Outcrop analog for Trenton–Black River hydrothermal dolomite reservoirs, Mohawk Valley, New York

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ABSTRACT
Geochemical analysis and field relations of linear dolomite bodies occurring in outcrop in the Mohawk Valley of New York suggest that the area has undergone a significant fault-related hydrothermal alteration. The dolomite occurs in the Lower Ordovician Tribes Hill Formation, which is regionally a Lower Ordovician shaley limestone with patchy dolomitization. The outcrop has an en echelon fault, fracture, and fold pattern. A three-dimensional (3-D) ground-penetrating radar (GPR) survey of the quarry floor has helped to map out faults, fractures, anticlines, synclines, and the extent of dolomitization. Most of the dolomitization occurs in fault-bounded synclines or sags flanked by anticlines. The dolomite structures are highly localized, occurring around faults, and are absent away from the faults and fractures. Trenches cut across the outcrop help relate offset along faults to the overall geometry of the dolomitized bodies. Geochemical analysis, although helpful in characterizing the conditions of dolomitization, does not define its origin absolutely. This study uses fluid inclusions, stable isotopes, 3-D GPR, core analysis, and surficial observations, which all show a link between faulting, dolomitization, and other hydrothermal alteration. Although the outcrop is much too small and shallow to act as a producing gas field, it serves as a scaled analog for the Trenton–Black River hydrothermal dolomite reservoirs of eastern United States. It may therefore be studied to help petroleum geologists characterize existing gas plays and prospect future areas of exploration.

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INTRODUCTION

Oil and gas have been produced from what are interpreted to be fault-controlled hydrothermal dolomite reservoirs in the Ordovician Trenton and Black River carbonates since the late 19th century (Harding, 1974; Hurley and Budros, 1990; Wickstrom et al., 1992; Smith, 2006). Whereas the play has been active for more than 130 yr, new fields are still being discovered because of their unconventional structural style. At least 30 new gas fields were discovered in the Black River Group in New York over the last 15 yr (Figure 1). The fields are detectable on seismic profiles as elongate, fault-bound structural lows or sags associated with trans-tensional wrench faulting (Smith, 2006). Dolomite and porosity form around the faults but are absent away from the faults where the formations are composed primarily of impermeable limestone that forms a lateral seal (Smith, 2006). The cores from these fields and others like them commonly contain matrix dolomite as well as fractures, breccias, and vugs lined with white saddle dolomite (Davies and Smith, 2006). Fluid inclusions and geochemical analyses suggest that the dolomites formed in a burial environment from high-temperature saline brines that passed through the basement or immature siliciclastics overlying the basement before precipitating the dolomite. These structures have been interpreted to form when oblique strike-slip faulting allows pressurized fluids to travel upward along fault planes to shallower units (Harding, 1974).

Much of the research involving the formation and characterization of hydrothermal dolomite reservoirs has involved an interpretation of subsurface data including well logs, seismic data, and cores. Three-dimensional (3-D) seismic data and maps of productive wells suggest that the dolomite occurs in en echelon bodies interpreted to have formed around synthetic shear faults associated with a deeper master fault (Harding, 1974; Hurley and Budros, 1990). However, many details of the fault geometry, distribution of dolomite, brecciation patterns, and facies control on dolomitization are difficult to determine with these data sets.

An exposure of dolomite located in the Lower Ordovician Tribes Hill Formation in Mohawk Valley, New York (Figure 1) appears to be an excellent small-scale analog for the lower Paleozoic hydrothermal dolomite reservoirs of eastern United States. This article is based on a graduate project at the State University of New York at Albany (Slater, 2007). The discovery of this outcrop has allowed the shape, size, structure, and origin of hydrothermal dolomite reservoirs to be more deeply investigated. The dolomite occurs in three en echelon bodies that form in and around sags associated with what appears to be a deeper fault zone. The purpose of this study is to characterize the stratigraphy, structure, and geochemistry of the outcrop to establish its hydrothermal origin so that it can be used to better understand the complex nature of productive reservoirs.

GEOLOGIC SETTING

The Palatine Bridge quarry is in the Lower Ordovician Tribes Hill Formation of the Beekmantown Group (Figure 2) in the Mohawk Valley of New York, just south of the Adirondack Mountains. It is a thin- to medium-bedded argillaceous limestone with patchy dolomitization (Landing et al., 1996). Fluid inclusions and geochemical analyses suggest that the dolomites formed in a burial environment from high-temperature saline brines that passed through the basement or immature siliciclastics overlying the basement before precipitating the dolomite. These structures have been interpreted to form when oblique strike-slip faulting allows pressurized fluids to travel upward along fault planes to shallower units (Harding, 1974).

The Tribes Hill unconformably overlies the Upper Cambrian Little Falls Dolomite that is described as a thick-beded dolomite and is believed to have formed by deposition in a shallow, peritidal to subtidal environment (Zenger, 1981). The Little Falls is approximately 400 ft (~120 m) thick in this part of the Mohawk Valley (Zenger, 1981). It
commonly overlies the Galway Formation and Potsdam Sandstone, which may or may not be present below the quarry, as they thin to the northeast and the nearest outcrops are of a significant distance from the quarry. The Potsdam Sandstone is believed to overly the Precambrian basement.

