of the world because they are commonly contained in subtle diagenetic traps that are easily bypassed by drilling.

Hydrothermal alteration is not restricted to local dolomitization and other mineralization around faults in a few localities, but occurs in a wide variety of structural and stratigraphic settings all over the world. Hydrothermal alteration products may include, but are not restricted to, matrix and fracture-filling dolomite, recrystallized limestone (including development of microporosity), bedded and fracture-filling chert and chalcedony, dilational breccias and fractures, pore- and fracture-filling anhydrite, calcite, ferroan calcite, quartz, fluorite, barite, bitumen, authigenic clay minerals, sulfides and more. Furthermore, leaching of limestone, dolomite and other minerals is a common occurrence in hydrothermally-altered reservoirs and can be a primary control on reservoir quality.

Fault-related hydrothermal alteration occurs when high-pressure, high-temperature fluids flow up active faults and move laterally into permeable formations that underlie sealing shales, argillaceous limestones or evaporites. Alteration occurs due to the episodic influx of fluid up the fault, the mixing of that fluid with the fluid in the formation and during the subsequent equilibration with the formation conditions. Solubility of carbonates (and other minerals) is directly affected by changes in temperature, pressure, P_{CO_2}, pH, and salinity and all of these are fluctuating on short time scales in hydrothermal systems. This rapid change in fluid chemistry is what makes fault-sourced hydrothermal fluids capable of causing significant diagenesis in relatively short periods of time.

Much has been made of hydrothermal dolomite over the past few years, but just as *or more* important for oil and gas reservoirs is the capacity for hydrothermal fluids to leach limestone and, in some cases, dolomite. The solubility of carbonate minerals is strongly affected by temperature, P_{CO_2}, salinity and pH. Calcite and dolomite have retrograde solubility, which means that cooler fluids can hold more of these minerals in solution than relatively warmer fluids. Hot, fault-sourced fluids may precipitate dolomite or calcite when they first enter the formation, and then will become progressively more undersaturated and capable of leaching as they cool to the ambient temperature. Carbon dioxide also has retrograde solubility, so any CO_2 vapor that forms as mineralization proceeds, may go into solution as carbonic acid as the fluid cools. This can drop the pH significantly and add to the potential for the cooling hydrothermal fluids to leach limestone. Furthermore, there is a clear trend towards higher salinity and lower pH with depth in sedimentary basins (Hanor, 1993). Brines flowing up faults will likely have lower pH and higher salinity than fluids higher in the section. Fluid inclusions in most hydrothermal cements show elevated salinity with an average of about 20wt%. So cooling, CO_2-charged saline brines should extensively leach limestone. Fluid evolution and leaching mechanisms are discussed at length below.

First-order controls on hydrothermal alteration products include: composition, thickness, porosity and permeability of the host rock, the pressure, temperature and chemistry of the hydrothermal fluid, the effectiveness of the seal, distance to the basement and basal sandstone aquifer, and the type and timing of faulting.

Structural settings where hydrothermally altered carbonates are commonly found include around margin-bounding faults, over newly-rifted basement and active normal faults, at fault intersections and around wrench faults that are activated during mountain building events. The wrench faults commonly express themselves as subtle flower structures that are difficult to interpret if one is not looking for them. Once they are recognized it becomes clear that they are very common in many settings. The seismic expression of many hydrothermally-altered reservoirs is in structural sags produced by transtensional faulting. Reefs and mounds commonly form over faults and are then altered by fluids flowing up the same faults.

Preservation of porosity at great depth may be more common in hydrothermally-altered reservoirs because of the abundance of secondary and fracture porosity. Secondary and fracture porosity may stay open at greater depths because there is a rigid framework around the pores that holds them open.

Discussion

This report is in part a presentation of new ideas and in part a review of literature and existing concepts. Supporting presentations are included on the project's ftp site. No other single reference covers hydrothermal alteration of carbonate reservoirs more exhaustively than the Graham Davies Report on Hydrothermal (Thermobaric) Dolomite Reservoir Facies (Davies, 2001). Anyone who is interested in hydrothermal alteration is encouraged to read this excellent paper. Although an effort has been made to provide new material in this report, some of the ideas presented in Davies (2001) will necessarily be repeated for the sake of clarity. While the whole paper is interesting, the most important points, are these:

- Most saddle dolomite forms rapidly from hot, saline, highly supersaturated hydrothermal fluids – saddle dolomite is an indicator of hydrothermal alteration
- Hydrothermal dolomites generally, but not always, have primary fluid inclusion homogenization temperatures between 75 and 225°C, fluid inclusion salinities between 10-30 wt% with an average of 20 wt%, negative $\delta^{18}O$ stable isotope values, and radiogenic strontium isotope ratios relative to seawater for the time that the carbonates were deposited.
- The link between hydrothermal SEDEX (shale-hosted sulfide ore deposits), carbonate-hosted hydrothermal MVT ore deposits and hydrothermal dolomite reservoirs
- The association of the aforementioned hydrothermal alteration and transtensional, strike-slip and extensional faults

- Review of fluid flow in faults and presentation of evidence that suggests that most fluid flow occurs during the time period when the faults are actively moving and when the altered formations are buried to depths of less than a kilometer (and more commonly less than 500 meters)
- Demonstration that matrix dolomitization occurs at the same time and due to the same process that makes saddle dolomite
- Link between leached limestone and hydrothermal dolomite and presentation of a model wherein dolomitization occurs nearest to the faults and leached limestone occurs in areas dominated by fluid cooling
- Extensive work on zebra fabrics, boxwork fabrics and other diagenetic features peculiar to hydrothermally altered reservoirs.

This report (Davies, 2001) is highly recommended reading. The basic model for alteration – that significant diagenesis occurs during periods of active faulting and upward fluid flow – is the same, but some new aspects and examples will be discussed in this report. Also new in this report is a study of possible fault-related, hydrothermal-leaching mechanisms, discussion of fluid evolution and fluid mixing, illustrations of how hydrothermal alteration may proceed and a host of new examples of hydrothermal alteration.

Hydrothermal alteration of carbonates and carbonate reservoirs is difficult or impossible to directly observe. This is in contrast to some other diagenesis that is occurring at or near the surface today. Because it is difficult to impossible to directly observe, fault-related hydrothermal alteration has historically been underapplied or ignored as a possible diagenetic model. Features that may have been produced by hydrothermal alteration are commonly interpreted to have formed in the near surface (meteoric, reflux and mixing zone) or "deep burial" environments. Because they have already been interpreted differently, there is some resistance to the ideas presented in this report and in Graham Davies' work.

In this report, new ideas are presented, some of them controversial. Some are supported by hard data, whereas others are more conceptual and need to be tested. The most controversial ideas have been put forward intentionally in order to spur discussion. Some ideas may change as more data become available, but the thinking is that many of them will gain more support with time and the sort of detailed integrated study necessary to demonstrate a hydrothermal origin for diagenesis.

Definitions

Hydrothermal simply means "hot water." A *hydrothermal fluid* in the geological sense is any fluid that is warmer than the ambient temperature at a given depth with a given regional geothermal gradient (White, 1957; Machel and Lonee, 2002). Some suggest that the fluids must be at least 5°C warmer than the ambient temperature (Machel and Lonee, 2002) and this may be a reasonable cutoff since temperatures could vary within a 5°C range for reasons other than introduction of an extra-stratal fluid. For strata buried to a depth where the ambient temperature is X°C, any fluid that is greater than (X+5)°C is then considered a hydrothermal fluid. So, for example, if the ambient burial temperature of a given formation is 25°C, any fluid warmer than 30°C would be considered hydrothermal.

In fault-related hydrothermal systems where fluids are flowing up faults, not only is the fluid warmer than the ambient temperature of the formation, the pressure is likely to be higher, the salinity is likely to be higher and the chemistry is likely to be different. The term hydrothermal does not capture all of these attributes, but in this report, the term will be used to describe a fluid that has all of these properties. Davies used the term *thermobaric* to describe fluids that are both high-pressure and high-temperature relative to the host rock. The term "fault-related" is used to point out that not all hydrothermal activity is related to igneous intrusions. Fluids can be hydrothermal and have nothing to do with igneous processes.

Hydrothermal alteration occurs when rocks are mineralized, leached or otherwise modified by a fluid that is at least 5°C warmer than the ambient burial temperature when it is *first introduced* to the formation at a given depth. These fluids will mix with *in situ* fluids and eventually cool to the ambient temperature. Further diagenesis is likely to occur during periods of mixing and cooling. There are documented examples in this report where hydrothermal fluids that altered carbonate reservoirs were at least 150°C warmer than the ambient burial temperature and examples where the hydrothermal fluids were probably less than 30°C warmer than the ambient temperature. In the absence of any local igneous activity, hydrothermal fluid flow would almost necessarily require upward fluid flow from greater depths through fault or fracture conduits. It is only in faults and fractures that permeabilities would be high enough to preserve fluid temperatures that are significantly higher than the ambient burial temperature.

Hydrothermal alteration is not necessarily "deep burial" diagenesis and this term will be avoided in this report. In fact, much of what will be described herein may better be termed "shallow burial" diagenesis, where most of the alteration takes place in the first kilometer of burial. Much of the alteration that other authors have attributed to "deep burial" diagenesis may in fact take place at much shallower depths. That is not to say that all hydrothermal alteration occurs at shallow depths of less than a kilometer, because there are certainly cases where it has not. But it must be clear that many of the processes described in this report can and frequently do happen very early in the burial history. An exploration strategy that follows this concept is to look for carbonates offset by faults that moved in the first kilometer of burial, and preferably did not move significantly thereafter.

In a critique of hydrothermal dolomitization, Machel and Lonee (2002) proposed the term *geothermal* dolomitization to describe dolomites formed in the deep burial environment where fluid flow is primarily lateral within a given formation or occurs very slowly by free convection through unfractured and unfaulted strata. In general, geothermal dolomitization is a good term and may be used in the sense that it was defined to discriminate it from fault- and fracture-controlled hydrothermal dolomitization. It is still unclear whether or not dolomites formed by lateral flow within a formation or by free convection are very common, but those models will be discussed further in this report.

The Hydrothermal Alteration Model

This model accommodates reservoir creating or enhancing diagenesis associated with basement-rooted extensional, transtensional and strike-slip faults, and is very similar to that proposed by Davies (2001). Reservoir-destructive alteration such as the calcite-cemented breccias and cements in the Madison Formation are treated separately.

This is a simplified sequence of events:

1. Carbonates deposited. Altered carbonates are commonly regional limestones, but early dolomites also can be altered by hydrothermal fluids.
2. Tectonic activity either during or shortly after deposition initiates strike-slip, extensional or transtensional faulting. Knipe (1993), Sibson (1990, 1994, 2000) and Muirwood and King (1993) show that fluids move up these fault types when the faults are active, but are less likely to do so during periods of tectonic quiescence.
3. Hydrothermal fluids flow up actively-moving, strike-slip and wrench faults, hit low permeability beds and flow out laterally into underlying permeable limestones. These faults may move many times over the course of the tectonic event, each time providing a conduit for upward-flowing hydrothermal fluids. The wrench faulting produces a network of open faults, fractures and breccias. Cooling hydrothermal fluids leach the limestone, and produce vugs and microporosity in a migrating front moving away from the fault zone. As permeability is enhanced by fracturing and leaching, warmer dolomite-saturated fluids may migrate farther from the fault zone, precipitating dolomite. These fluids first produce a halo of matrix dolomite, particularly on the downthrown sides of faults in negative flower structures. Because the fluids flow up from greater depths where pressures are higher, the elevated pressure of the fluids may lead to hydro-fracturing, enlargement of existing fractures and further brecciation. Some dissolution vugs may form during matrix dolomitization. Matrix dolomitization is followed by further fracturing, brecciation and vug development as tectonic activity continues. Fractures and vugs are lined or filled with saddle dolomite soon after their formation.
4. As time passes, fluids evolve and may precipitate a range of other minerals including quartz, bitumen, sulfides, sulfates and calcite. Leaching of dolomite may occur due to cooling temperatures and/or an increase in Ca-Mg ratio. Calcite or anhydrite may fill leached dolomite rhombs. Calcite commonly postdates bitumen. Most of this alteration may occur at depths of less than a kilometer or even 500 meters. In most cases, mineralized fractures related to the hydrothermal alteration event do not cut across major stylolites and faults that are interpreted to source the hydrothermal fluids commonly die out within the altered zone or just above it.

Figure 28 shows the idealized permeability evolution of a fault zone (from Knipe, 1993 and Davies, 2001). Prior to slip on the fault, very little fluid flows up the fault. There is a surge of fluid flow during the main seismic event and for a period of time afterward when aftershocks occur, but with time (a few months or years), fluid flow in the fault zone returns to its relatively low pre-seismic rate. This process has been termed “seismic pumping” and was covered extensively in Davies’ 2001 report.

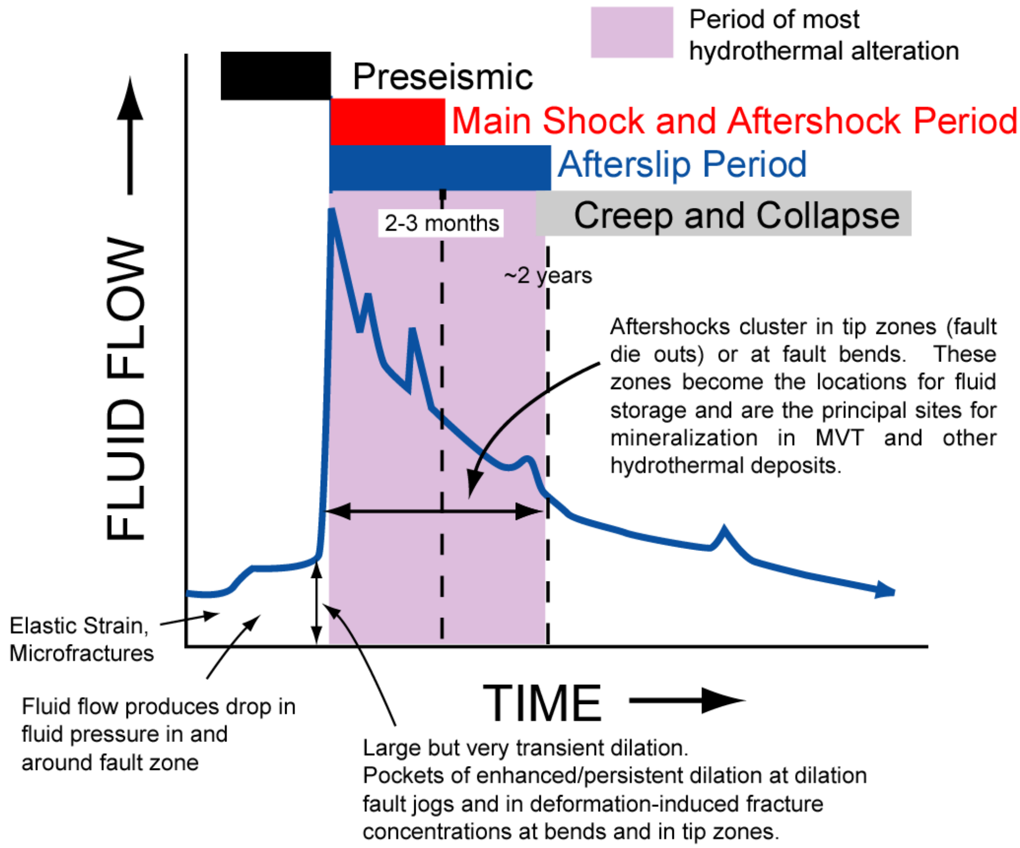


Figure 28. Idealized permeability evolution of a fault zone (modified from Knipe, 1993 and Davies, 2001)

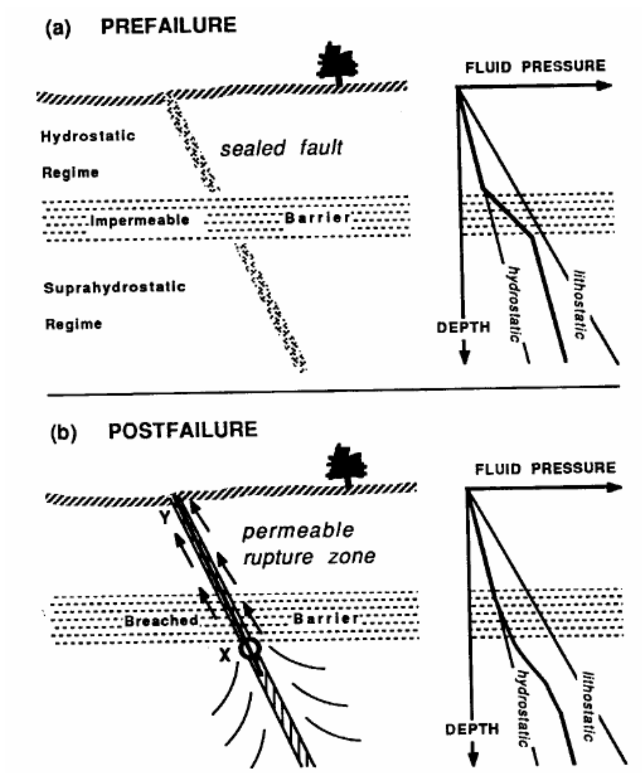


Figure 29. Pressure builds up beneath perm barrier. When fault moves, overpressured fluids flow up fault (from Sibson, 1994).

