PS Silurian Tuscarora Sandstone in Western West Virginia: Will It Work as a Geothermal Reservoir Rock?*

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Abstract

More than twenty years of bedrock mapping experience with the Silurian Tuscarora Sandstone in the Fold and Thrust Belt of eastern West Virginia suggests that it should be a low permeability reservoir rock because of deformation and associated heavy silica cementation. Therefore, the choice of the Tuscarora as the target reservoir for a geothermal energy project in north-central West Virginia generated a great deal of scientific interest . . . and some surprise. At the proposed well location on the West Virginia University campus in Morgantown, WV, the Tuscarora is approximately 10,000 feet (3000 m) below surface, lies on the eastern margin of the Rome Trough, and is approximately 300 feet (90 m) thick. A search of the WVGES core and sample inventory yielded thin sections and drill core for wells from Kanawha, Clay, Harrison, and Preston counties in West Virginia, all reasonably close to Morgantown.

Thin sections from Kanawha 2751, Kanawha 3914, Clay 513, and Preston 119 were examined with the intent of estimating "visual" porosity and searching for features that might contribute or detract from permeability. Petrographic analysis yielded rare instances of "visual" porosity as high as 25%; typical porosity estimates were 1-2% or less. Not readily apparent in most of the thin sections was extensive silica overgrowth and cementation expected based on experience with exposures of Tuscarora in eastern West Virginia.

Because of its proximity (37 miles; 60 km) to Morgantown, Preston 119 was chosen for permeability analysis. Air-injection-permeability sampling concentrated primarily on observed fractures but also included matrix and unusual features (such as bioturbation and stylolites) encountered in the core. Fracture lengths, widths, and orientations were measured and recorded together with permeability. Fracture permeabilities as high as a Darcy were observed; the sandstone matrix was typically "tight" with less than 1-2 mD of permeability. Whether or not higher observed fracture permeabilities are present and accessible at the proposed well site remains to be seen. However, large, open voids associated with vertical and oblique fractures in the Preston 119 core suggest that rock with properties amenable to geothermal fluid circulation may be present in the Tuscarora.

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SILURIAN TUSCARORA SANDSTONE IN WESTERN WEST VIRGINIA: WILL IT WORK AS A GEOTHERMAL RESERVOIR ROCK?

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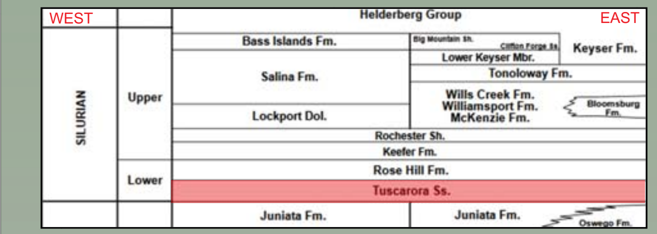
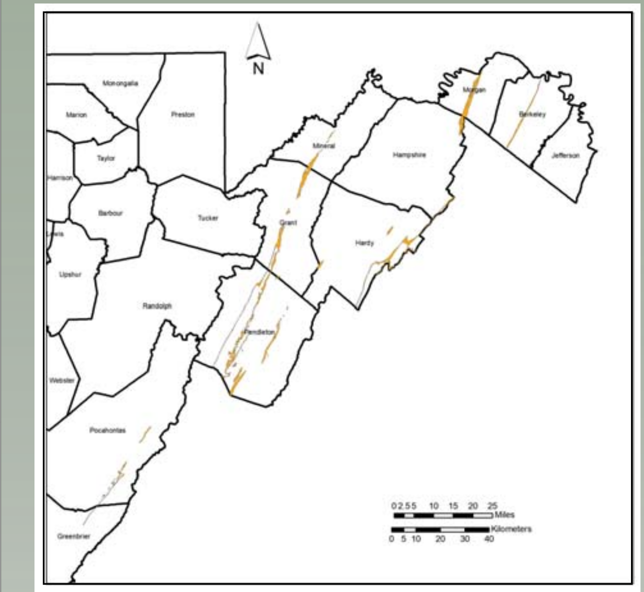
Because of its proximity (37 miles; 60 km) to Morgantown, Preston 119 was chosen for permeability analysis. Air-injection-permeability sampling concentrated primarily on observed fractures but also included matrix and unusual features (such as bioturbation and stylolites) encountered in the core. Fracture lengths, widths, and orientations were measured and recorded together with permeability. Fracture permeabilities as high as a Darcy were observed; the sandstone matrix was typically "tight" with less than 1-2 mD of permeability. Whether or not higher observed fracture permeabilities are present and accessible at the proposed well site remains to be seen. However, large, open voids associated with vertical and oblique fractures in the Preston 119 core suggest that rock with properties amenable to geothermal fluid circulation may be present in the Tuscarora.