The basement rock of New York state consists mainly of granitic gneiss. It is part of the Grenville Province that formed approximately 1.1 Ga during the Grenville orogeny. Many thrust and tear faults formed during this orogeny. In the late Precambrian, the existing supercontinent rifted apart, forming a margin to the present-day east. Many failed rifts were observed, such as the Rome trough, that were affected by strike-slip as well as extensional faulting. Some of this rifting may have occurred along preexisting faults that originally formed during the Grenville orogeny (Bird and Dewey, 1970; Jacobi and Fountain, 2005). The deposition of the Potsdam Sandstone, Beekmantown Group, and Black River Limestone during the Late Cambrian and Early Ordovician is thought to have occurred along a south-facing passive margin following the opening of the Iapetus Ocean. In the Late Ordovician, the Taconic orogeny occurred when a volcanic island arc collided with eastern North America. This collision caused significant faulting in the Mohawk Valley (Bradley and Kusky, 1986; Bradley and Kidd, 1991;
Joy, 2000). Downwarping of the North American plate beneath the island arc led to extensional faulting and produced a series of northeast-southwest–striking normal faults, some with more than 1000 ft (>305 m) of throw (Jacobi, 1981; Bradley and Kidd, 1991). Some strike-slip faulting associated with this mountain-building event is likely to have existed as well. Older, appropriately oriented faults may have been reactivated at this time in either a right-lateral or left-lateral sense (Smith, 2006). The closing of the Iapetus Ocean during the Devonian (410–380 Ma) caused another mountain-building event known as the Acadian orogeny. The last orogeny recorded in New York occurred during the Late Mississippian and Early Permian (330–250 Ma). This collision involved a part of proto-Africa colliding with eastern proto–North America and is known as the Alleghanian orogeny.

**METHODS**

The floor of the Palatine Bridge quarry was initially covered in most places by approximately 3 ft (~0.9 m) of overburden. A Dingo (walk-behind bucket loader) and a Caterpillar (skid-steer bucket loader) were used to push aside the overburden and expose the dolomite bodies. High-pressure hoses were then used to spray off the outcrop with water from a nearby pond. This served to remove the remaining debris and wash the in-situ rock surface. Excavation was followed by extensive photography both on the ground and from a 60-ft (20-m) boom. A detailed fracture map was then constructed over the entire outcrop (Figure 3). The occurrence of vugs and brecciation was also noted.

During the excavation process, whereas much of the outcrop was still covered by overburden, a 3-D ground-penetrating radar (GPR) survey was run over the unexposed outcrop (Grasmueck et al., 2005). Data were collected using a shielded bi-static 250-MHz antenna and then processed using ProMAX 3D™ and GeoProbe™ software.

The New York State Department of Transportation drilled a series of six 2-in. cores in the study area. These holes ranged in depth from 38 to 73 ft (12–22 m). Three of the cores were drilled inside the dolomite bodies. One was drilled in the surrounding fracture zone, another was drilled outside the fracture zone, and the last was drilled in the limestone area separating two of the dolomite bodies. All six cores were slabbed and then described at the New York State Museum.

Six trenches were cut across the dolomite bodies. These trenches each measure approximately 3 ft (~1 m) wide, 15 ft (5 m) long, and 18 in. (76 cm)
deep. The perimeter cuts for each trench were made using a 36-in. rail-mounted circular wet saw. Once the cuts had been made, a jackhammer was used to break apart the interior for removal. A series of digital photographs was taken and seamed together to make mosaic cross sections of each exposed wall.

Stable isotopes of carbon and oxygen were measured by Stephen Howe at the University at Albany and Peter Swart at the University of Miami. For the samples analyzed at Albany, approximately 200 μg of powdered sample was dissolved in 100% phosphoric acid at 90°C in individual reaction vessels in a MultiPrep sample preparation device. The evolved CO₂ gas was then analyzed using a Micromass Optima gas-source triple-collector isotope ratio mass spectrometer. Samples of international standard NBS-19 were interspersed among the quarry-derived samples in analytical runs. The Miami samples were reacted for 10 min using the common acid bath method at 90°C, and the CO₂ produced was analyzed using a Finnigan MAT 251 mass spectrometer. The reaction was conducted for a period of 10 min at 90°C. Standard isobaric corrections were applied, but no correction was applied for the differences in the fractionation of δ¹⁸O as a result of the dissolution of dolomite and calcite by phosphoric acid (Swart et al., 2005). All carbon and oxygen isotopic compositions are reported as per mil deviations relative to the Vienna Peedee belemnite.

Strontium isotope ratios were analyzed by Mihai Ducea at the University of Arizona. Approximately 100 mg of each sample was powdered, dissolved in 3.5-M nitric acid, and measured using a VG Sector 54 multi-collector thermal ionisation mass spectrometry instrument fitted with adjustable 1011 O Faraday collectors and Daly photomultipliers. Multiple analyses of standard SRM 987 were used for calibration, and δ⁸⁷Sr values are reported as the actual ratio of ⁸⁷Sr to ⁸⁶Sr. Two sets of fluid inclusion analyses were performed on various samples taken from the quarry.