Overpressured fluids flow up open parts of the fault zone after active slip has breached the confining unit above the overpressured zone or zones (Figure 29; Sibson, 1990, 1994, 2000). The faulting itself may actually form a vacuum or suction pump that draws fluids up the fault as well, as long as the seal overlying the fault and altered zone is not breached (Davies, 2001).

Faults and fractures are likely to be mineralized or otherwise sealed shortly after the faults move, and the mineralization or other seals slow the rate of upward fluid flow or stop it altogether. It is during the period of high-rate fluid flow that most hydrothermal alteration is thought to occur. Fluid flow rates could be greater than 1m/s in fault zones. Eicchubl and Boles (2000) showed that fluids flowed as high as 6 m/s in fault zones cutting the Miocene Monterrey Formation in California.

There may then be long periods when little or no diagenesis occurs and then another episode of faulting, fluid flow and hydrothermal alteration when the fault moves again. This may occur many times over thousands or millions of years before the period of tectonic activity is over. Over time, the fluid composition may evolve or other conditions may change and different minerals may form and be dissolved at the end of the alteration period than formed and were dissolved in the beginning. For instance, limestone may be leached and dolomite precipitated early in the paragenetic sequence, but after time passes and fluids evolve or conditions otherwise change, dolomite may be leached and calcite precipitated.

Depth of Alteration

Most hydrothermal alteration is here thought to occur at relatively shallow depths of less than a kilometer or even 500 meters (see Davies, 2001). This is supported by direct observations and theoretical concepts. Observations common to many hydrothermally altered reservoirs include:

1) Faults thought to be the source of the hydrothermal fluids commonly die out within or just above the altered zone on seismic lines (Figure 30).
2) Major tectonic activity is known to have occurred in the area at the time that the altered formation was less than 1 km deep.
3) Hydrothermal matrix dolomitization preceded fault and fracture cementation, which occurred during and just after the period of active faulting. That moves most of the timing of diagenesis up to the period of active faulting.
4) In some cases, sediments are still soft when fractures cut them and seismites or seismically disturbed bedding forms. Figure 31 shows a saddle dolomite-filled fracture cutting through what appears to have been soft sediment in the Trenton of Ohio.
5) Leached and cemented *horizontal* fractures are common – these generally form to a depth of about 500 meters and should then be rare.
6) Cemented fractures rarely, if ever, cut across <u>major</u> stylolites, but instead are *consumed* and offset at stylolites. There commonly is some <u>minor</u> pressure solution (mainly grain suturing) prior to dolomitization, but grain suturing has been demonstrated to start at depths as shallow as 30 meters (Railsback, 1993).
7) Theoretically, overpressured fluids are seeking the zone of lowest pressure and will flow upward until they get to the surface or as close to the surface as possible. It is unlikely that

an overpressured fluid would flow up a fault and then laterally into an aquifer at several km, when it was possible for the fluids to continue to flow upward to near surface pressures.

8) Theoretically, the greater the contrast between the conditions at the base of the fault and the conditions in the altered zone, the more diagenesis will be likely to occur.

Some proponents of deep burial diagenesis see most alteration as largely postdating significant pressure solution. They present examples of dolomite clearly postdating some minor pressure solution. Similar examples have been observed in the Trenton-Black River, but most major stylolites clearly postdate dolomitization. Dolomite-cemented fractures never cut across major stylolites. They always are consumed at stylolites (Figure 32).

The depth at which pressure solution begins is somewhat controversial. Railsback (1993) has presented evidence that grain suturing can begin at depths as shallow as 20 meters. The opinion herein is that the evidence for pressure solution that predates dolomitization is likely to be minor grain suturing rather than the development of large stylolites. This is an important point that needs further study.

One important point is that many hydrothermal dolomite reservoirs with abundant saddle dolomite occur in places that have never been buried more than 1 km or even 500 meters (see Ellenburger and Trenton-Black River examples).

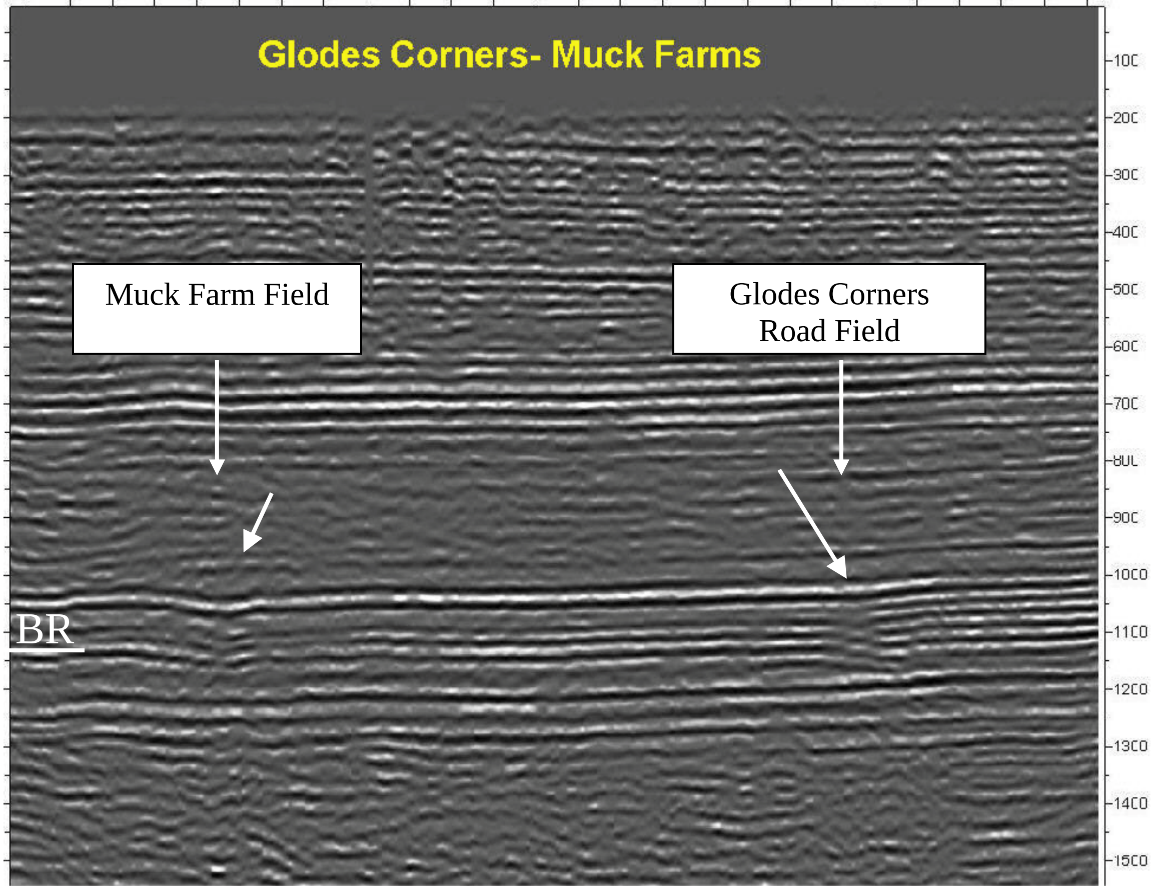


Figure 30. Sags accommodated in first few hundred meters of burial – faulting was early

Figure 31. Saddle dolomite filled fracture appears to have cut soft sediment

Figure 32. Core from hydrothermally altered Black River in New York showing dolomite-cemented fractures consumed and offset at stylolites. Stylolites postdate dolomitization

When most people think of hydrothermal diagenesis they think of zebra fabrics and coarse, white, saddle dolomite in a few vugs and fractures around faults and sulfide ore deposits. While these are certainly part of the hydrothermal alteration story, many more features are produced by fluids flowing up faults, mixing with in situ fluids and equilibrating with the ambient conditions. Matrix-replacive dolomitization, leached limestone and dolomite, microporosity, and quartz, carbonate and sulfate mineralization all can be part of the spectrum of hydrothermal alteration.

A typical paragenetic sequence for a hydrothermally altered reservoir is illustrated in Figure 33. The most obvious fault-related hydrothermal alteration features such as brecciation, hydrofracturing and zebra fabrics occur near fault zones in low permeability host rocks and may not be present in every hydrothermally altered reservoir. The low permeability of the host keeps the pressure high leading to obviously pressure related fabrics. Fault-controlled thermobaric breccias form due to a combination of active faulting and associated high-pressure, high-temperature fluid flow. Fault-controlled thermobaric or dilational brecciation primarily occurs where space has been created in a fault zone such as dilational jogs on strike-slip faults (Sibson, 2000). Fragments of host rock and matrix cements precipitated from hydrothermal fluids fill the voids created in or near the fault zones soon after the fault has moved. Dissolution of limestone and hydrofracturing by the high-pressure fluids may also contribute to brecciation.

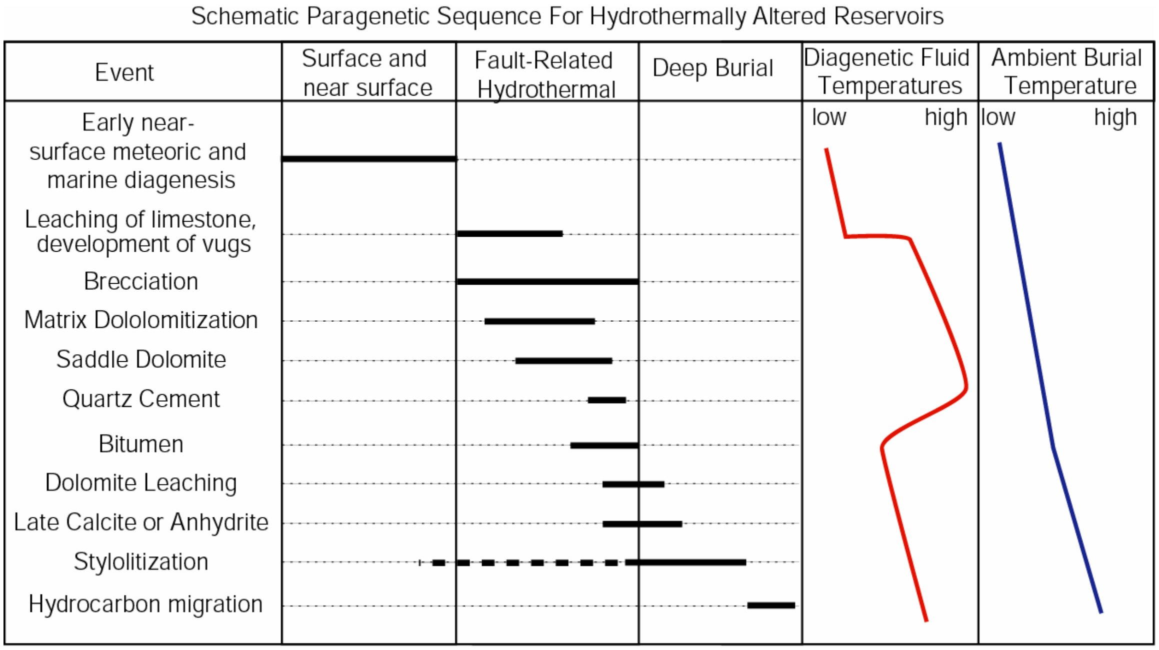


Figure 33. Schematic Paragenetic sequence for hydrothermally altered carbonate reservoir. Not all of these occur in every reservoir and other diagenetic features may be present.

Saddle dolomite commonly lines or fills vugs, space around breccia fragments and fractures. Saddle dolomite forms rapidly from highly supersaturated fluids. Gonzalez et al. (1992) showed that curved crystal faces form in calcite from highly supersaturated solutions (15-19 times saturation). The best way to achieve that degree of supersaturation is by rapidly changing the conditions of a solution. The sudden pressure drop of a fluid flowing up a fault leads to degassing and rapid precipitation from a fluid that has rapidly become highly supersaturated. Much saddle dolomite probably forms in this way from hydrothermal or thermobaric fluids.

Some matrix-replacive dolomitization occurs during the pressure drop and degassing, but much matrix dolomitization probably occurs when hydrothermal fluids mix with *in situ* fluids already residing in the formation. Altered formations are likely to be filled with seawater or slightly modified seawater prior to alteration. Seawater is supersaturated with respect to dolomite, but has kinetic barriers to formation at lower temperatures. Heating of the *in situ* waters by mixing with hydrothermal solutions will lead to precipitation of dolomite. Matrix replacive dolomitization occurs when fluids are heated and dolomite forms and then limestone is leached as the fluids cool back to the ambient temperature (see section on leaching). Matrix replacive dolomite in hydrothermal dolomite reservoirs is commonly fabric destructive. In the Trenton-Black River play of eastern North America, more than 95% of the dolomite is matrix dolomite rather than saddle dolomite, so matrix dolomitization is a very common product of hydrothermal alteration.

Much has been made of hydrothermal mineralization, but just as or more important for oil and gas reservoirs is the capacity for hydrothermal fluids to leach limestone and in some cases dolomite. The solubility of carbonate minerals is strongly affected by temperature, PCO_2, salinity and pH. Calcite and dolomite have retrograde solubility, which means that cooler fluids can hold more of these minerals in solution than relatively warmer fluids. Hot, fault-sourced fluids may precipitate dolomite or calcite when they first enter the formation, and then will become progressively more undersaturated and capable of leaching as they cool to the ambient temperature.

Carbon dioxide also has retrograde solubility, so any CO_2 vapor that forms as mineralization proceeds, may go into solution as carbonic acid as the fluid cools. This can drop the pH and add to the potential for the cooling hydrothermal fluids to leach limestone. The pressure drop to ambient conditions as the fluids flow up the fault will be almost instantaneous, but the temperature drop could take much longer. This could act as a “time release” mechanism that could promote leaching far from the fault source. As fluids flow away from the fault, they continue to cool and take in more CO_2, which prolongs their aggressiveness.

Furthermore, there is a clear trend towards higher salinity and lower pH with depth in sedimentary basins (Hanor, 1993). Brines flowing up faults will likely have lower pH and higher salinity than fluids higher in the section. Both higher salinity and lower pH fluids will promote leaching of limestone (Rimstidt, 1997). Fluid inclusions in most hydrothermal cements show elevated salinity with an average of about 20wt% vs. about 3.5wt% for normal seawater. This strongly supports a model where fluids from much deeper in the sedimentary basin or even in the basement are flowing up faults and altering strata higher in the section. So cooling, saline brines from deeper in the section have the capacity to extensively leach limestone. Fault-related hydrothermal leaching should be considered as a possible origin for leached limestone reservoirs, particularly where leaching is laterally heterogeneous.

Quartz is also a very common part of the paragenetic sequence in hydrothermally altered reservoirs. It is present as chert, chalcedony and doubly terminated crystals. These postdate dolomitization and leaching but typically predate the late calcite. Formation temperatures of fluid inclusions in quartz are commonly very high and can be hotter, or as hot, as the highest dolomite homogenization temperatures. The presence of authigenic quartz in a carbonate formation is highly suggestive of fault-related fluid flow, particularly when it is found in fractures and pores.

Bitumen or pyrobitumen is present in most hydrothermally altered reservoirs and also occurs in many carbonate-hosted Mississippi Valley Type hydrothermal ore deposits. Bitumen commonly lines some fractures and pores, and was emplaced before, during and after the late calcite was formed. This bitumen probably does not represent a full-scale charge of the reservoir. Instead, it probably formed when kerogen within the altered formation and near the faults was heated by the hydrothermal fluids and small quantities of oil formed (“forced maturation” of Davies, 2001). As the formation cooled back to ambient temperatures and the oil mixed with cooler water, bitumen formed. Bitumen almost always is postdated by late calcite cement.

Many other minerals can be precipitated in carbonate reservoirs during hydrothermal alteration. Common minerals found include: sulfates (anhydrite, barite, celestite, others), sulfides (pyrite, sphalerite, galena), carbonates (magnesite, ankerite), clay minerals (kaolinite, illite), potassium feldspar and fluorite. These typically postdate dolomitization, but predate late calcite (where present).

Matrix and saddle dolomite leaching also is common in hydrothermally altered reservoirs (Figure 34). In many cases, dolomite that is demonstrably of a high-temperature origin is leached, which helps to rule out meteoric diagenesis as a possible origin for the dolomite leaching. Individual zones or cores of dolomite rhombs may be selectively leached. Reservoir quality may be greatly improved by this dolomite leaching if later cements do not plug the leached pores.

Dolomite leaching may occur during dolomitization (and be obvious in CL where etched internal zone boundaries can be seen), but mostly occurs afterward and is commonly associated with calcite and anhydrite cementation. Leaching of dolomite and precipitation of calcite and anhydrite suggests that either the fluid chemistry has become more calcium-rich and/or the temperature has decreased or both (Figure 35). If hydrothermal dolomitization and leaching occur in a closed or semi-closed system, fluids will become more calcium-rich with time. As the fault zones become progressively less active, the temperature may drop back to the ambient temperature. The late calcite could be precipitated from hydrothermal fluids or could precipitate during burial and pressure solution. Late calcite fluid inclusions are almost always lower temperature and lower salinity than the fluid inclusions in the earlier dolomite.

When present, diagenetic anhydrite precipitation typically postdates matrix and saddle dolomite. The abundance of sulfate in formation waters greatly decreases after a burial depth of about 1- 1.5 km in sedimentary basins (Figure 37; see the Heydari, 1997). If this is true in most or all basins, it strongly suggests that anhydrite precipitation should occur at depths of 1.5 km or less and that pushes the matrix and saddle dolomite precipitation to the shallower depths where we believe that hydrothermal alteration is likely to occur (<1km burial).

As stated earlier, major stylolite formation postdates fracturing, dolomitization and most mineralization. The late calcite may form during major pressure solution in deeper burial settings

Fracturing, brecciation and leaching of limestone and dolomite are reservoir-enhancing processes, whereas all mineralization generally degrades reservoir quality. Some or all of these features and more may be present in a hydrothermally altered reservoir.

There is a continuum of hydrothermally altered reservoirs from leached limestone with microporosity and some high-T cements in a few pores to pervasively dolomitized zones with massive breccias and zebra fabrics and abundant saddle dolomite cement (Trenton-Black River; Ellenburger/Knox). In some cases leaching may be more common than mineralization, while in others there may be little obvious evidence for leaching and massive mineralization. In this sense there is a spectrum of hydrothermally altered reservoirs. All form from similar processes but with key variables differing in each case. But if the reservoir has a patchy distribution of porosity or reservoir quality, finding a link to faults visible on seismic data may be the key to economic development.

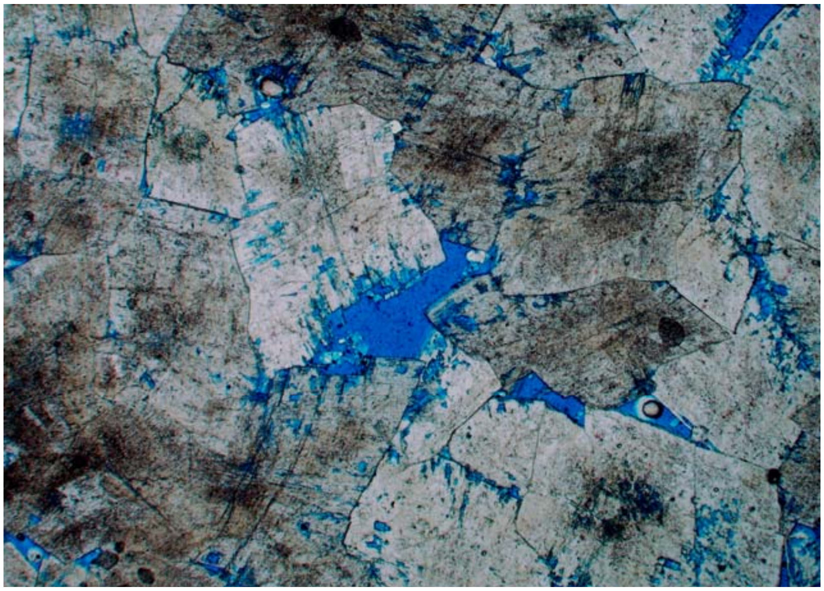


Figure 34. Leached saddle dolomite. Leaching clearly postdates hydrothermal fluid flow and therefore is probably of a subsurface origin.

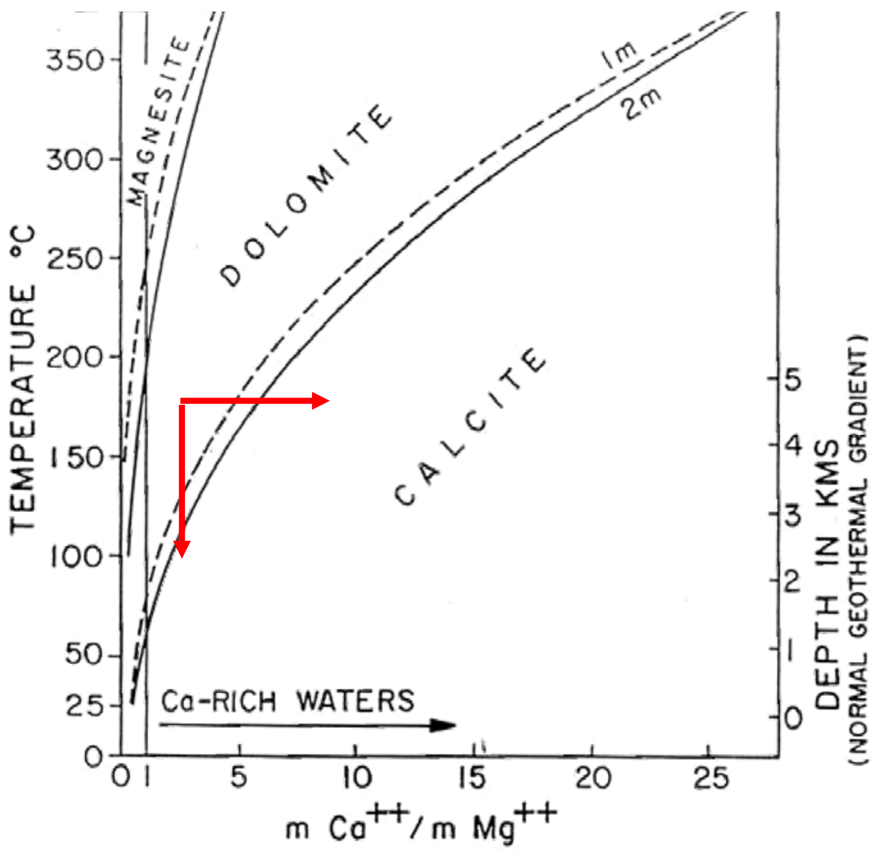


Figure 35. Dolomite leaching and calcite cementation might occur if the fluids either cooled significantly and if the Ca/Mg ratio greatly increased.

Controls on Type of Alteration

First order-controls on hydrothermal alteration products include: composition, thickness, porosity and permeability of the host rock, the volume, pressure, temperature and chemistry of the hydrothermal fluid, distance to the basement and basal sandstone aquifer, and the type and timing of faulting.

Stratigraphy and pre-existing porosity and permeability distribution help control the lateral extent and type of alteration. Strata with no permeability at all may have some cemented fractures, but alteration will be limited to an area very close to the fault zone. Strata with low pre-existing permeability may be intensely altered in and near the fault zone with common pressure-related fabrics such as breccias, cemented fractures and zebra fabrics. Strata with high pre-existing porosity and permeability may be altered far from the fault zone and the alteration may be less obviously fault-related. Leached limestone and microporosity appear to be more common in strata with good precursor porosity and permeability. Fluids can cool slowly as they flow from the fault which prolongs the period when leaching may occur.

Large volumes of fluid will be likely to alter larger volumes of rock than smaller volumes of similar fluid. Fluids that are hotter, under higher pressure or of a drastically different chemistry than the fluids residing in the altered strata will do far more diagenesis than fluids that are only marginally different, though both may have some effect. Dolomitization is more likely to occur from fluids that are above a critical temperature at which dolomite forms readily (60-75°C?). Hydrothermal fluids below a certain temperature or that are only marginally warmer than the host rock fluids may be more likely to leach limestone or recrystallize limestone and create microporosity. Fluids with a lower Ca/Mg ratio will be more likely to precipitate dolomite than fluids with higher Ca/Mg ratios at a given temperature. Fluids with relatively low pH will be more likely to leach limestone than fluids with higher pH. There are many variables and different combinations will produce different results.

Proximity to the basement and a basal sandstone aquifer appear to have a major impact on the type of alteration. In a given basin, hydrothermally-altered strata closest to the basement are most likely to be brecciated, dolomitized, and have significant quantities of saddle dolomite and other minerals, whereas overlying altered formations are likely to have leached limestone, microporosity and less mineralization. In the Middle East, for instance, the Permian Khuff has common saddle dolomite, zebra fabrics and sulfide mineralization, whereas hydrothermally-altered formations higher in the section are primarily leached and microporous. The thickness of section beneath the altered interval has a major impact on how hot the fluids can remain as they flow up the faults. Formations lower in the section are more likely to be altered by high-temperature, high-pressure fluids sourced from the basement or a basal sandstone aquifer, whereas those higher in the section are more likely to be altered by cooling fluids. The Trenton Limestone and Black River Group, for instance, are typically dolomitized when they are less than 1500 feet from the basement. In places where the section beneath them is thicker than 1500 feet, no dolomitized reservoirs have been found even in structures that look prospective.

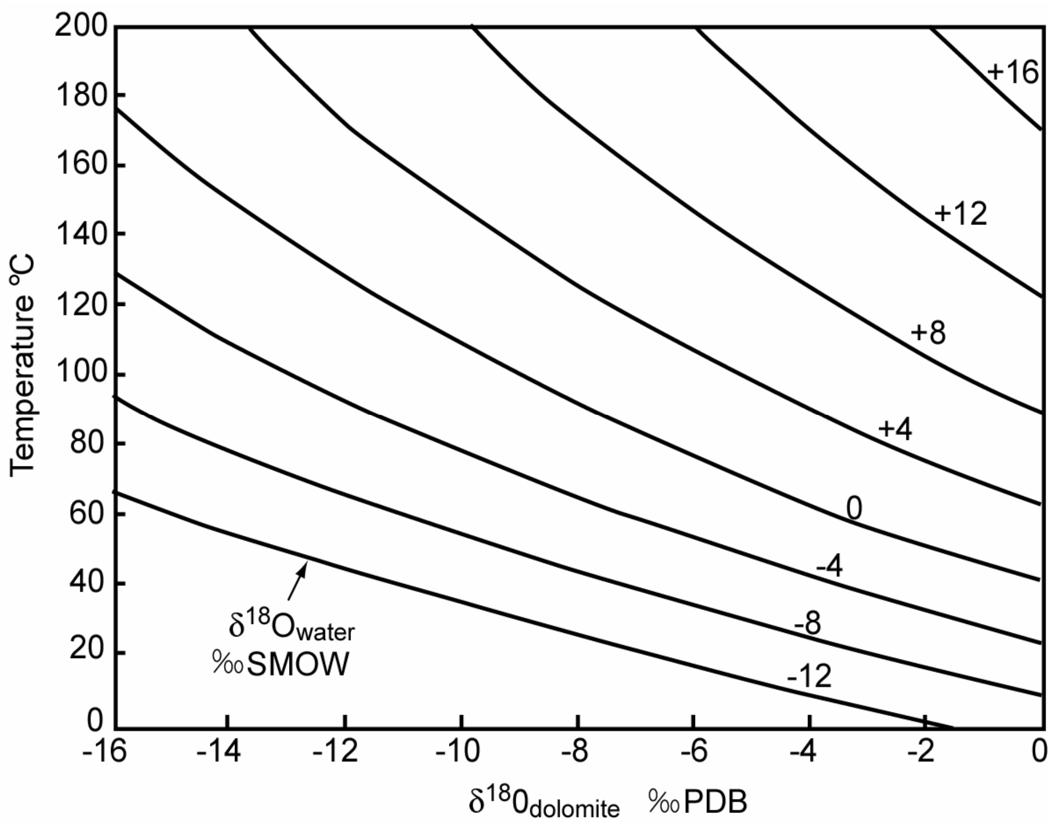


Figure 36. Graph for determining fluid composition. Plot fluid inclusion homogenization temperature vs. $\delta^{18}0$ for same sample or suite of samples. Once fluid composition is known, oxygen isotopes can be used to determine temperature.

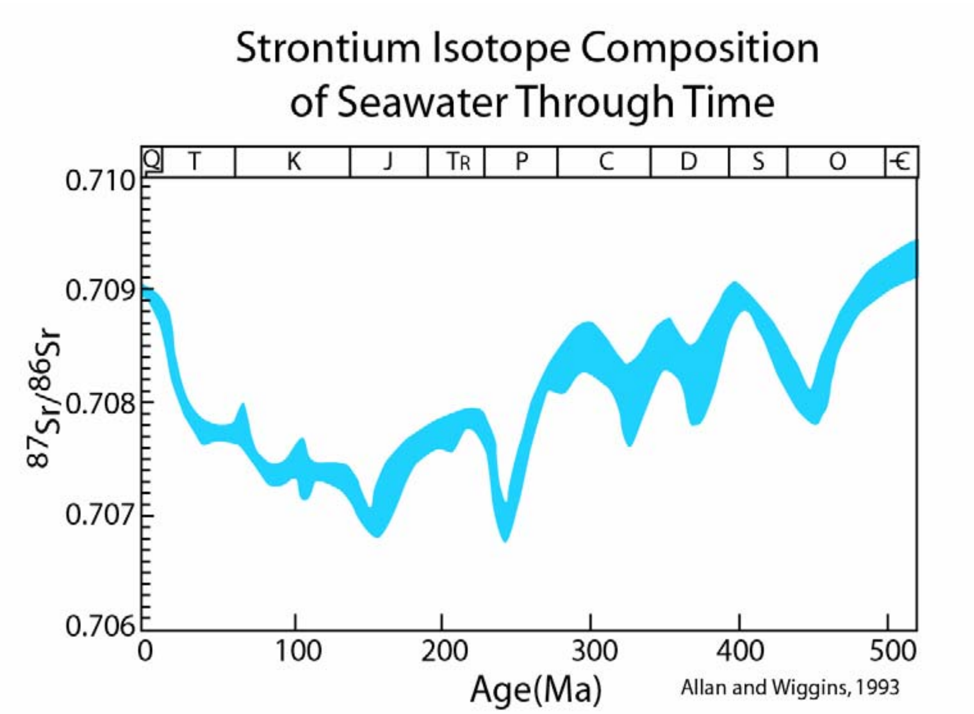


Figure 37. Strontium isotope composition of seawater through time. Hydrothermal dolomites typically plot above seawater for the age of the host rock.

Fault types most likely to have associated reservoir-enhancing or reservoir-creating hydrothermal alteration have been discussed at length in Davies (2001). Basement-rooted extensional, strike-slip and especially transtensional faults appear to be the best. When transtensional or dilational segments of strike-slip faults move, they create space and open conduits to great depths that are pathways for hydrothermal fluids that flow upward from more deeply buried formations and/or from the basement. Straight or compressional segments of strike-slip faults do not open to great depth and are less likely to be conduits for hydrothermal fluids. Extensional faults may be effective conduits, especially if there is magmatic activity at depth along them, as is commonly the case in rifted margins.

Most hydrothermally-altered reservoirs are associated with fault-controlled margins, intra-platform wrench faults and fault intersections, and over newly rifted basement and active basement-rooted extensional faults. The wrench faults commonly express themselves as subtle flower structures or "sags" that are difficult to interpret if one is not looking for them. Once they are recognized, however, it becomes clear that these subtle wrench faults are very common. It appears that relatively minor vertical offset at the time of alteration may be optimal for hydrothermal alteration.

Indicators of Hydrothermal Alteration

Certain features are indicative of hydrothermal alteration. If any of the following occur in a given carbonate reservoir, hydrothermal alteration should be considered as a possible diagenetic model.

1. Heterogeneity - patchiness of diagenetic features (dolomitization, leaching). If the distribution of mineralization such as dolomitization and degree of leaching varies significantly from well to well, fault-related hydrothermal alteration should be considered. If it can be linked to faults, particularly very subtle faults, hydrothermal alteration is likely to have been an important factor in reservoir development.
2. Same minerals in fractures and matrix - if the same minerals are found filling fractures that are found plugging pores and vugs or replacing the matrix, it is likely that at least some of these cements were sourced from faults and fractures. Geochemistry and fluid inclusion analysis can help confirm whether fluids were hot saline brines or fluids of a cooler, near surface origin.
3. Common or abundant saddle dolomite – Saddle dolomite forms at high rates in highly supersaturated solutions (>15 times saturation? – Rimstidt, 1997; Gonzalez et al, 1992). The best way to reach high degrees of supersaturation with dolomite and other carbonate minerals is to suddenly change the conditions. Rapid pressure drop and CO_2 degassing associated with movement up a fault can lead to high degrees of supersaturation and massive precipitation of saddle dolomite and other minerals. Saddle dolomite may be a good fault-proximity indicator; the closer to the fault zone, the more saddle dolomite.
4. Occurrence of minerals in a formation that are clearly not sourced from the formation, such as authigenic quartz and clay minerals in clean carbonates or saddle dolomite in quartz sandstones.
5. Zebra fabrics, boxwork fabrics and breccias with high-temperature cements such as saddle dolomite, calcite and/or anhydrite. These, too, are good fault proximity indicators.

6. Geochemical and fluid inclusion attributes of hydrothermal cements as laid out in this report and by Davies (2001).
7. Higher fluid inclusion homogenization temperatures in cements than the maximum interpreted burial temperature or known burial temperature at time of alteration.

Geochemistry of Hydrothermal Dolomite Cements

Matrix and saddle dolomite precipitated from hydrothermal fluids *generally* (but not always) have:

- Fluid inclusions homogenization temperatures between 75º and 250ºC and salinities between 8 and 30 wt% with an average of 20 wt%
- Negative $\delta^{18}O$ isotope values (PDB) that are lighter than the marine signature (need to know composition of fluid)
- Radiogenic $^{87}Sr/^{86}Sr$ ratios relative to seawater for the time of deposition
- Relatively high Fe and Mn contents

There are important exceptions to all of these and it is always best to do a full suite of analyses on the same samples.

Fluid inclusion analysis is the cornerstone for this effort and should always be done on pore and fracture-filling cements, as well as on the matrix dolomites. Homogenization temperatures from primary inclusions give minimum estimates for the temperature of the fluids that precipitated the dolomites. High salinities in the fluid inclusions support a subsurface origin for the cements as these salinities exceed any near surface fluid values.