A set of two samples from the quarry was sent to Fluid Inclusion Technologies, Inc., where doubly polished thick sections were prepared and then analyzed using a Fluid Inc.—adapted United States Geological Survey (USGS)—type heating-freezing
stage. Samples were heated by passing air through a heating element and then over the sample, located in a special chamber designed to minimize lateral and vertical thermal gradients. Similarly, for freezing the samples, nitrogen gas cooled by liquid nitrogen was passed through an unheated element before entering the sample chamber. Both homogenization temperatures ($T_{H}$) and freezing temperatures ($T_{M}$) were recorded to the nearest degree Celsius, and inferred salinities were reported to the nearest 0.1 wt. %. A second set of samples was analyzed at the University at Albany using a similar USGS-type heating-freezing stage. The second set consisted of two surface samples collected from the dolomite bodies, two samples taken from the interior of vugs lined with saddle dolomite crystals, three sections made from mineralized veins in the fracture zone surrounding the outcrop, and three matrix dolomite sections from core plugs at intervals where grain texture was most coarse. A total of 41 fluid inclusions were located and analyzed in this second set.

DATA

Structure

The dolomite outcrop occurs as three elongate en echelon segments (Figure 3). Two of the segments connect to form a single body with an obvious bend, or jog, whereas the third is separated from the other two by a section of limestone. Each dolomite body is characterized by a central sag flanked by antiformal structures on both sides (Figure 4). Brecciation occurs throughout the dolomite bodies but is most common at or near the tips of each segment. Vugs lined with saddle dolomite, calcite, and quartz located near the tips are also observed (Figure 4). The contact between dolomite bodies and surrounding limestone is gradational, occurring over a very short distance of less than 5 in. (<13 cm). A deformation zone surrounds the dolomite and contains a series of mineralized faults and fractures that generally run parallel to the dolomite bodies. A series of fractures that begin parallel, then turn

Figure 4. Photo mosaic of key field relations and structures and their locations. (A) Central sag with flanking anticlines. (B) Vug containing quartz, calcite, and saddle dolomite. (C) Eastern tip of dolomite body terminating in a calcite vein. (D) Bend, or jog, in dolomite body. (E) A fault scarp in the fracture network surrounding the dolomite bodies. (F) Limestone gap, or bridge, between two dolomite bodies.
and cross the bodies at an angle, also exists. Fracture widths range from less than 0.25 to 1 in. (<0.6–2.5 cm) and can be as much as 100 ft (30 m) long. The tips of each dolomite body (excluding the jog) terminate in calcite veins (Figure 4), which run along the strike of the outcrop for a few feet then die out or, in one case, bifurcate into smaller veins then die out. Further data regarding the faults, fractures, breccias, and extent of dolomitization are presented in this section.

The GPR survey was completed before the outcrop was fully exposed. Its main purpose was to aid in directing the excavation process. However, not only did the radar results help pinpoint the dolomite bodies beneath the talus, but they also gave an excellent cross section of the structure of the bodies at depth. A horizontal time slice from the 3-D survey clearly shows a part of the outcrop, including the jog that connects two of the dolomite bodies (Figure 5A). A sharp contact between the structure of the body and the relatively flat-lying unaltered limestone is observed. A vertical slice of the survey shows that the dolomite body appears as a sag flanked by anticlines on either side (Figure 5B). This image serves to illustrate that the structure is not just a surface expression but extends down to the maximum depth of the survey. Because of uncontrollable circumstances such as wet soil and clay-rich interbeddings, the radar signal was dampened and only penetrated to a depth of approximately 5 ft (~1.5 m).

The trench walls provide a physical cross section of the deformation zone without the need for an interpretation of secondary data such as seismic reflections or correlations between cores or logs (Figure 6). The trench walls also show that mineralized faults in the surrounding fracture zone change both dip direction and sense of movement as they propagate upward. In more competent limestone, the faults display pure extension and tend to dip away from the dolomite body. However, as they cross the shaly partings, their movement is controlled by shear failure and they dip toward the dolomite body. The development of this type of fracture pattern is described by Sibson (1994) and may account for at least a part of the sag formation. Note that faults closer to the bodies are more open, with some secondary porosity, whereas the faults on the outer extremes of the deformation zone are entirely healed by minerals such as calcite and dolomite. The trench walls reveal that brecciation is not limited to those areas on the fracture map. In fact, all three dolomite bodies appear to be brecciated throughout their entire length. Breccia clasts within the bodies follow folds in bedding, and it is obvious how the pieces fit back together (Figure 6C). The trench walls also reveal a relatively sharp contact between the dolomite and limestone. The cross-body fault previously mentioned in this report is exposed in four trench walls as it cuts across the outcrop at the jog. This fault begins on the southern side of the body and dips to the north as it runs subparallel to the dolomite body. As the fault approaches the jog, its dip steepens. The fault is nearly vertical as it intersects and cuts through the dolomite body. After exiting the northern side of the body, the fault bends back to subparallel but now dips to the south. In this way, the fault changes dip as it crosses the dolomite body and may be referred to as a scissor fault (Figure 7).