Stable isotopes of oxygen should never be used by themselves to determine temperatures of formation. They must first be cross-plotted with fluid inclusion homogenization temperatures from the same samples using the graph in Figure 36 to learn the composition of the dolomitizing fluid. Fluids that make hydrothermal dolomites are typically isotopically heavier than seawater (generally 0 to +10 per mil). Once the fluid composition is known, stable isotopes can be used to determine temperature by plotting them on the graph.

Strontium isotopes are valuable in many cases. Continental basement rocks and immature feldspar-rich siliciclastics are enriched in ^{87}Sr while mantle rocks are enriched in ^{86}Sr. The composition of seawater over time has varied with varying seafloor spreading and erosion rates (Figure 37). Hydrothermal dolomites will generally have $^{87}Sr/^{86}Sr$ ratios that are greater than seawater for the time that the host carbonates were deposited. This is because the fluids pass through basement or feldspar-rich siliciclastics overlying the basement prior to making the dolomite. In some cases, matrix dolomites might be less radiogenic than saddle dolomites. This is because the Sr from the limestones that have been replaced has been reused.

Trace elements are cheap and can provide useful information. One mainly looks at iron and manganese concentrations. Iron and manganese are virtually absent from seawater because they get oxidized and will not build up in any significant concentrations. Reduced subsurface fluids can build up substantial quantities of iron and manganese and hydrothermal dolomites commonly have very high iron and manganese values. Dolomites with high iron and manganese could not form from seawater, so this is a valuable tool for eliminating near surface dolomitization models.

Carbonate Solubility

Carbonate solubility is directly affected by changes in temperature, pressure, P_{CO_2}, pH, and salinity, and all of these are fluctuating on short time scales in hydrothermal systems. This rapid change in fluid chemistry is what makes fault-sourced hydrothermal fluids capable of causing significant diagenesis in relatively short periods of time. Fluids overcome rock buffering because they are introduced rapidly at a point or planar source, rather than slowly flowing laterally through a formation. Meteoric caves form where water can be rapidly introduced via fractures without interacting with the wall rock on the way. Once this flow path is established, caves can form quickly as fluids maintain their aggressiveness after they enter the formation (Palmer, 1986). The same is true for fault-sourced hydrothermal fluids. Because they are introduced rapidly with little wall-rock interaction on the way up, the hydrothermal fluids maintain their ability to diagenetically alter the formation.

Rimstidt (1997) states that there are four important ways to precipitate carbonate minerals from hydrothermal solutions:

1. Heating the solution at low salinities and/or temperatures
2. Degassing CO_2, where HCO_3^- (bicarbonate) is dominant over H_2CO_3 (carbonic acid)
3. Decreasing the salinity
4. Increasing the pH

It then follows that carbonate minerals can be leached in hydrothermal systems by:

1. Cooling the solution at high salinities/and or from high temperatures
2. Dissolution of CO_2 where H_2CO_3 (carbonic acid) is dominant over HCO_3^-
3. Increasing the salinity
4. Decreasing the pH

Rimstidt also points out that mixing of two saturated solutions at two different temperatures but at the same P_{CO_2} will produce a supersaturated solution and should lead to precipitation.

Rimstidt makes the following points about crystal shape and its implications for saturation state:

1. Minerals precipitated near equilibrium result in crystals with smooth faces.
2. Beyond a critical degree of supersaturation, surfaces become roughened.
3. At still higher degrees of supersaturation, curved crystal faces form.

Gonzales et al. (1992) showed that calcite with curved crystal faces (“saddle calcite?”- it does occur) forms where solution was supersaturated between 16 and 19 times greater than the saturation point. Saddle dolomite almost certainly forms in solutions that are highly supersaturated with respect to dolomite, which is what gives them their curved shape. The easiest way to produce a highly supersaturated solution is to suddenly change the conditions of a fluid such as a rapid pressure drop or temperature increase. This is exactly what happens in fault-related hydrothermal systems.

Nucleation rates increase with temperature and degree of supersaturation (more crystals will nucleate in a highly supersaturated solution). Conversely, nucleation rates decrease with decreasing temperature and lower degrees of supersaturation. It is thus easier to make a lot of dolomite in a short amount of time from a highly supersaturated fluid (as one would find in a hydrothermal system) than it would be in a fluid that was near equilibrium.

Fluids in Sedimentary Basins and the Earth's Crust

In sedimentary basins, fluid temperature, pressure and salinity generally increase with depth (Hanor, 1993; Heydari, 1997). Fluid pH generally decreases with depth (Hanor, 1993; Heydari, 1997), particularly if there are siliciclastics lower in the section. Fluids flowing up faults will, therefore, generally have higher temperature, pressure and salinity and lower pH than fluids higher in the section.

Temperature increases with depth along a geothermal gradient. Fluids flowing up faults will in almost all cases be warmer than fluids in shallower strata. As fluids flow up faults, the temperature will eventually fall and equilibrate with the ambient host temperature. Fluids at lower temperatures can hold more calcite or dolomite in solution than fluids at higher temperatures because of the retrograde solubility of carbonate minerals. A cooling fluid, therefore, is capable of leaching limestone and dolomite. The greater the temperature drop the greater the capacity for leaching. The capacity for a fluid to maintain its higher temperature is directly related to the permeability of the fault and fracture system and the near-surface formation that is altered. Low permeability faults and strata will lead to rapid cooling and highly localized leaching, whereas high-permeability faults and strata will lead to slower cooling and more widespread leaching.

Fluids generally flow *up* faults when they are overpressured or at significantly higher pressure than the fluids where they are flowing (Sibson, 2000). Fluids under high pressure can hold more calcite and dolomite and CO_2 in solution than fluids at lower pressures. As fluids flow up faults and laterally into shallower, lower pressure zones, the pressure drops, CO_2 degasses and mineralization will occur. In carbonate systems, dolomite or calcite is likely to precipitate, depending on the temperature and other factors. CO_2 should come out of solution as a vapor. The greater the pressure differential from the base of the fault to the altered zone, the more mineralization should occur. Pressure should drop much faster than temperature.

The salinity of fluids in sedimentary basins commonly increases with depth, and pH generally decreases with depth (Figures 38 and 39). The salinity of fluids in crystalline basement rocks also increases with depth (Figure 38). In both settings, salinity approaches halite saturation at a depth of a few kilometers. Fluids flowing up faults should have higher salinity than fluids in overlying strata, particularly if it they are near the surface. Salinities from fluid inclusions in most hydrothermal dolomites are typically between 10 and 30 wt% with an average of around 20 wt%. This suggests that they were formed from fluids that were sourced from deep in sedimentary basins or the basement. High salinity fluids commonly have lower pH (Figure 39) and the higher the salinity, the lower the pH. At least partly as a function of salinity, pH generally decreases with depth in sedimentary basins and perhaps in basement rocks as well. So, fluids flowing up faults should have higher salinity and lower pH, which should promote leaching of limestone. Importantly, $\delta^{18}O$ also increases with depth and increasing salinity. Fluids flowing up faults will be isotopically heavier than fluids in overlying formations and this has great implications for interpretation of stable isotope data.

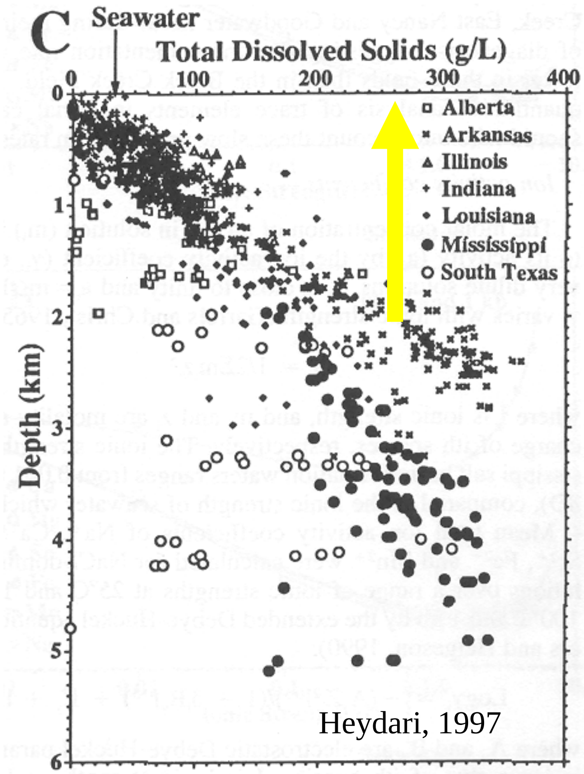
Leaching by Fault-Sourced Hydrothermal Fluids

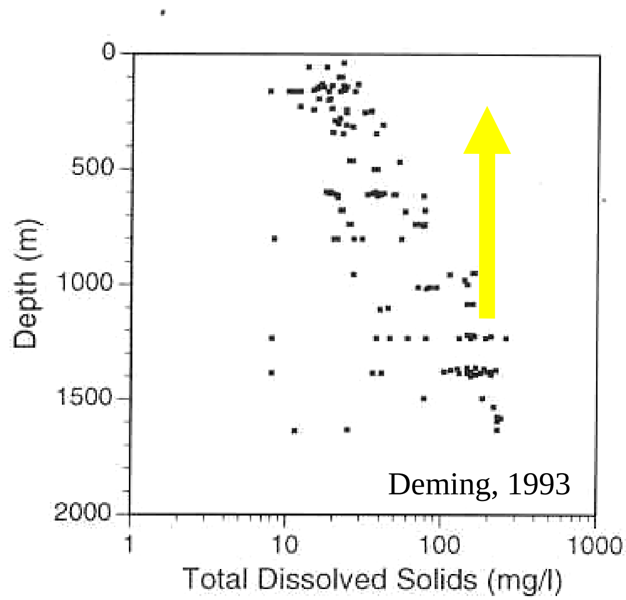
Ascending, fault-sourced hydrothermal fluids have a great capacity to leach limestone. One very interesting question is, how much leaching in limestone reservoirs is related to hydrothermal alteration? The idea of “hydrothermal karsting” has been around since at least the 1970s. However, it is best not to use the word “karst” when discussing hydrothermal alteration, as it leads to confusion with meteoric karst. Instead, simply use the term “leaching.” Fluids could go through multiple changes in the carbonate saturation state as hot solutions flow up faults, experience a pressure drop, mix with *in situ* fluids of a different PCO2, temperature, salinity and pH, and ultimately cool to the ambient temperature.

Although other factors are important, the activity of CO_2 may be the most important control on carbonate solubility. After fluids have flowed up the faults, CO_2 has degassed and mineralization has occurred, most factors then would promote leaching. As the fluid cools to the ambient temperature it will become progressively undersaturated. CO_2 also has retrograde solubility, so a cooling fluid will be able to hold progressively more CO_2 in solution. Adding CO_2 to the solution will cause a drop in pH due to the formation of carbonic acid (H_2CO_3), which also will promote leaching. If the fluid flows laterally as it cools, it should be able to continue leaching until it finally cools to the ambient temperature.

The cooling temperature of the fluid, the decrease in pH as CO2 goes back into solution and the relatively low pH and high salinity of the original fault-derived fluid all should work together to promote leaching as the fluid flows laterally into the formation.

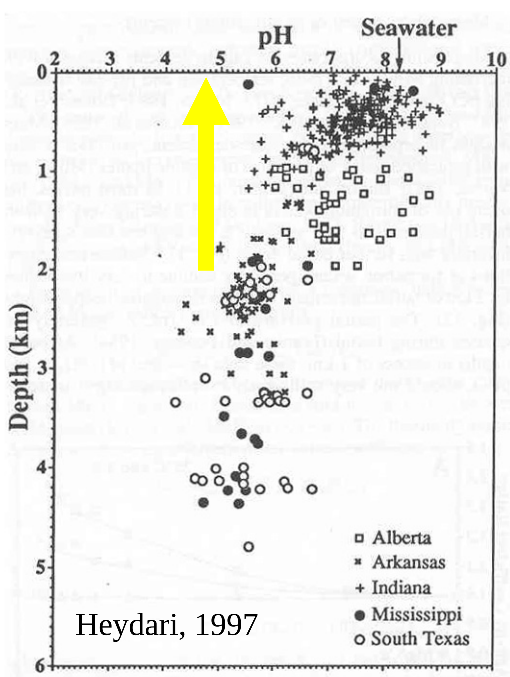
There are two well-documented examples of clear fault-controlled hydrothermal alteration with associated leached limestone and microporosity that can be cited in this report.





Salinities of pore fluids from crystalline rocks in the Canadian Shield (after Frape & Fritz 1987).

Figure 38. Salinity increases with depth in sedimentary basins and in crystalline basement rocks. Fluids flowing up faults will have higher salinity than fluids higher in the section.



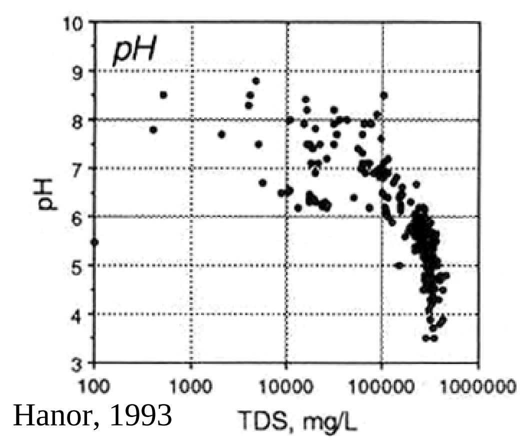


Figure 39. pH decreases with depth and with increasing salinity. Fluids flowing up faults should have lower pH than fluids higher in the section.

The first is the Devonian Slave Point Formation in the Western Canada Sedimentary Basin (WCSB) and the second is the Jurassic Abenaki Formation, offshore Nova Scotia. The Cogollo Limestone in Venezuela (report included) is another example of probable hydrothermal leaching. Only probable because, when there is little or no obvious hydrothermal mineralization it is difficult to be certain of the origin of leaching, but in the case of the Cogollo (and many other leached limestones) it is likely that hydrothermal fluids at least play a role in enhancing porosity.

Fluid Evolution and Mixing

The preceding section laid the groundwork for a discussion of fluid evolution (Figure 40). Fluids undergoing changes in pressure, temperature and salinity could and should evolve rapidly. In a typical earthquake cycle, hydrothermal fluids ascending a fault may experience a significant pressure drop, degassing of CO_2 and rapid precipitation of dolomite or calcite. Further precipitation may be driven by mixing with *in situ* fluids that may also be saturated with dolomite or calcite but at a lower temperature. Remember, mixing of two fluids that are saturated with respect to carbonate minerals at the same P_{CO_2} but different temperatures will result in a supersaturated solution (Rimstidt, 1997). However, as the hydrothermal fluid cools, it will be able to hold more carbonate minerals in solution and may become capable of leaching. CO_2 also has retrograde solubility, so any CO_2 vapor present may re-enter the solution, react with water to make carbonic acid, which will then drop the pH and make the fluid capable of further leaching. Leaching will continue until the fluid equilibrates with the ambient conditions.

Matrix-replacive dolomitization and recrystallization of limestone with micro-rhombic calcite may occur in systems undergoing fluid evolution. Matrix dolomite may grow in warming waters and limestone may get leached in cooling fluids. Similarly, microporosity may form when small crystals of calcite form in warming waters, while the less stable original limestone is leached in cooling waters. Control on whether dolomite or calcite forms is likely related to the temperature of the hydrothermal fluids.

Fluids also may evolve over longer periods of time. If dolomitization proceeds in a closed or semi-closed system, fluids will have progressively higher Ca/Mg ratios because one Mg^{2+} ion is lost and one Ca^{2+} ion is gained for each two molecules of calcite that are replaced with dolomite. If fluids become enriched in Ca^{2+}, eventually dolomite leaching and calcite and/or anhydrite precipitation will occur.

Link Between Leaching and Microporosity

Leached limestones and microporosity commonly occur together. Leached limestones that form halos around hydrothermal dolomites in the Jurassic Abenaki Formation and the Slave Point reservoirs also are microporous. In the Cogollo Limestone (and many other limestones), only the beds that are leached are microporous. Much mud occurs in the formation that is not leached and not microporous, so microporosity development is directly related to the diagenesis that did the leaching (Figure 41). This microporosity appears to form as a by-product

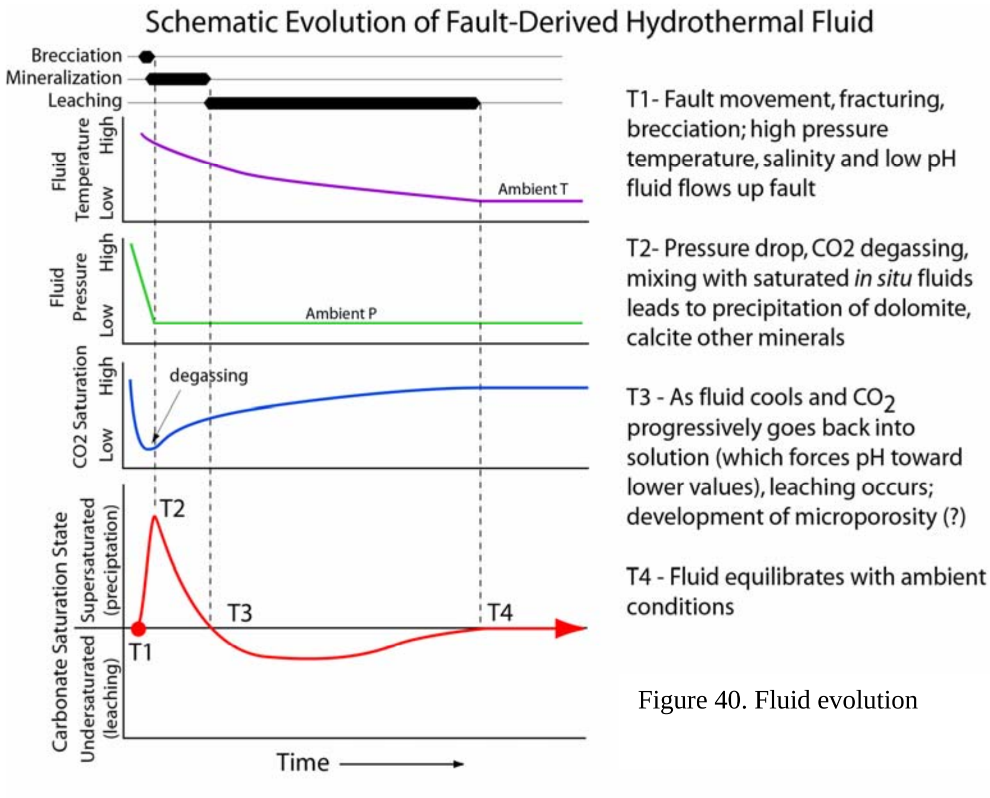


Figure 40. Fluid evolution

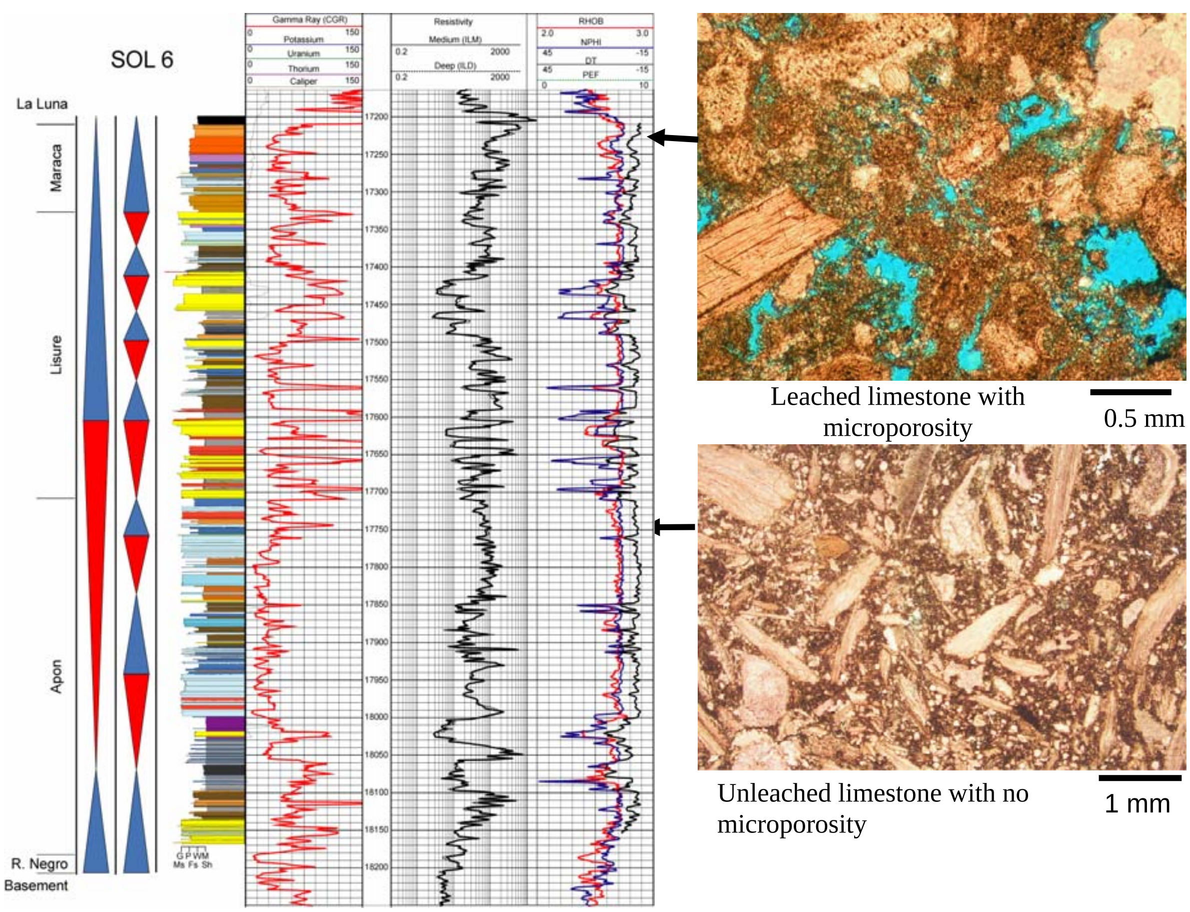


Figure 41. Same basic rock type is leached and microporous in the Maraca at the top of the formation and not leached or microporous lower in the section.

of recrystallization and replacement of unstable calcite or aragonite with small rhombs of more stable calcite. Microporosity forms when all of the unstable mud is leached but the newly formed stable calcite does not fill all the porosity (Moshier, 1987, 1989). In many ways this recrystallization is similar to matrix-replacive dolomitization but with stable calcite instead of dolomite. Most micro-rhombic calcite crystals are from 5-20 microns and micropores have throats that are less than a micron in diameter. In some cases, the crystals can become quite coarse and the rock is basically a cement rock.

Microporosity may in fact have many different origins (like dolomite). Many are quick to attribute leaching and microporosity development to meteoric fluids (Budd, 1989). While this may be the case in some instances, most leaching and microporosity development in carbonate reservoirs is probably of a later subsurface origin and in some cases clearly related to hydrothermal fluid flow.

Microporosity can be as high as 30% in some strata. Identification of microporosity is important because it can contain large volumes of hydrocarbons that are hard to access and can pull water far above the free water contact by capillary pressure due to the small pore throat size.

Fluid Flow Models

A very large volume of fluid is required to make dolomite. Machel and Mountjoy (1987) calculated that it would take 625 volumes of seawater to make one volume of dolomite and about 30 volumes of saline brine at 100°C to make one volume of dolomite from a limestone that had 40% porosity. A quick back-of-the-envelope calculation of the volume of dolomite at Albion-Scipio Field (Figure 42 - a clearly hydrothermal dolomite field in Michigan) reveals that there is about 7.5 million m^3 of dolomite there (50 km long, 1 km wide and 0.15 km thick). Using Machel and Mountjoy's estimate of 30 volumes of fluid to make one volume of dolomite, 225 billion m^3 or 1.4 trillion barrels of water would be required. That is assuming that the limestone had 40% porosity at the time of alteration, which it almost certainly did not, so it is only a minimum estimate. That is a lot of water, and Albion-Scipio is only one of many hydrothermal dolomite bodies in the Trenton-Black River. Almost certainly, tens or hundreds of trillions of barrels of water would be required to create all of the clearly fault-related dolomite bodies in the Trenton-Black River.

First of all, that calculation demonstrates that large volumes of fluid can flow up faults and that this is an efficient and important mechanism for diagenesis. Secondly, this volume of fluid may be more than was contained in the Appalachian and Michigan Basins at the time of alteration. Fluid flow models need to take this into account.

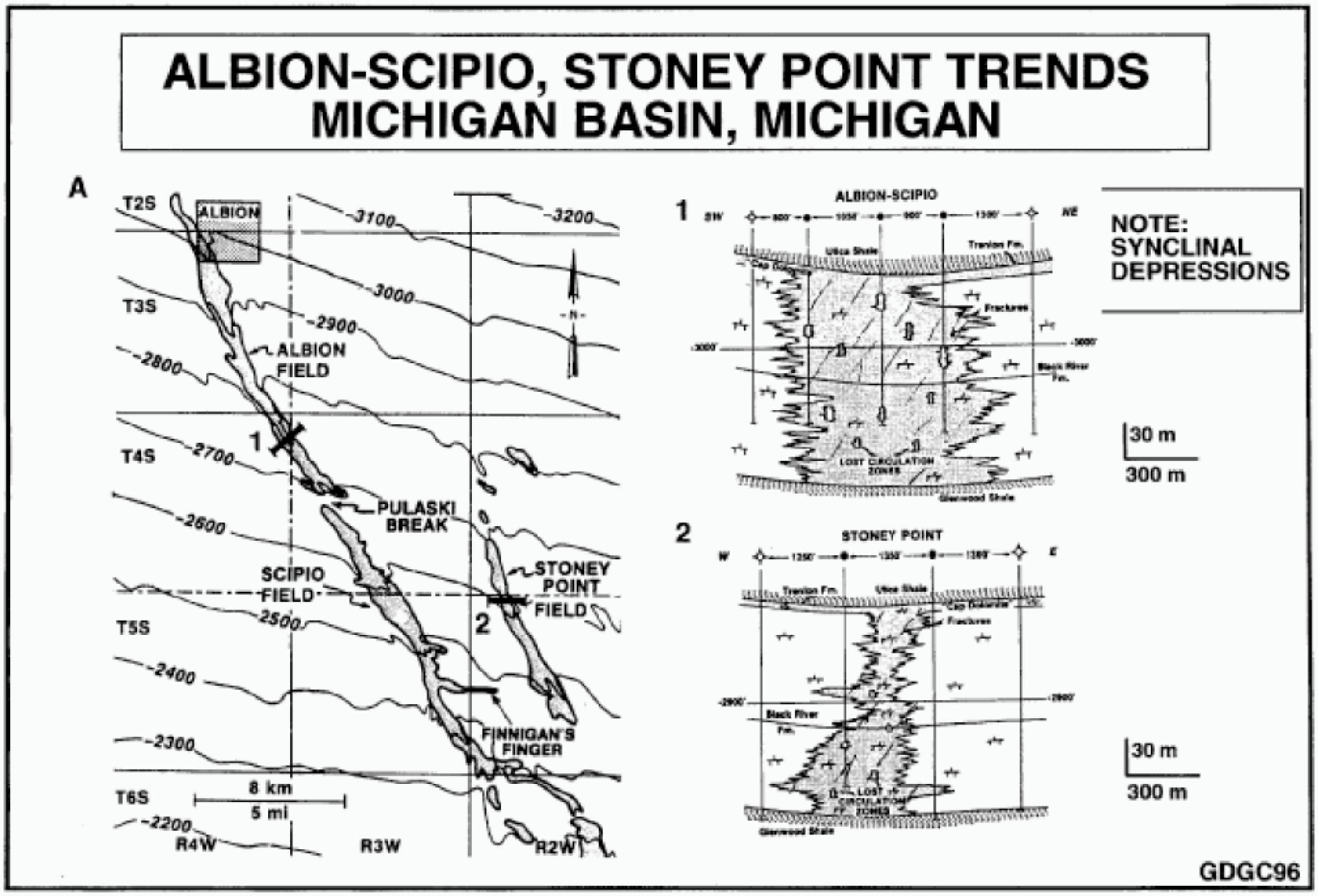


Figure 42 Albion Scipio Field – Dolomitized zone about 50 km long, 1-2 km wide and 150 m thick. From Hurley and Budros, 1990.

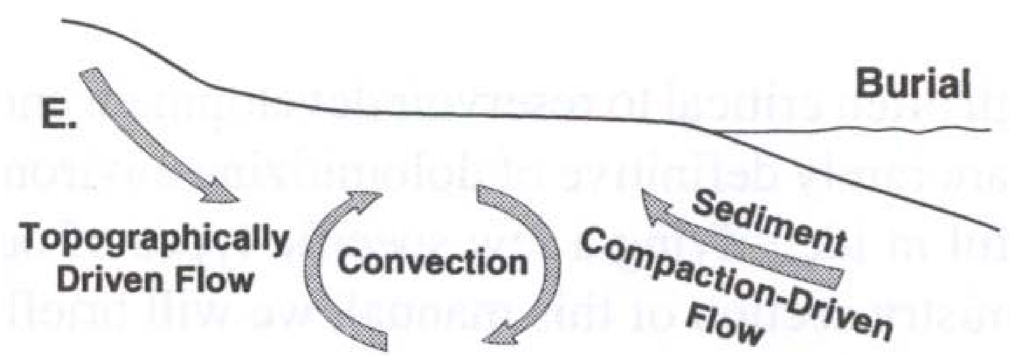


Figure 43. Commonly applied subsurface dolomitization models (from Allan and Wiggins, 1993).

Many flow models have been presented over the years for subsurface dolomitization (Figure 43). These include topographic recharge, tectonic loading, compaction and free convection. These models could all contribute something, but each has their own set of problems.

Topographic recharge can move large volumes of fluid, but the problem is that the fluid is fresh to begin with. Most hydrothermal dolomites form from saline brines with an average of 20 wt% salinity (6 times seawater). Some salinity could be picked up in the subsurface, but it would be difficult to maintain these high salinities when starting with a fluid that was originally fresh. Furthermore, because calcite has retrograde solubility, the fluids will leach limestone near the surface and then precipitate calcite as they descend and become progressively warmer. These fluids would not be leaching fluids, but calcite-precipitating fluids. If any fluids were introduced to the Black River reservoirs via topographic recharge, they probably precipitated the late calcite cements, which are generally lower salinity than the earlier dolomites.

Tectonic loading and shale compaction could contribute some fluid, but not enough. Once the shales have been compacted, that would be the end of the process, and a lot of this fluid probably would find its way to the surface rather than remaining in the subsurface.

Significant free convection is unlikely because of vertical permeability barriers (shales, tight limestones, etc) that would stop convection or prevent it from ever starting.

Therefore, it is proposed herein that much fluid moves in fault zones by “forced episodic convection” (Figure 44). In this model, fluids move up faults when the faults are active. They are forced (not free) by the fault movement and pressure and are episodic in that convection would only occur when faults are actively moving and would slow down or stop during periods of inactivity. These fluids will be hot, high pressure, high salinity, low pH and capable of significant dissolution and precipitation. Fluids in the altered zones would mix with the fluids coming up the faults but would also have to circulate back out of the altered zone. Some fluids may find their way to the surface or might be able to flow laterally, but some fluids also would circulate back down through faults and fractures to zones lower in the sedimentary column or even into the basement. Fluid inclusion homogenization temperatures in the Trenton and Black River and other hydrothermally altered reservoirs almost require a component of vertical flow coming out of the basement. The forced episodic convection model includes convection in the sedimentary column but also in the basement. Some seawater may get drawn into the cycle by slowly descending through the sedimentary column and feeding in laterally, providing needed magnesium to the system.

This model would help to overcome some of the fluid volume problem by recycling fluids back down to the basement or near basement be used again. This sort of semi-closed system could lead to evolution of fluids from Mg-rich dolomitizing brines toward calcium-rich fluids capable of leaching dolomite and precipitating calcite or anhydrite.

This model is in an early stage of development, and input from other project tasks has yet to be completed. Whatever fluid flow model ends up being used, the model needs to explain the salinity and homogenization temperatures of the fluid inclusions and the mass balance problems of dolomitization.