Stratigraphy

Cores taken from the quarry reveal several features, such as mineralized fractures, fault breccias, soft sediment deformation, and vuggy porosity. Mineralized fractures and vugs contain an assemblage of minerals, including dolomite, calcite, pyrite, bitumen, and quartz. Hole 4, drilled into the limestone gap between two dolomite bodies, begins as an unaltered limestone but becomes dolomitized after crossing a fault at a depth of 3 ft (0.9 m). This implies that, although the two dolomite bodies are separate on the quarry floor, they actually connect at depth, forming one continuous body. Figure 8 shows a cross section connecting hole 1, located inside the dolomite body; hole 2, located in the surrounding fracture zone; and hole 6, located in the unaltered Tribes Hill Limestone. This cross section serves to show the highly localized nature of these dolomite bodies. Hole 6 is located just 15 ft (4.6 m) outside the dolomite body, yet it shows no sign of hydrothermal alteration with the exception of a
Figure 5. (A) Three-dimensional (3-D) ground-penetrating radar (GPR) survey, with a line marking the location of vertical slice. (B) Vertical slice from the 3-D GPR survey. (C) Interpreted vertical slice from the 3-D GPR survey. Central sag and flanking anticlines are marked in white.
Figure 6. (A) Eastern wall of Trench 4. (B) Interpretation of (A). (C) Dolomitic section of the western wall of Trench 4, with breccia clasts outlined in white.
thin tongue of dolomite at a depth of 21 ft (6.4 m). Perhaps, the most interesting part of this cross section is that hole 2, which was drilled in fractured, but undolomitized, limestone becomes dolomitized after crossing a fault at a depth of 16 ft (4.9 m). This provides further evidence for the link between the occurrence of dolomite and fault-related fluid flow.

**Paragenetic Sequence**

The paragenetic sequence of events was determined using thin sections made from core plugs (Figure 9). The earliest processes to affect the Tribes Hill are fragmentation, desiccation, and lithification, which are not interpreted to have a direct function in dolomitization. Some minor dolomite replacement is associated with burrows occurred before fracturing began and therefore should not be considered hydrothermal in origin. The first stage of fracturing was followed by a second period of dolomite replacement and precipitation of saddle dolomite crystals. In this setting, the dolomitization was directly related to faulting and may be considered epigenetic in origin. The saddle crystals are zoned with alternating iron-rich and iron-deficient stages. Later, dedolomitization and dissolution of saddle dolomite occurred, followed by oil emplacement, which was preserved as bitumen. A second fracturing event

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**Figure 7.** (A) Aerial photograph of the jog. (B) Illustrated interpretation of (A), with faults and fractures marked in black. Note that the cross-basin fault changes dip direction from one side to the other. (C) Illustrated model of a cross-basin fault.
caused another episode of fluid flow and precipitation of saddle dolomite, pyrite, and calcite. The precipitation of Herkimer Diamond-type quartz crystals and late calcite spar was the last stage in the diagenesis of the Tribes Hill outcrop. These quartz crystals commonly contain solid bitumen inclusions.

**Geochemistry**

Two sets of fluid inclusion analyses were done. The first set was sent to an outside contractor and included two samples designated as PB200 and PB201. Sample PB200 is composed of a coarse matrix dolomite, early matrix calcite, very coarse saddle
dolomite, and late calcite. Primary inclusions in the matrix dolomite give homogenization temperatures ranging from 120 to 130°C and have indeterminate salinities. Secondary or pseudosecondary inclusions in the early calcite give homogenization temperatures of 80 to 95°C, with salinities of 26 to 28 wt. % NaCl equivalent. Secondary or pseudosecondary inclusions in the late calcite cement have homogenization temperatures of 65 to 75°C and salinities of 14.5 to 18.6 wt. % NaCl equivalent. Sample PB201 consists mainly of coarse zoned dolomite with some late calcite spar. Primary aqueous inclusions in the dolomite have homogenization temperatures of 105 to 132°C, and secondary or pseudosecondary inclusions have homogenization temperatures of 90 to 129°C. Salinities ranged from 26 to 30 wt. % NaCl (near halite saturation).

The second set of samples was analyzed in-house and consisted of 10 samples. In the 10 samples, 41 primary or pseudosecondary inclusions were found based on the criteria set forth by Goldstein and Reynolds (1994). Inclusions that are confined to growth zones were labeled primary, whereas inclusions with seemingly random distribution, no association with secondary features, and no clear association with growth zonation were labeled pseudosecondary. Unfortunately, all 41 of the inclusions found were extremely small, less than 3 μm in diameter, and were not frozen because the ice would be too difficult to observe. Therefore, no melting temperatures or subsequent salinities were obtained from these analyses. Vapor bubbles were clearly visible in every inclusion, and homogenization temperatures were measured to the nearest 1.0°C. The inclusions found in saddle dolomite crystals yielded the highest homogenization temperatures, ranging from 132 to 154°C, with an average of 139°C (Figure 10). Matrix dolomite inclusions were slightly cooler, ranging from 107 to 135°C and having an average of 121°C. The calcite inclusions were also cooler than the saddle crystals. They range from 104 to 132°C, with an average of 117°C.