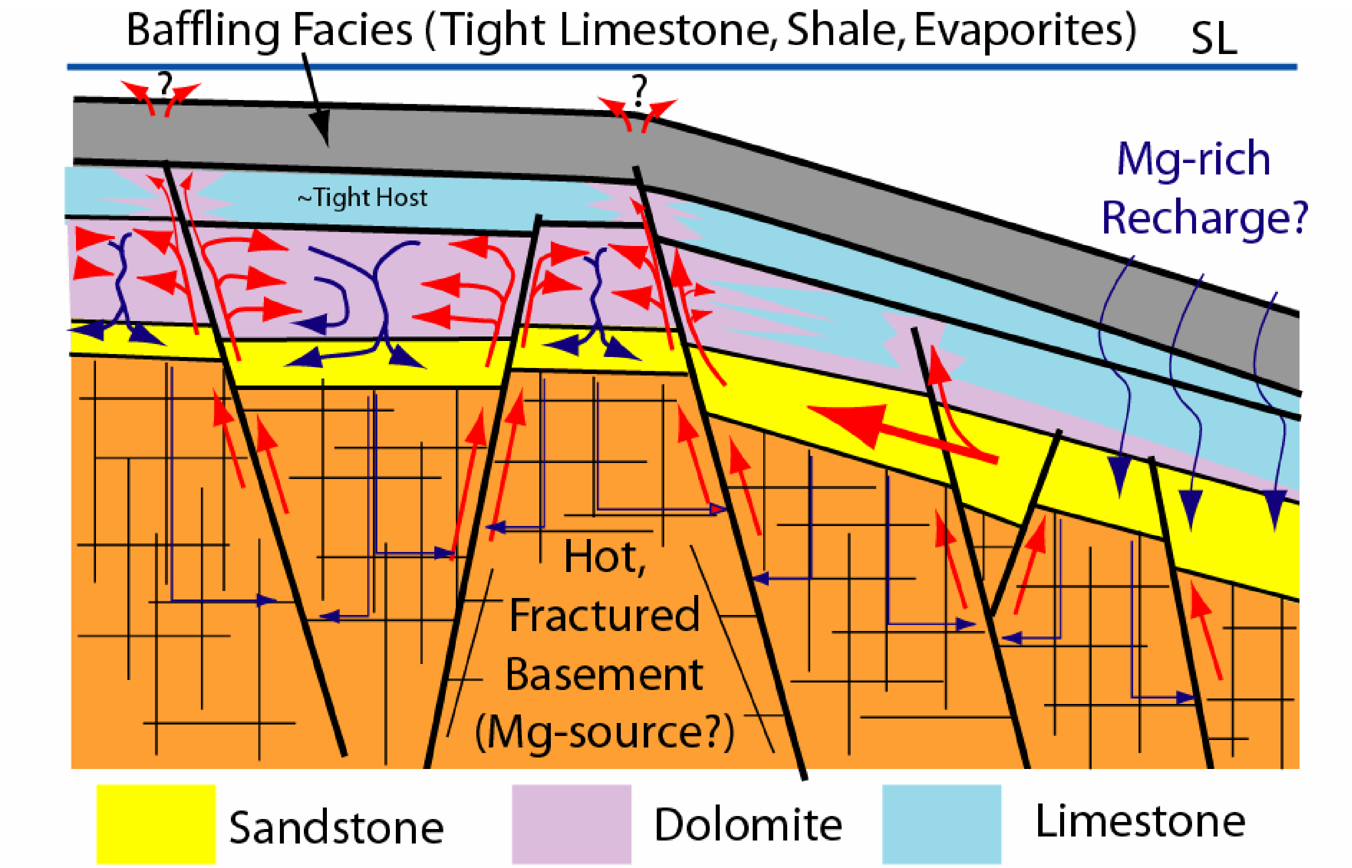


Figure 44. Schematic model for forced episodic convection. Active faulting causes hot fluids to flow upward from basement and lower in the sedimentary section. Introduction of fluids to altered zones higher in the section forces cooler fluids downward. Some fluids may circulate in sedimentary column while others may circulate through basement. Fluids are reused which helps overcome fluid volume problem. Some seawater may sink downward and eventually be drawn into the circulation over time bringing magnesium.

Impact of Hydrothermal Alteration on Carbonate Reservoirs

Fault-related hydrothermal diagenesis produces <u>heterogeneity</u> in carbonate reservoirs. This is because diagenetic fluids are introduced at a point or planar source rather than across a wide area. If the diagenesis observed within a formation varies significantly from well to well (i.e. patchy distribution of mineralization or leaching), fault-related, hydrothermal alteration should be considered as a possible cause of that variation.

Machel and Lonee (2002) suggest that zones of hydrothermal dolomitization are relatively small and restricted to mineralization around faults where, in fact, zones of hydrothermal alteration are scale-independent and may occur across a wide area. Factors that control the lateral extent of a hydrothermally altered zone include precursor porosity and permeability, length of the fault zone, the spacing between faults, the amount of fluid and the duration of the event. Fault-related hydrothermal diagenesis can fully create reservoirs in a tight host rock, enhance porosity in an already porous host or degrade what would otherwise have been good reservoir. If this diagenetic variability can be traced to mappable faults, better exploration and development plans can be made.

Origin

Fault-related hydrothermal diagenesis can produce reservoirs where none would otherwise exist. Examples of this type of alteration would be the Ordovician Trenton-Black River Play in eastern North America and the Devonian Slave Point Formation in Western Canada (Ladyfern, others). Wells that encountered tight, non-productive limestone are drilled in close proximity to wells that encountered highly productive, dolomitized, brecciated and leached limestone in both of these trends. Without the fault-related diagenesis there would be no reservoirs in these cases. Much of the porosity in this type of reservoir occurs in fractures, breccias and vugs but also can occur in matrix dolomite, leached dolomite, leached limestone and microporosity.

Enhancement

Fault-related diagenesis can enhance what otherwise might be productive or marginally productive carbonate reservoirs. Most examples of this involve solution enhancement of porosity. Examples of this include the Cogollo Limestone in Lake Maracaibo, Venezuela, the James Play in the Eastern Gulf of Mexico and many other Mesozoic reservoirs in the Middle East and around the world. More will be discussed on leaching of limestone later in the report.

Super-K Zones

In some cases, porosity is enhanced to the point where “super-k zones” may develop. “Super-k zones” are zones of very high permeability that can, in many cases, cause production problems. Super-k zones can occur in limestone or dolomite host rocks and could be wide-open fractured zones or zones of dissolution and cavernous porosity. Water is produced out of these zones long before the rest of the matrix has been drained of oil or gas. An example of this is in the Arab-D reservoir at Ghawar Field (Cantrell et al., 2005).

Degradation

Fault-related diagenesis also can degrade or destroy what would otherwise be good reservoir facies. Actually, most carbonate reservoirs probably have some degradation associated with fault-derived fluids. Saddle dolomite, for instance, mainly plugs porosity. Its presence helps us understand that the reservoir we are studying has possibly seen some hydrothermal diagenesis, but the reservoir would probably be better if saddle dolomite were not plugging pores and fractures. Much anhydrite, calcite, quartz and dolomite cementation found in fractures and larger pores is probably of a fault-related hydrothermal origin. A good example of this is later reservoir-degrading calcite cement in the Madison Formation in Wyoming and Montana.

New Interpretations for Some Diagenetic Features

Features likely to be produced by faulting and fault-related hydrothermal alteration have historically been attributed to other processes. Leached limestone reservoirs are commonly attributed to meteoric diagenesis, even where there is no evidence for exposure. In many cases, leached intervals do not underlie sequence boundaries. In the Cogollo Limestone, for instance, the leached interval *overlies* a sequence boundary and was probably never exposed to meteoric fluids because the depositional environments deepen upward to deep water black shale.

Significant porosity enhancement can occur in the vadose zone under sequence boundaries (see the Miami oolite as an example), but in most cases it should be most intense at the exposure surface and progressively lessen downward to a depth of a few meters where it should cease (Art Palmer, karst expert, pers. comm). In the absence of fractures, meteoric fluids will equilibrate rapidly with exposed limestone and lose their aggressiveness. If the leached zone cannot be directly tied to an exposure surface and does not intensify upwards towards the surface, it is unlikely that the leaching is meteoric in origin.

Many dolomites that have been interpreted to be of a seawater-meteoric water mixing zone origin in the past are likely to be of a higher temperature hydrothermal or mixed hydrothermal-seawater origin. The seawater-meteoric water mixing zone model is commonly invoked when stable isotopes of oxygen are depleted relative to expected reflux values. $\delta^{18}O$ values can be driven toward more negative values by mixing with meteoric water, but they can also be driven toward negative values by elevated temperature. The mixing zone dolomitization model has been abandoned by most carbonate workers for many reasons, the most obvious being that in all the mixing zones in the world today very little dolomite is forming. Luczaj (in review) has demonstrated that the type section for mixing zone dolomitization in Wisconsin is likely of a hydrothermal origin.

Fault-related breccias formed in the subsurface and cemented with high-temperature minerals precipitated from hydrothermal fluids, such as saddle dolomite, have in many cases been interpreted as meteoric karst breccias. PowerPoint slides from a talk presented at the domestic meeting of the American Association of Petroleum Geologists (AAPG) this year are included on the project website. These slides set criteria for discrimination of meteoric karst breccias from dilational or tectono-thermobaric breccias. This also is the topic of the next section.

Origin of Mineralized Breccias: Meteoric Karst or Tectono-Thermobaric?

One of the more controversial aspects of this area of study is the origin of breccias that host hydrothermal ore deposits and some oil and gas reservoirs. This controversy has raged for decades in the mining industry and that has recently carried over into the oil and gas industry (see Loucks, 2003a, 2003b; Davies, 2001; Smith et al., 2005). The controversy has mainly been around saddle dolomite-cemented breccias in the Cambro-Ordovician Ellenburger Formation in Texas and similar breccias in the Upper Ordovician Trenton and Black River of eastern North America. Loucks (1999, 2003, 2004; Figure 45) suggests that the breccias formed by:

1) Formation of many meteoric caves under a major unconformity;
2) Burial of intact caves;
3) Collapse and coalescence of caves into widespread breccia (up to hundreds of meters wide and long);
4) Cementation by hot or moderately hot fluids during deeper burial from fluids flowing laterally through the collapsed cave system. Strata that overlie the collapsed caves are also interpreted by Loucks to have been fractured and brecciated during the cave collapse.

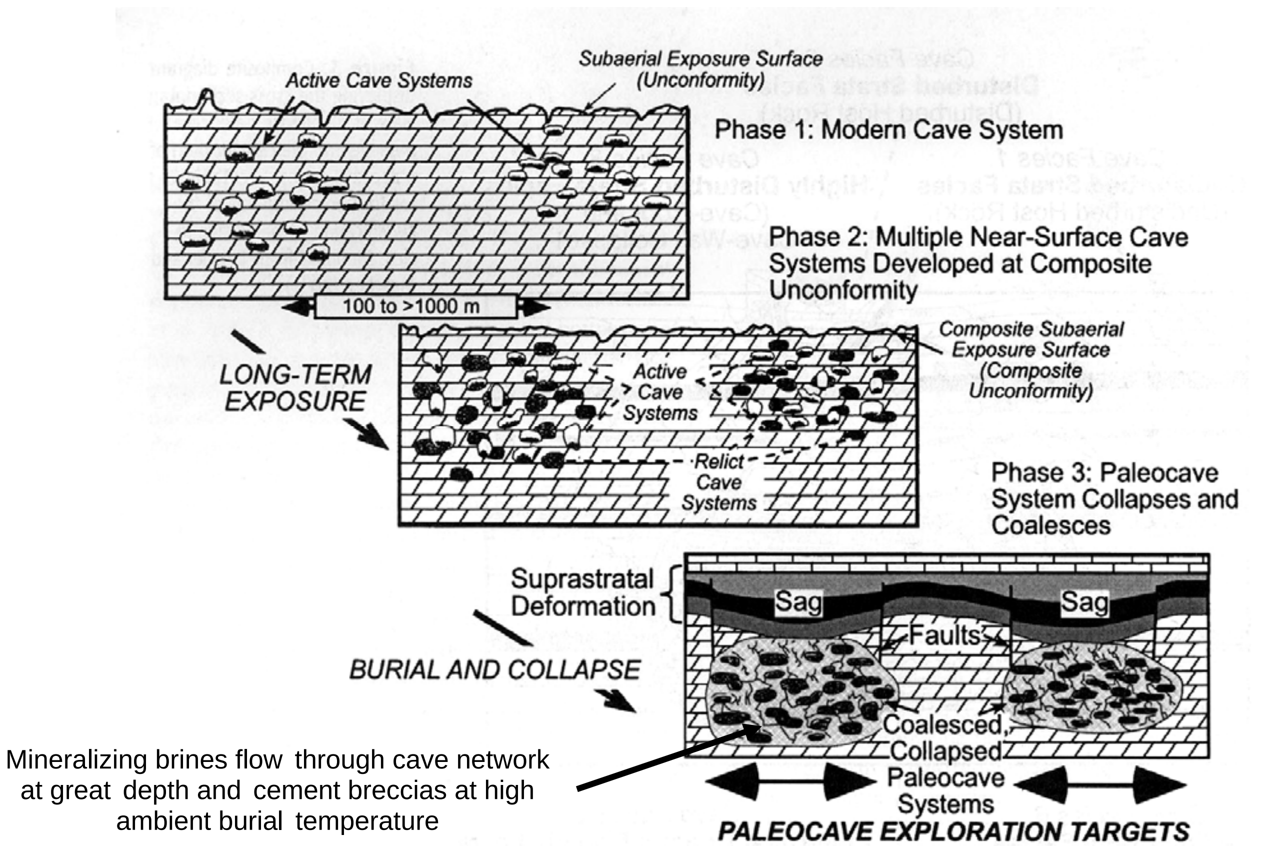


Figure 45. Summary of Loucks' Model for "coalesced collapsed cave" development. Saddle dolomite cement is theorized to form long after brecciation at high ambient burial temperatures. From Loucks (2003).

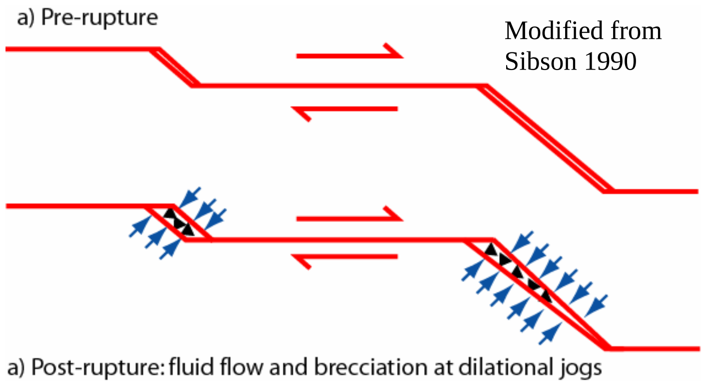
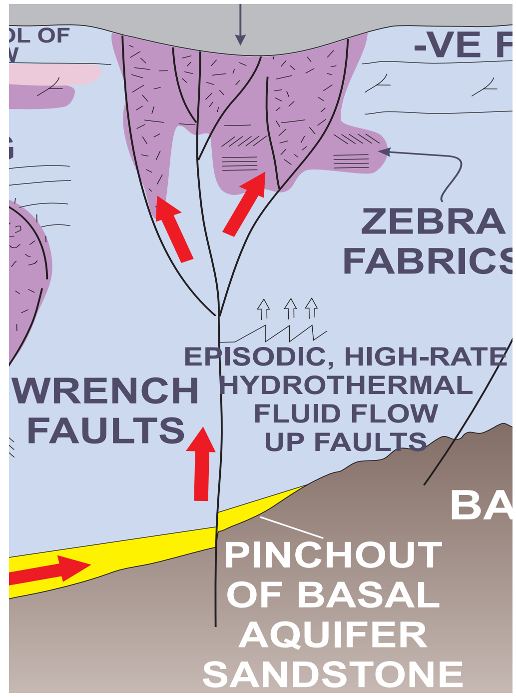


Figure 46. Tectono-thermobaric or dilational brecciation model. Breccias form where space is created in and around fault zones. During fault movement, thermobaric fluids flow up faults and precipitate saddle dolomite, calcite, sulfides or other high-Tminerals



It is the contention of this paper that breccias primarily cemented with saddle dolomite or other high-T minerals are probably of a tectono-thermobaric origin. In this model, breccias form where space is created in fault zones (Figure 46). Some have called this dilational breccia (Tarasewicz et al, 2005) and this is a good term as it forms where an opening has developed. Saddle dolomite and other high-T cements are thought to precipitate rapidly from fluids flowing up the faults, holding the clasts in place. This type of brecciation is scale-independent – it could occur at any scale from the thin section scale to wide as hundreds of meters. Some brecciation may also occur due to dissolution of limestone matrix by hydrothermal fluids and hydro-fracturing by high-pressure fluids.

Origin of Brecciated Lower Paleozoic Reservoirs

The following is an extended abstract that was submitted to a Hedberg Conference organized by Bob Loucks, Charlie Kerans and Jerry Lucia of the Texas Bureau of Economic Geology on the Origin of Lower Paleozoic Breccias. The conference was cancelled by the organizers about 2 months before it was supposed to occur.

FAULT-CONTROLLED THERMOBARIC ORIGIN OF LOWER PALEOZOIC BRECCIATED CARBONATE RESERVOIRS

Langhorne Smith, Reservoir Characterization Group, New York State Museum, Albany, NY 12230; Lsmith@mail.nysed.gov

Carbonate breccias form in many settings, but only certain types of breccia make good reservoirs. Carbonate breccias are here divided into two main types: those that form due to downward meteoric fluid flow and those that form due to active faulting, fracturing and upward thermobaric (high-pressure, high-temperature) fluid flow. It is the position of this paper that most carbonate breccia oil and gas reservoirs and breccia hosted Mississippi Valley Type ore deposits are of the second type. These breccia types can generally be discriminated by the composition of the matrix, their vertical and lateral distribution and their structural and stratigraphic context.

Breccias Formed by Downward Meteoric Fluid Flow

Breccias that form by downward meteoric fluid flow include surficial and penetrative meteoric karst, some evaporite dissolution collapse and soil regoliths. Surficial karst and soil regoliths are common directly under sequence boundaries. These breccias typically consist of small mm- to cm-scale clasts in an argillaceous or micritic matrix. Breccias related to soils would be much more common after land plants became widespread in the Devonian and would be less common prior to that time. This type of breccia is rarely if ever an oil and gas reservoir and is more commonly a sealing facies. Examples will be presented from the Mississippian Ste. Genevieve of the Illinois Basin and Madison Formation of Wyoming.

Penetrative karst consists of vertical and horizontal cave deposits. These breccias consist of mm- to meter-scale clasts that have fallen into empty void space formed by meteoric dissolution of limestone. These breccias tend to have a siliciclastic-rich or micritic matrix, particularly at the base where layered cave sediment should occur. When present, this matrix generally makes these breccias non-reservoir. Penetrative karst commonly follows pre-existing fractures, but does not require a link to faults. Speleothems are likely to be present in most meteoric cave deposits. Calcite associated with speleothems may precipitate in open fractures in the roof of caves. Meteoric caves are more likely to form in a humid climate, in limestone vs. dolomite, in locations with a fairly steep hydraulic gradient that keeps fluids moving, in locations with a well-developed surface drainage system and in fractured, indurated rocks (White, 1988; many others). An example of a sinkhole breccia that formed over a collapsed cave from the Madison Formation of Wyoming will be presented.