Carbon isotope values for dolomite in the Tribes Hill range from −1.31 to −3.06‰, with an average

Figure 9. Plot of paragenetic sequence in relative time.
of –2.01‰. The values for the surrounding limestone are slightly more negative, having a range of –1.70 to –3.25‰ and an average of –2.19‰. The δ18O results follow a similar pattern. In the dolomite, values range from –7.66 to –10.74‰, with an average of –8.86‰, whereas in the limestone, ratios range from –8.52 to –11.40‰ and have an average of –9.49‰. The measured δ18O values do not necessarily reflect the composition of the original parent fluid. The temperature of the parent fluid must be considered when working out its original composition. Using the calculations from Friedman and O’Neil (1977), a TH versus δ18O crossplot was constructed for water in equilibrium with dolomite at varying temperatures and δ18O values. The quarry samples lie in the range of –8 to –10‰ δ18O, whereas water in equilibrium with dolomite of these compositions would have values of +2 to +4‰ at 120°C (Figure 11). Unevolved Late Ordovician—aged seawater has been calculated to have a δ18O of approximately –6 to –10‰ (Smith, 2006).

Strontium isotope values for the dolomite ranged from 0.7095 to 0.7103 87Sr/86Sr, with an average of 0.7098 and a standard deviation of 4.21 × 10⁻⁴. The 0.7090 value appears to be an outlier from the other data because it is significantly different than any of the other samples. The limestone values are lower than those of the dolomite. They range from 0.7091 to 0.7094 87Sr/86Sr, with an average of 0.7093 and a standard deviation of 1.25 × 10⁻⁴. The 87Sr/86Sr values of the calcite samples are even lower, with the exception of one outlier. They have a range of 0.7091 to 0.7116 87Sr/86Sr, with an average of 0.7099 and a standard deviation of 1.28 × 10⁻³.

DISCUSSION

Orientation and Structure of Faulting

The displacement in the study area is predominantly extensional, as recognized in the normal faults of the fracture zone and the central sag of the dolomite bodies. However, the origin of the stresses

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Figure 10. Fluid inclusion homogenization temperatures from samples analyzed at the University of Albany.

Figure 11. Crossplot of stable isotope ratios in limestone and dolomite samples from the Palatine Bridge quarry outcrop. Note that the seawater dolomite window is based on limestone values.
necessary to account for this deformation is probably more complicated. The main problem with a purely extensional model is that a 100% extension cannot account for features such as the anticlines that flank the entire length of the dolomite bodies. A component of strike-slip faulting is necessary to account for the observed characteristics.

Faults in the Mohawk Valley generally have two orientations: north-northeast and northwest (Bradley and Kidd, 1991; Jacobi and Mitchell, 2002). With a strike of 305° (west-northwest), the dolomite bodies of the quarry display a trend most closely related to the northwest faults described by Jacobi and Mitchell (2002). These faults are believed to be Grenville-aged faults that were reactivated during the Taconic orogeny. Rifting associated with the opening of the Iapetus Ocean during the Late Cambrian parallels the northeast-striking fault system and is thought by some to be related to the faulting. Consequently, transfer zones between the Iapetan rift segments may correspond to the northwest-striking fault system and, possibly, to the Palatine Bridge quarry outcrop. The effects of the Iapetan rifting are not well documented and may not have extended as far west as the Palatine Bridge site. However, multiple sites in close proximity to the quarry in which horizontal slickensides have been found are observed. In the neighboring town of Little Falls, horizontal slicks have been found in the Precambrian basement, with a trend similar to that of the quarry bodies.

Sandbox modeling of strike-slip pull-apart basins has revealed that lateral motion is not always recorded in slip along basin faults. In many cases, faults surrounding a transtensional system may only show vertical offset, whereas lateral displacement occurs at greater depth (Dooley and McClay, 1997). Strike-slip motion along a releasing bend can create a relatively open space into which overlying units collapse. As this deformation propagates upward, a negative flower structure consisting of normal fault displacement will form. This system may also involve a component of reverse faulting along the edges of the basin (Dooley and McClay, 1997). The flanking anticlines observed in the quarry may be a surface expression of this phenomenon. The cross-body scissor fault also gives good evidence for a transtensional origin of the quarry fault and fracture system. The sandbox modeling of pull-aparts depicts similar faults that change dip direction as they cross the basin (Dooley and McClay, 1997). Therefore, although the most common indications of strike-slip motion (horizontal slickensides or laterally offset markers) are absent from the outcrop, the structural characteristics that are observed strongly support a transtensional interpretation.

**Hydrothermal Alteration**

Although no single characteristic of the Palatine Bridge outcrop that can unequivocally prove its origin to be hydrothermal exists, the compilation of data from fluid inclusion, geochemical, structural, and petrographic analyses makes a strong argument for dolomitization by means of relatively hot fluids that have traveled upward from depth through faults and fractures.

The most obvious indications of fault control on dolomitization are field relations and geometry of the rock types in the outcrop. Other near-surface processes of dolomitization typically produce a more widespread, laterally extensive dolomite. The quarry dolomite only occurs around mineralized faults and fractures and is absent away from the faults. Fluid flow along fault planes is also evident in the cores. Calcite and dolomite mineralization along the fractures gives good evidence for the passage of fluids and precipitation of minerals. The dolomitized breccias present at the tips and within the dolomite bodies suggest fault control on dolomitization. This texture has been interpreted as a fault breccia and is related to the lengthwise propagation of the bodies as they developed.

Homogenization temperatures measured in primary aqueous inclusions give the minimum temperature of the parent fluid from which a given crystal was precipitated. Therefore, by comparing the homogenization temperatures of a hydrothermal formation to the maximum burial temperature of the unaltered host rock, one may demonstrate that the fluids were hotter than the host rock. Such is the case for many hydrothermal dolomite gas fields (Allan and Wiggins, 1993; Davies and Smith, 2006; Smith, 2006). Not all hydrothermal dolomites have...
homogenization temperatures greater than the maximum ambient burial temperature. A unit may be altered at a shallow depth when the fluids traveling upward along fault planes are hotter than the surrounding rock. Then, subsequent burial may expose the dolomite unit and the surrounding limestone host to temperatures greater than that of the previous hydrothermal fluid. In such a case, homogenization temperatures would not be higher than the maximum burial temperature of the unit, yet the dolomites or other hydrothermal diagenesis would still be hydrothermal in origin.

Comparison of the quarry homogenization temperatures and New York burial temperature data from previous studies do not prove conclusively that the dolomite formed by hydrothermal fluid flow. Conodont alteration studies performed in upstate New York report conodont alteration index (CAI) values of 3.5 in the Ordovician-aged rocks of the Mohawk Valley (Weary et al., 2001). Using the equations established by Hulver (1997), these CAI values translate to a burial temperature between 142°C and 206°C. Therefore, the homogenization temperatures from the quarry inclusions (107–154°C) may fall above or below the actual maximum ambient burial temperature for the Tribes Hill Formation at this location. When this is the case, field relations and other geochemical attributes can be used to determine whether a hydrothermal origin best explains the diagenetic features found.

As a general rule, the δ¹⁸O values for a dolomite that formed from the same fluid as a limestone are generally 3‰ heavier than that limestone (Friedman and O’Neil, 1977). Therefore, using the oxygen isotope values for the unaltered Tribes Hill Limestone, we should be able to predict where the dolomite that formed from the same fluid should plot. Figure 12 shows that the dolomites from the quarry do not plot in this window. This indicates that they did not form from the same fluid as the Tribes Hill Limestone.

Plotting the ⁸⁷Sr/⁸⁶Sr values for the quarry samples against historical seawater values from Burke (1982) demonstrates that the unaltered Tribes Hill Limestone samples lie directly on the seawater curve for the Early Ordovician, the time of their deposition (Figure 13). The dolomite samples, however, plot well above the seawater curve, indicating that they did not precipitate from the same marine fluids. In fact, the Sr values for dolomites plot above all the values of the seawater curve interpretation. This enrichment of dolomite in radiogenic strontium may be attributed to the interaction between the parent fluid and the basement rock or immature sandstones (Allan and Wiggins, 1993). Therefore, these fluids must have circulated through the basement
or overlying siliciclastics before precipitating dolomite, strongly suggesting a hydrothermal origin.

Where salinities could be measured, the fluid inclusions had values of 26 to 30 wt. % NaCl equivalent. These values are much higher than seawater salinity; in fact, they border on halite saturation (31–32 wt. % NaCl equivalent). These values are, however, consistent with saddle dolomites on a global scale (Davies and Smith, 2006). When combined with the strontium and stable isotope data, it becomes clear that the dolomitization of the quarry outcrop occurred under the influence of fluids that were geochemically disparate from normal ocean water.

The high primary fluid-inclusion temperatures, high salinity fluid inclusions, and radiogenic strontium isotope values suggest dolomitization from a hydrothermal fluid that moved upward from the basement or basal immature sandstones into the formation. That plus the link to faults and fractures suggest a fault-related hydrothermal origin for the dolomite.

**Timing of Faulting and Fluid Flow**

The formation of hydrothermal dolomite is reliant on the release of pressurized fluids trapped at depth. Therefore, faulting and fracturing are necessary components of the process (Davies and Smith, 2006). Geochemical analyses of saddle dolomite crystals from around the world have shown that the crystals are typically zoned, like those found in the Palatine Bridge quarry (Braithwaite and Rizzi, 1997; Auajjar and Boulegue, 2002). The chemical composition of the fluid may have changed during crystallization whereas fluid flow itself remained continuous. But, more likely, the crystals grew episodically with a series of short fluid flow events, each with a slightly different chemical composition. Episodic fluid flow may be caused by the cyclic increase in pressure before a fracturing event and decrease in pressure immediately following the event. The growth of crystals along open fractures may block fluid flow by occluding the pore-fracture network. This condition may persist until the buildup of pressure reactivates the fault or creates a new one. Sibson (1994) discusses the cyclic time scale of accumulation and release of stress in a hydrothermal system. He states that the buildup of shear stress during the interseismic period can last tens to many thousands of years. However, during a rupture, the drop in shear stress and subsequent fluid flow may last only a few seconds. This is followed by a period of postseismic adjustment, which may last for days to years.