Many evaporite dissolution collapse breccias form due to meteoric dissolution of evaporite minerals and collapse of interbedded and overlying strata into the void. These breccias are typically composed of mm- to meter-scale clasts and have a micritic or siliciclastic-rich matrix. Dissolution of bedded evaporites could lead to development of breccias over a wide area. They can be distinguished from meteoric karst breccias by their greater lateral extent and strataform base and irregular top. Evaporite solution collapse breccias formed due to meteoric dissolution are generally non-reservoir due to their impermeable matrix. An example from the Madison Formation of Wyoming will be presented.

Breccias Formed by Faulting and Upward Thermobaric Fluid Flow

Tectono-thermobaric breccias form during active faulting and associated fluid flow in fault zones. This is especially common at any point along a fault plane where space is being created such as dilational jogs on strike slip faults (Sibson, 2000).

These brecciated zones may cut across previously karsted intervals, but are more common in rock that was not previously brecciated. Breccias consist of mm- to meter-scale scale clasts cemented with dolomite, calcite, anhydrite or some other type of cement. Some of these breccias appear to have clasts floating in cement, which occurs when the rock is brecciated and simultaneous rapid precipitation of cement occurs during fluid pressure drop. These breccias commonly have associated zebra fabrics and boxwork structures (Davies, 2001).

There may also be leaching of limestone associated with the thermobaric fluid flow, which produces vugs and brecciation. Cooling hydrothermal fluids become undersaturated with respect to calcite because calcite has retrograde solubility. Carbon dioxide also has retrograde solubility and cooling fluids can hold progressively more CO_2, which could further enhance their solutional aggressiveness. The upward flowing fluids could also be charged with H_2S or acids acquired from underlying units that could further enhance their solutional aggressiveness.

Sand and shale from formations cut by fault zones may be mobilized by thermobaric fluids and end up in the matrix of breccias in underlying or overlying formations. One example will be presented of a green shale matrix in a breccia that is clearly fault-related thermobaric in origin. Some internal sediment within faults zones can have a cross-bedded appearance and large clasts can be moved laterally as fluid flow rates can be very high (up to 6 m/s) within the fault zones (Eicchubl and Boles, 2000).

These breccias commonly form in linear to sub-circular “pull-aparts” or negative flower structures where space has been created along a fault zone. In some cases the circular sags resemble sinkholes in overlying formations, but they are structural pull-apart features that form along strike slip faults. Examples will be presented from the Ordovician Trenton Black River of the Appalachian Basin, the Cambro-Ordovician Beekmantown of New York and Ellenburger of Central Texas.

Thermobaric breccias form in a variety of tectonic settings, but those with the best reservoir quality occur around basement-rooted strike-slip, transtensional and extensional faults (Davies, 2001). Faults with little vertical offset may be the best, because they are less likely to breach the overlying seal. It is in these settings that space is created at certain points along the fault zone and conduits are opened that provide a pathway for upward flowing thermobaric fluids. Much brecciation and alteration may occur in the first kilometer of burial.
Most reservoir-quality carbonate breccias are at least partially cemented with saddle dolomite, which forms from highly supersaturated solutions. High degrees of supersaturation would not be attained in a deep burial setting with slow lateral flow but instead forms in thermobaric settings where P-T conditions change rapidly. Other products of thermobaric fluid flow and diagenesis are matrix, vug- and fracture-filling dolomite, calcite, anhydrite, bitumen, sulfides, barite, quartz, celestite, fluorite, microporosity in limestones and more. Leached limestone and in some cases leached dolomite are also common. The presence of any combination of these features

suggests that there may have been some kind of hydrothermal or thermobaric alteration.

Some thermobaric breccias also form in places where space is created in thrust sheets. These breccias are typically cemented with calcite and destroy reservoir quality. There are common calcite-cemented breccias in the Appalachians and Rocky Mountains that formed during thrusting. Examples will be presented from the Madison Formation of Wyoming.

Origin of Carbonate Breccia Reservoirs

It is the position of this paper that most Lower Paleozoic carbonate breccias that host oil and gas reservoirs and MVT ore deposits are of a fault-related thermobaric origin. Thermobaric breccias commonly host ore deposits, because the same plumbing system that brought the thermobaric fluids also brings in the metals and other minerals, sometimes from deep down in the basement. These breccias make good oil and gas reservoirs because the hydrocarbons commonly use the same plumbing system as the hydrothermal fluids and the brecciated zones are commonly isolated within tight rocks, which form lateral and vertical seals around the reservoir. Because the breccias are related to basement-rooted faults, potential reservoir zones can commonly be recognized on seismic data and discovered by playing around the faults.

Breccias in the fault-controlled hydrothermal dolomite reservoirs in the Ordovician Trenton Black River Play in the Appalachian Basin, Michigan and Ontario are all of a thermobaric origin. In this play, evidence for hydrothermal alteration includes matrix, vug and fracture filling dolomite, quartz, sulfide minerals, dissolutional vugs, bitumen, and some breccias. The hydrothermal alteration only occurs around negative flower structures formed over basement-rooted strike-slip faults that were active in the Late Ordovician and Early Silurian. These are unequivocally fault-controlled thermobaric dolomites and breccias.

Loucks (2003) proposed a model for the Trenton Black River breccias that is similar to the one he and others have proposed for the Cambro-Ordovician Ellenburger of West Texas. He asserts that meteoric caves in the underlying Cambro-Ordovician Beekmantown and equivalents have collapsed and that the sags and breccias in the Trenton Black River are produced by collapse into these caves. This argument is easily refuted. In Ontario, seismic lines over Trenton Black River brecciated dolomite reservoirs show the exact same sags that occur in the Appalachian Basin and Michigan but there is no underlying Cambro-Ordovician Beekmantown/Ellenburger equivalent there. The Black River sits directly on siliciclastics that sit directly on basement. If there is no Beekmantown, there can be no caves in it to collapse. Again, the sags and fault-controlled diagenesis in the Trenton Black River in Ontario are identical to that in the Appalachian and Michigan Basins.

It is the position of this paper that there are at least two main breccia types in the underlying Cambro-Ordovician Ellenburger/Knox/Beekmantown: surficial meteoric karst breccias and thermobaric breccias. This was the conclusion of Montanez (1997) in her excellent work on the time-equivalent Knox Formation in Tennessee. Directly under the major Knox unconformity there is commonly (but not always) a brecciated zone with an argillaceous or micritic matrix. This zone may extend several meters down into the Ellenburger and equivalents and is interpreted to be a surficial karst breccia. Where present, this breccia type is generally non-reservoir. Similar breccias may occur under sequence boundaries within the Ellenburger.

The second type of breccia in the Ellenburger and equivalents is saddle dolomite-cemented thermobaric breccia. These breccias may form across many different stratigraphic intervals as there is no genetic link to an exposure surface and breccias can and do extend upward into overlying formations. The thermobaric breccias commonly retain porosity and make good oil and gas reservoirs and hosts for hydrothermal ore deposits.

Some breccias that have been previously interpreted as collapsed meteoric cave breccias are fault-controlled thermobaric in origin. The breccias in the quarries that we will visit on the first field trip (Marble Falls) are almost entirely cemented with high-temperature saddle dolomite. There is no evidence of a pre-saddle dolomite siliciclastic or micritic matrix in any of the breccias and there are no speleothems. There is some quartz sand in one of the outcrops, put it clearly postdates saddle dolomite. The area that is brecciated in the quarries is too laterally extensive to have been a meteoric cave. Caves would not coalesce because meteoric fluids would continue to flow through the first cave, even if it had collapsed.
Furthermore, it is unlikely that a widespread deep-penetrating meteoric cave system would have developed under the much of the Knox unconformity. The hydraulic gradient would have been very low in places far from the coast, and relatively rapid movement of meteoric water is essential to meteoric cave development. Given the general lack of Ordovician incised valleys on the unconformity surface, there was no well-established surface drainage system on the Knox unconformity. Surface discharge is an essential component of meteoric cave development because the calcite-saturated water must be discharged after it has been leached from the cave. The Ellenburger and equivalents experienced some early dolomitization (although some matrix dolomite is clearly hydrothermal in origin) and caves are much less likely to form in dolomite than they are in limestone. Apparent sinkholes or collapsed caves on seismic are in fact pull-aparts that formed at dilational jogs along or between basement-rooted strike-slip faults (Lacozette et al., 2004). These pull-aparts would be ideal locations for thermobaric brecciation, reservoir formation and ore deposition.

Fault-controlled thermobaric and hydrothermal alteration of carbonate reservoirs are historically overlooked processes that create, enhance or degrade porosity in carbonate reservoirs around the world. Some of these hydrothermally altered reservoirs have associated breccias, while others do not. These are integrated structural-stratigraphic-diagenetic plays that can be laterally heterogeneous for structural, stratigraphic and diagenetic reasons. A better understanding of the processes and products of hydrothermal alteration will help to improve the bottom line for oil and gas exploration and development companies.

(End of Abstract)

The aforementioned conference was going to include field trips to quarries in Marble Falls, Texas and the Franklin Mountains in El Paso, Texas. The author of these notes had already attended Bob Louck's field trip to Marble Falls, Texas that had the theme of "Paleokarst reservoirs" of the Ellenburger Formation. The trip includes a trip to a modern meteoric cave and then to two quarries in the Ellenburger. The quarries consist almost entirely of saddle dolomite cemented breccia, with some boxwork fabrics and saddle dolomite lined vugs. The scale of the brecciation is impressive – at least 100 meters wide and long and clasts range from cm- to meter-scale. Cores show epikarst is common on the top of the Ellenburger and on sequence boundaries within the Ellenburger. The epikarst breccias are impermeable and for the most part do not host ore minerals or hydrocarbons.

The saddle dolomite-cemented breccias and associated boxwork fabrics and vugs do have some porosity (Figure 47). Loucks had not done any geochemistry or fluid inclusion analysis of the dolomites, but had looked at some thin sections and decided that there were no two-phase fluid inclusions in the saddle dolomites (Loucks, 2004). He then made the interpretation that these were low temperature saddle dolomites that formed at a temperature of ~50°C (Loucks, 2004). Two samples were taken by the author of these notes and sent to Fluid Inclusion Technologies Inc. for fluid inclusion analysis. Both the matrix and saddle dolomites have abundant two-phase fluid inclusions, which have homogenization temperatures of 90-120°C and salinities of around 20 wt% (Figure 21). These values are typical of hydrothermal dolomites.

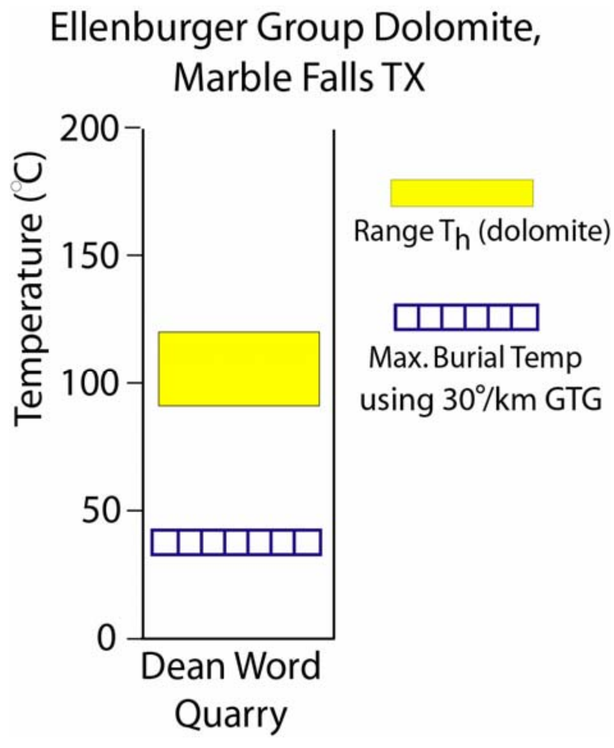
Kupecz and Land (1991) determined that the quarries at Marble Falls have never been buried to a depth of more than 350 meters. This would put the maximum burial temperature at no more than 40°C (Figure 21). The homogenization temperatures therefore exceed the maximum burial temperature by 50-80°C making both the saddle dolomite and at least some of the matrix-replacive dolomite *unequivocally* hydrothermal in origin. The only way to get fluids that hot up to the shallow depths is via faults. The Marble Falls quarries are also interpreted to be located within a negative flower structure (Loucks, pers. comm.), which is the ideal setting for fault-related hydrothermal alteration.

These quarries may, ironically, be one of the world's great hydrothermal dolomite outcrops. Further study of these and any nearby outcrops is warranted. Not only is it a place where the line between hydrothermal and meteoric diagenesis could be drawn, but they are also spectacularly exposed.

Figure 47. Saddle dolomite cemented breccia from Ellenburger Group, Marble Falls, TX

Table 8: EF-2,Marble Falls Quarry		
Population	**Th aq (°C)**	**Sal (wt%)**
pr; outer clear dol A	95-105 (6)	20.2-21.0
pr; outer clear dol B	95-100 (4)	21.0-21.7
pr; outermost clr dol C	110-120 (4)	21.7-22.4
pr; core/rim dol D	100-105 (4)	20.2-21.0
pr; outer clear dol E	91 (1)	20.2
pr; outer clear dol F	90-100 (7)	21.0-21.7
pr; outermost clr dol G	119 (1)	22.4
pr; outermost clr dol H	110-120 (7)	21.0-21.7
pr; core saddle dol I	100-110 (5)	21.7-22.4
pr; core saddle dol J	105-110 (3)	21.7

Figure 48. Fluid Inclusion data for matrix and saddle dolomite from quarry above (analysis by Fluid Inclusion Technologies Inc.). Dolomite formed from fluids between 90-120°C and salinities of around 20 wt%. Regional geology and CAI suggest that quarry was never buried more than 350 meters – Dolomite is unequivocally hydrothermal in origin.



Conclusions on Hydrothermal Alteration of Carbonate Reservoirs

These are the main conclusions from this discussion of hydrothermal alteration of carbonate reservoirs:

1. Fault-related hydrothermal alteration is a dynamic process with many variables and many possible products that can have a major impact on carbonate reservoirs.
2. There is a spectrum of possible hydrothermal alteration features in reservoirs ranging from leached limestone and microporosity to matrix dolomite to saddle dolomite-lined breccias, zebra fabrics and fractures. In some cases, alteration is very obvious whereas in others it may be much harder to detect.
3. Mineralization likely occurs during the pressure drop after fluids flow up faults and is due to mixing of hydrothermal fluids with *in situ* fluids.
4. Leaching of limestone likely occurs in cooling hydrothermal fluids. Hydrothermal fluids that flow up faults are likely to have lower pH and higher salinity than fluids in the altered zone. Cooling fluids will be progressively undersaturated with respect to calcite and $CO_{4.}$ As fluids cool they will leach limestone and take more CO_2 into solution, which will further drop the pH and further enhance their ability to leach limestone.
5. Microporosity is common in leached limestones and likely forms during hydrothermal alteration in some cases.
6. Leached dolomite occurs in some hydrothermally altered reservoirs and may significantly enhance porosity. Dolomite leaching occurs near the end of the Paragenetic sequence but is typically followed by precipitation of calcite or anhydrite. This suggests that fluids evolve to be more calcium-rich with time.
7. Hydrothermal alteration may be more common than previously thought and some features previously attributed to meteoric, mixing zone or deep burial diagenesis may in fact be hydrothermal in origin.

Analysis of Production Data

This task will identify fairways in gas production and assess the ultimate gas resource of the Trenton and Black River intervals. Cumulative production figures have been compiled for Ohio, Kentucky, New York and West Virginia. A literature search found that an easily-constructed graph that plots annual production against cumulative production can be used to predict ultimate recovery from a field or region (Figure 49). However, this approach is limited to estimating remaining reserves if the total production history is unavailable. Also, it only works once production is in decline and cannot account for new discovery of reserves. Nevertheless, it may be useful for mature fields.

Plans for the next six months are to convene a meeting of state researchers, possibly with experts in resource assessment from industry and the US Geological Survey, to determine a procedure for a regional resource assessment. Necessary geologic conditions leading to production fairways will be used to constrain the geographic and stratigraphic extent of the resource. Resulting maps can be used with past production to estimate the resource.