Considering this concept, the timing for the formation of the Palatine Bridge quarry outcrop is likely restricted to the period of active faulting. The faulting that affects the Cambrian and Ordovician units of the Mohawk Valley occurred during the Late Ordovician Taconic orogeny (Bradley and Kidd, 1991). These faults were not reactivated during the subsequent orogenies because no units younger than the Utica are offset by the faults.

During the Taconic orogeny and the period of active faulting, the Tribes Hill was shallowly buried beneath the Black River, Trenton, and newly deposited Utica Shale to an estimated depth between 500 and 1500 ft (152–457 m). Such a shallow depth could not account for the primary fluid-inclusion homogenization temperatures determined from the dolomites (104–154°C). The geothermal gradient would have to have been at least 295°C/mi (184°C/km) to produce the fluid inclusion homogenization temperatures recorded in the quarry samples, which is not realistic for any nonvolcanic setting. Even using
a relatively high geothermal gradient of 50°C/km, the maximum ambient burial temperature at the time of faulting would only have been 30 to 45°C. Reactivation of preexisting basement faults during the onset of the Taconic orogeny would have allowed higher temperature fluids to travel from greater depths upward into the Tribes Hill. The elevated strontium content of the dolomite samples also supports this theory by suggesting that the fluids were in prolonged contact with basement rocks.

The core descriptions also support the interpretation that the Tribes Hill Formation experienced faulting relatively early in its burial history. The soft sediment deformation observed in the cores verifies that the unit was not fully lithified during the onset of tectonic activity. However, the extensive brecciation throughout the dolomite bodies is an indication that, at some point during its alteration, the rock was at least partly lithified. This contrast in evidence implies that dolomitization was episodic, occurring initially while the sediments were unconsolidated then later when lithified. A separate tectonic event is not necessary because the Taconic orogeny occurred over 40 m.y., which is more than enough time for the Tribes Hill to lithify. Paragenetic sequencing from thin-section analysis shows reactivation of bitumen-filled fractures, with an influx of late-stage calcite and quartz. This event possibly occurred during a later orogeny because no direct association between these minerals and the breccia exists. The system may have become reactivated during the Devonian Acadian orogeny or the Carboniferous to Permian Alleghanian orogeny, but little, if any, evidence for this exists.

Comparison to Producing Fields

As oil and gas reservoirs, occurrences of hydrothermal dolomite have attracted increasing attention with each successful field discovered. Among the most productive of these fields are the Ladyfern field of British Columbia, the Albion and Scipio fields in south-central Michigan, the Rochester field in southern Ontario, and the Trenton–Black River fields of south-central New York. Each of these fields shares some geometrical and geologic characteristics with the Palatine Bridge quarry outcrop.

At the time of its discovery in 2000, the Devonian Ladyfern reservoir was the largest onshore gas discovery of Canada in 20 yr (Boreen and Davies, 2004). By the end of March 2002, the field consisted of 40 wells producing a total of 777 million ft³ (22 million m³) of gas per day. Like the quarry outcrop, the Ladyfern reservoir is a fault-controlled hydrothermal dolomite alteration with associated leached limestones. According to Boreen and Davies, the “episodic burial reactivation of faults has resulted in extensive fracturing and created active conduits for hydrothermal fluids that have variably leached, dolomitized, and cemented the rock. In areas of maximum extension near fault intersections, intense dissolution, brecciation, and hydrothermal dolomitization have resulted in seismically resolvable collapse synclines.” In many ways, this description mirrors that of the Palatine Bridge dolomite structure. The same type of collapse synclines has been described and can be seen in the GPR data and trench walls. The leached rock texture and brecciation are also characteristics common to the quarry outcrop.

The Albion and Scipio fields of south-central Michigan cover approximately 22 mi² (~58 km²) and produce from the hydrothermally dolomitized regions of the Trenton–Black River formations. At the time of their discovery in 1957, these fields were estimated to contain more than 290 million bbl oil, with a range of 6.4 to 16.0 million bbl/1 mi² (2.6 km²; Hurley and Budros, 1990). They are considered unusual because the hydrocarbon-bearing structures are synclinal saglike features instead of typical anticlinal traps. This sag is characteristic of most hydrothermal dolomite reservoirs and the Palatine Bridge outcrop. The Albion and Scipio fields also resemble the quarry bodies in cross section. They occur as long, linear en echelon segments and have been interpreted to be associated with the synthetic Riedel shears of a strike-slip fault system (Figure 14). The Pulaski break between the Albion and Scipio fields bears a striking resemblance to the limestone gap between two of the quarry bodies. Other similarities between the Michigan fields and quarry outcrop include vuggy porosity, brecciation, and occurrences of saddle dolomite, calcite, and pyrite.
The Ordovician Rochester field is located in southern Ontario, Canada, near Lake Erie, east of Detroit. It is one of the six major oil and gas pools of the area, all of which produce from hydrothermally altered sections of the Trenton–Black River. As of 2005, the Rochester field had cumulative oil production of 1.5 million bbl and a cumulative gas production of 1.45 bcf (Carter et al., 2005). The reservoir is associated with basement-related synthetic shear faults that compartmentalize the dolomite bodies (Ogiesoba and Hart, 2005). A 3-D seismic survey of the field shows that it occurs as a linear depression, or sag, in the Trenton Limestone. Seismic data also show that the field is a highly localized feature made up of three bodies that step to the right in an en echelon pattern. In this way, the Rochester field shares several geometric characteristics with the Palatine Bridge dolomite outcrop. In fact, when reflected, or flipped, vertically and compared to the Rochester and Albion-Scipio outlines, the outcrop fracture map appears to be strikingly similar to both fields (Figure 14).

Like the Albion and Scipio fields of Michigan and the Rochester field of Ontario, a large part of the hydrocarbon production in New York state is from the Trenton–Black River. Fields such as the Quackenbush Hill and the Wilson Hollow produce natural gas from the linear dolomitized sections of these limestone formations. Some fields contain wells that have produced more than 40 mmcf (1.1 million m³) gas/day. In map view, these fields appear as elongate fault-bounded structural lows (Figure 1) (Smith, 2006). Geochemical analysis of dolomitic cores taken from these fields yield $\delta^{18}O$ values between −9 and −12.5‰ (Smith, 2006). The cores also show elevated strontium content and vuggy porosity with saddle dolomite much like the quarry cores and outcrop. Fluid inclusions in the dolomite from the New York fields have homogenization temperatures ranging from 100 to 160°C and very high salinities.
(13–17 wt. % NaCl equivalent). The Palatine Bridge quarry values for these analyses lie within the same ranges.

CONCLUSIONS

The Palatine Bridge quarry outcrop occurs as a series of linear, laterally discontinuous fault-bounded structures in which the Tribes Hill Limestone has been altered to dolomite. The shape and en echelon orientation of these bodies support the interpretation that the outcrop formed under a transtensional stress regime.

Homogenization temperatures of fluid inclusions in the dolomite are not definitively higher than the maximum ambient burial temperature of the Tribes Hill in New York. Therefore, the outcrop cannot be demonstrated by this evidence to be unequivocally hydrothermal in origin. However, all other characteristics of the quarry point to fault-related fluid flow and precipitation of crystals at temperatures that were hotter than the shallowly buried Tribes Hill during the Taconic orogeny. Both GPR and core descriptions show that the outcrop is directly associated with faults and fractures, whereas the size and geometry of the bodies eliminate many other possible methods of dolomitization. Enrichment in radiogenic strontium indicates that the parent fluid interacted with the Precambrian basement before precipitating dolomite. This requires the fluids to have traveled from a much greater depth, making them hotter than the rock they intruded. In this way, hydrothermal alteration of the Tribes Hill is the only process by which these dolomite bodies could have formed.

The timing of this alteration is complicated by the issue of reactivated faults and episodic fluid flow. Fault activity during the Taconic orogeny (Middle to Late Ordovician) when the Tribes Hill was only shallowly buried would explain the soft sediment deformation seen in the cores. An upper limit on the timing is constrained by the termination of this regional fault set in the Trenton and Utica formations. However, the coexistence of soft sediment deformation and brecciation implies that the faulting was episodic and occurred while the Tribes Hill was relatively soft, then again after it had lithified.

As an analog for hydrothermal dolomite reservoirs, the Palatine Bridge outcrop appears to mirror every aspect of producing fields in western Canada and the northeastern United States, with the single exception of scale. Like its larger subsurface counterparts, the quarry outcrop occurs as long, linear, highly localized dolomite bodies. These bodies step in an en echelon pattern that is believed to be associated with Riedel shears in a strike-slip fault system. Similar interpretations have been made for many producing dolomite fields in Canada and the United States (Harding, 1974; Hurley and Budros, 1990; Davies and Smith, 2006; Smith 2006). In profile, both the quarry bodies and producing fields appear as depressions, or sags, that are commonly flanked by anticlines. Where data are available, the geochemical signature of the quarry dolomite is nearly identical with that of dolomite in producing reservoirs. Relatively negative $\delta^{18}$O values, elevated $\frac{\text{Sr}}{\text{Sr}}$ ratios, high salinities, and fluid inclusion homogenization temperatures ranging between 100 and 160°C, are all common between the quarry outcrop and the Trenton–Black River hydrothermal dolomite fields of south-central New York (Smith, 2006). This study has proven the value of the Palatine Bridge site as an outcrop analog of subsurface, structurally confined dolomite reservoirs so that it may be used in further research to aid in the exploration and prediction of future hydrothermal dolomite oil and gas reservoirs.

REFERENCES CITED


Boreen, T., and G. Davies, 2004, Hydrothermal dolomite