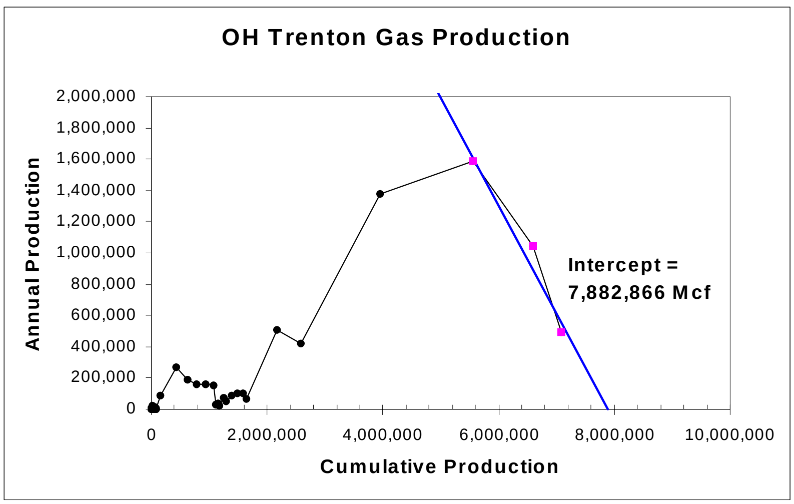


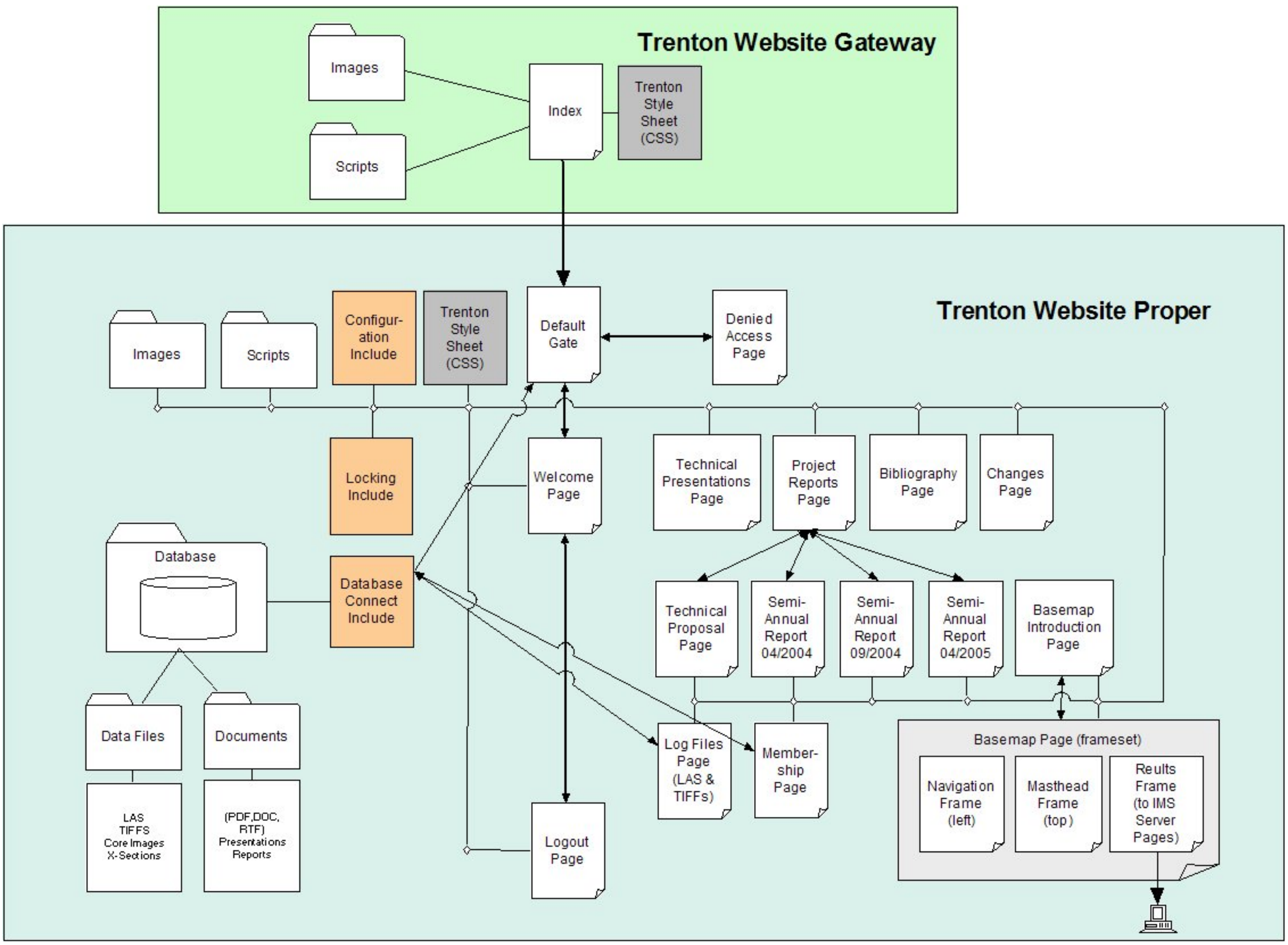
Figure 49. Graphical approach to predicting ultimate recovery. Fitting a line of best fit to the period of declining production is followed by computing the intercept on the x-axis. Given a complete production history, this is the ultimate cumulative production. If the complete production history is unavailable, remaining production can be computed as the difference between the most recent year's annual production and the x-intercept. Example uses data on Trenton, Black River and Utica production from wells in Ohio.

Database, GIS and Website Management

During this report period, the task team was involved in an assessment of the current state of the website and database.

The Website

The website, like the database, is a work in progress as mentioned in previous reports. In the current configuration, the website will grow only when the database grows. Some of the recent improvements to the website were in the areas on how we serve well log files (LAS and Tiffs).



The Trenton website actually consists of two websites (as shown in the chart). The first one serves as a gateway with standard non-secure (http) HTML. This one directs the user to the second, main and secure website (https) utilizing Active Server Pages (ASP), JavaScript, SQL and HTML. Other calls or directives to the web server are involved but are not shown for security concerns.

Above, all pages involve various images, scripts and include files. The "Default Gate" controls who has access to the site. The "Welcome Page" actually links in to most of the other pages, but for simplicity for the graphic, only links from the login "Default Gate" and "Logout Page" are shown.

The Database

At the partners' meeting on October 5, 2005, plans were to present a review and reiteration of the preferred header information which contains most of the general data pertaining to each well. It is acknowledged that not all data fields may have values, but all states were encouraged to provide as much information as possible. Some fields containing API and location information (e.g., UTM Lat/Long), for example, are absolutely necessary for the functional project database.

In terms of well data, we have the following tables created—all of which link to Wells Header Information as shown in the chart:

- Wells Header Information
- API Header Information (for codes)
- Well Production Data
    - Gas
    - Oil
    - Water
- Well Log Data, LAS Files (access to LAS text files)
- Well Log Data, Tiff Files (access to graphical files)
- Well Cores Data (access to graphical files)
- Well Cross Sections (access to graphical files)

Attribute Name	Attribute Description	Attribute Type	Given Actual Attribute Values or Examples (in quotations)
API (or UWI)	Well's full 14 digit API Number or other UWI (unique key)	num, 14d	"47001123450000", API preferred over other UWI
NEEDINFO	(have info for well but no header data)	varchar	(where I only have info from) "LAS", "TIFF", "Prod_Gas"
StateNo	State API Number (incorporated in API)	num, 2d	13, 16, 21, 31, 34, 37, 47, 78
CntyNo	County API Number (incorporated in API)	Num, 3d	
PrmtNo	Permit Number (incorporated in API)	num, 5d	
LatDD	Latitude (in NAD83)	num, 10d	
LonDD	Longitude (in NAD83)	num, 10d	
UTME	UTM Easting (in NAD83)	num	
UTMN	UTM Northing (in NAD83)	num	
Suffix		varchar(25)	Original Loc, Drilled Deeper, Worked Over, Dvtd Drld Dpr, Dvtd Worked Over, Dvtd Orig Drllg
SpudMn	Spud Month	num, 2d	
SpudDy	Spud Day	num, 2d	
SpudYr	Spud Year	num, 4d	
PlugMn	Plug Month	num, 2d	
PlugDy	Plug Day	num, 2d	
PlugYr	Plug Year	num, 4d	
CompMn	Completion Month	num, 2d	
CompDy	Completion Day	num, 2d	
CompYr	Completion Year	num, 4d	
Farm	Farm	varchar(100)	
WellNum	Well Number	varchar(15)	
CoNum	Company Number	num?	
Mineral_owner	Mineral Owner	varchar	
Operator	Operator	varchar	
Elev	Elevation	num, 5d	
Datum type	Datum (Elevation) Type	varchar(25)	Barometer, Casing, Derrick Floor, Casing Flange, Ground Level, Kelly Bushing, Questionable, Spirit Level, Topo Estimation, Unknown
Field	Field name as assigned by the state	varchar(100)	
DeepFm	Deepest Formation penetrated by well	varchar(100)	
DeepFmTstd	Deepest Formation fully Tested by well	varchar(100)	
InitClass	Initial Classification	varchar(25)	New-Field Wildcat, Deeper-Pool Test, Shallower-Pool Test, Outpost (Extn) Test, Development Well, Stratigraphic Test, Service Well, Misc Well, Unclassified, NA
FinalClass	Final Classification	varchar(25)	Unsuccessful, New-field Discovery, New-pool Discovery, Deeper-pool Discovery, Shallower-Pool Discover, Outpost (Extension) Well, Discovery Well, Misc Well, Unclassified, NA
WellTyp	Well type as originally drilled	varchar(50)	Gas, Oil, Oil&Gas, Dry Hole, Gas with Oil Show, Oil with Gas Show, Dry with Gas Show, Dry with Oil Show, Dry with Oil and Gas Show, Storage Well, Brine (Salina), Salt Water (Salt Sands), Industrial Waste Disposal, Salt Water Disposal, Gas Injection, CO2 Injection, Water Injection, Injection for In-Situ Comb, Observation, Other, NA
RigTyp	Rig Type	varchar(15)	Unknown, Rotary, Spudder, Cable Tool
CmpMth	Completion Method	varchar	Unknown, Nat/Open H, Acid, Frac, Acid&Frac, Shot, Shot+, Unstim, Unfn Stim
TD	Total Depth (in feet)	num, 5d	
NewFtg	New Footage (in feet)	num, 5d	
ExplFtg	Exploratory Footage (in feet)	num, 5d	
GasBfr	Gas Vol Before Treatment (Mcf/day)	num, 5d	
GasAftr	Gas Vol After Treatment (Mcf/day)	num, 5d	
NatPress	Natural Pressure (psi)	num, 4d	
NatTime	Natural Time (hours shut in)	num, 4d	
TrtPress	Treated Pressure (psi)	num, 4d	
TrtTime	Treated Time (hours shut in)	num, 4d	
top_TRNT_md	Top Trenton (in feet)	num, 4d	
datum_TRNT_top	Datum Trenton top (in feet)	num, 4d	
datum_type_TRNT _top	Datum Type Trenton Top	varchar(25)	Barometer, Casing, Derrick Floor, Casing Flange, Ground Level, Kelly Bushing, Questionable, Spirit Level, Topo Estimation, Unknown
TRNT_top_subsea	Trenton Top Subsea (in feet)	num, 5d	
Comments	Comments	varchar(250)	
Entered_Date	Date info added to database	date	"3/5/2005"
Provided_By	Provider of data for well info	varchar	"John Doe, State_GS"

Table 1. Wells' Header Information. Bold items are necessary. Items with the orange background will not be seen by a user.

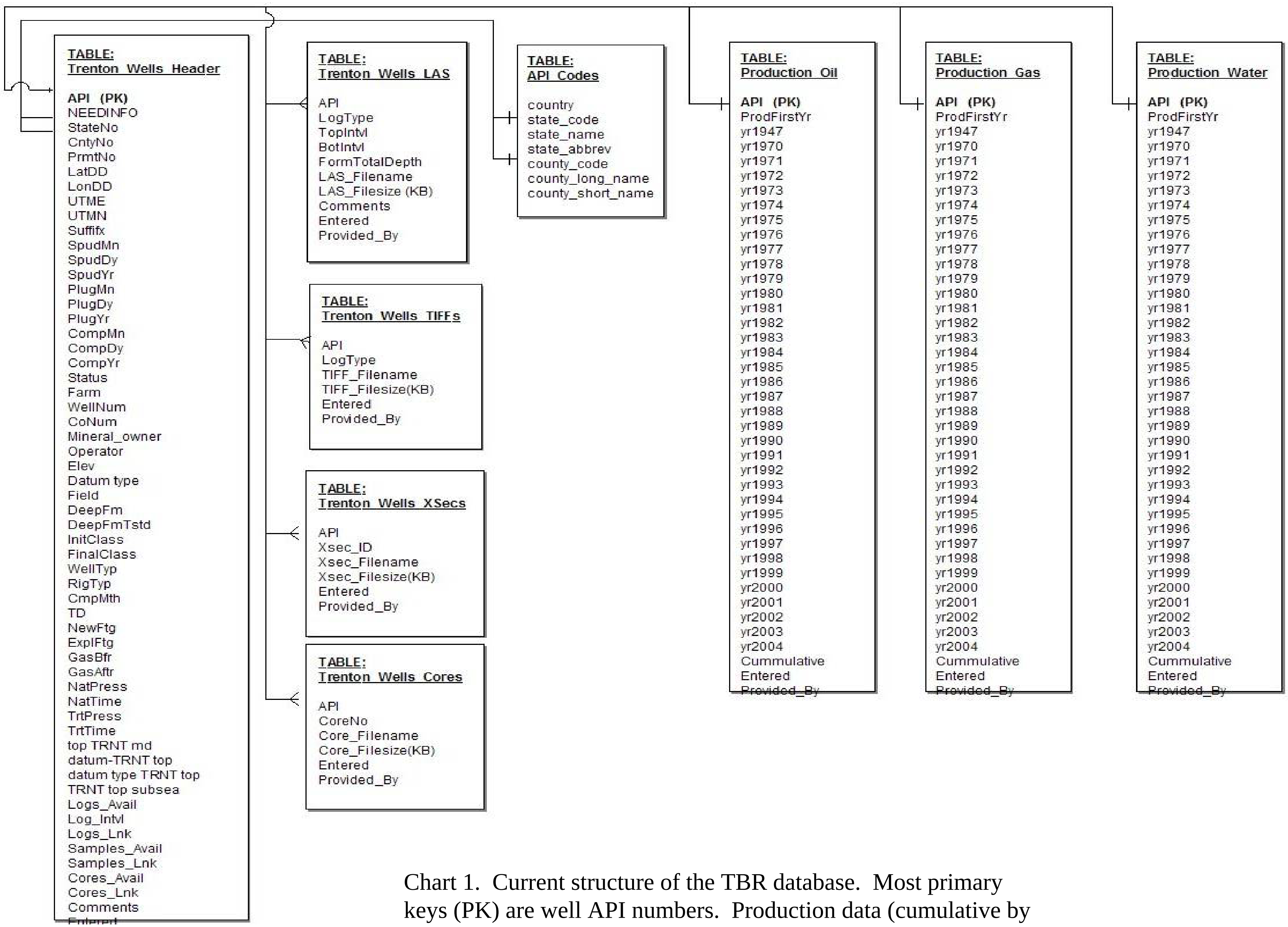


Chart 1. Current structure of the TBR database. Most primary keys (PK) are well API numbers. Production data (cumulative by well per year) will be adjusted for years not shown.

Other Database Items

With the completion of the cross section work by Ohio, we have received the data and have begun work on incorporating that information into the database and IMS applications. Associated LAS files with wells shown on cross sections will be accessible via hyperlinks from the website database access and/or the IMS application—the next major addition in this area.

Work has also begun on compiling well production data sets from Ohio, Kentucky, New York and West Virginia. Michael Hohn (WVGES) will continue analysis of this data which in turn will be employed in the website and/or IMS application.

CONCLUSIONS

Understanding the basin architecture and facies distribution has important implications for Trenton-Black River exploration.

Preliminary isopach and facies maps for the Trenton interval indicate that exploration potential exists along the entire platform margin, from Ohio into Ontario and Pennsylvania.

Clean grainstones that were deposited in skeletal shoals along the platform margin appear to be the prime intervals where hydrothermal dolomite reservoirs could be developed.

An upper, cleaner portion of the Trenton in western New York also may have potential for the development of hydrothermal dolomite reservoirs.

The more argillaceous nature of Trenton limestones in the basin to the east may have inhibited the process of hydrothermal dolomite development.

Trenton-Black River production in Kentucky and West Virginia thus far has been from fractured limestones.

Localized areas of cleaner carbonates in the eastern basin facies may be more conducive to hydrothermal dolomite development.

Maps of faults of suitable age, orientation and location may be relevant to predict fairways in which fault-related hydrothermal dolomite developed.

Numerous lines of evidence suggest that fluids that formed dolomites in the Black River migrated upward from basin-rooted faults.

Fault-related hydrothermal alteration is a dynamic process controlled by many variables and with many possible products that can have a major impact on carbonate reservoirs.

Proximity to the basement and a basal sandstone appear to have a major impact on the type of alteration, because the thickness of the section beneath the altered interval has a major impact on how hot the fluids can remain as they flow up the faults to a potential reservoir rock.

There is a broad spectrum of possible hydrothermal alteration features in reservoirs, ranging from leached limestone and microporosity to matrix dolomite, to saddle dolomite-lined breccias, zebra fabrics and fractures.

Mineralization of host limestones likely occurred during the time when pressure dropped after the fluid had flowed up the fault from the basement, and is due to mixing of hydrothermal fluids with *in situ* fluids.

Leaching of limestone host rock occurred as hydrothermal fluids cooled as became progressively undersaturated with respect to calcite and CO_4.

Microporosity is common in leached limestone and likely formed during hydrothermal alteration, at least in some cases.

Leached dolomite occurs in some hydrothermally-altered reservoirs and may significantly enhance porosity, but often is followed by precipitation of calcite or anhydrite, which decrease porosity.

Hydrothermal alteration may be more common than previously thought.

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