The Tuscarora Sandstone is a massive quartz sandstone unit named for exposures at Tuscarora Mountain in central southern Pennsylvania (Darton, 1896; Clark, 1897). The Tuscarora is Early Silurian in age and is overlain conformably by the Silurian Rose Hill Formation and underlain conformably by the Ordovician Juniata Formation. Thicknesses range from greater than 1000 feet in Pennsylvania to a few hundred feet in southern West Virginia.



Generalized Stratigraphic Chart for the Silurian Section in West Virginia



Outcrop Distribution of the Silurian Tuscarora Sandstone in West Virginia.

Although predominantly a quartz sandstone, the Tuscarora contains thin interbeds of black shale. Above is an outcrop along US 48 in northeastern West Virginia.

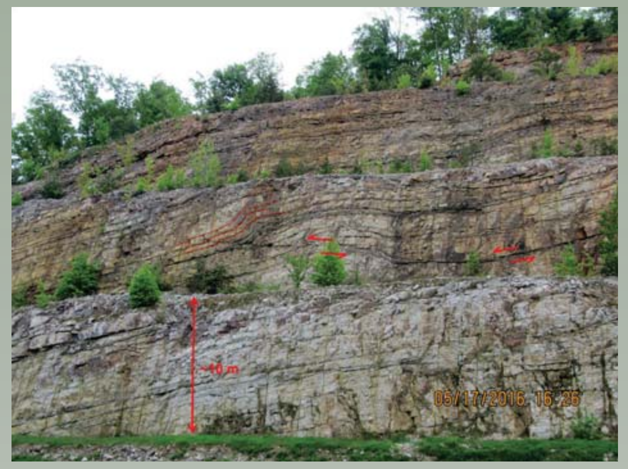
Shale layers within the Tuscarora are typically overlain by sandstone beds whose bottoms are marked by the characteristic trace fossil *Arthrophycus alleghaniensis*. *Arthrophycus* is thought to be the feeding traces of trilobites. Organic matter in the black shales may have been the food source.

Although generally considered to be fluvial to littoral in depositional origin (Smosna and Patchen, 1978; Castle and Byrnes, 2005) with land to the east and sea to the west (Cotter, 1983), the Tuscarora contains a low-diversity association of marine trace fossils along the outcrop belt in eastern West Virginia. Above are the entraceways to the dwelling "u-tubes" *Arenicolites* from an outcrop in Pocahontas Co., WV.

The Tuscarora occasionally exhibits high-angle crossbedding in outcrop. Steep, planar cross-sets at Devil's Backbone in Pocahontas Co., WV.

The Tuscarora Sandstone has experienced several episodes of deformation during the Acadian and Appalachian Orogenies. As a result, the unit exhibits features of brittle and, less commonly, ductile strain. Many of these are readily apparent in the outcrop exposures in eastern West Virginia.

Brittle deformation of the Tuscarora Sandstone produced this breccia. There does not appear to be displacement or rotation of individual clasts suggesting this is not a fault breccia. Coin is 3 cm in diameter.



Small thrust fault of indeterminate offset in the Tuscarora Sandstone exposed along US 48 near Baker, WV. Thrust has come from the east - right side of the photo.

Devil's Backbone is a picturesque exposure of Tuscarora Sandstone in Pocahontas Co., WV exemplifying ductile deformation of this unit and the underlying Ordovician Juniata Formation.

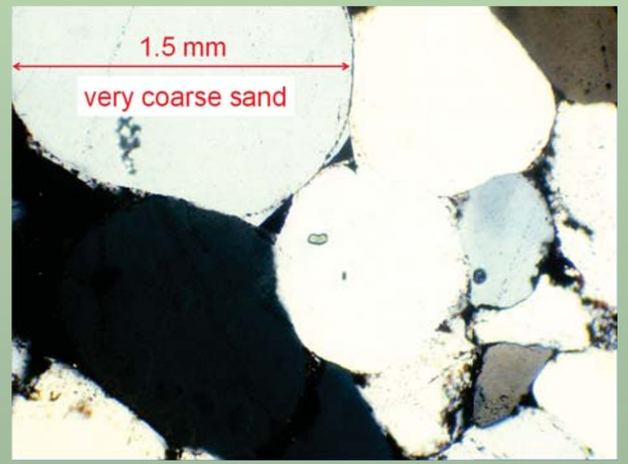
Looking north into Germany Valley in Pendleton Co., WV. The line reconstructs the Wills Mountain Anticline by connecting the two limbs of Tuscarora Sandstone from North Fork Mountain on the right to Seneca Rocks on the left, separated by approximately one mile across the Valley.

Seneca Rocks in Pendleton County, West Virginia is one of the most recognizable topographic features in the state. It is formed by a vertical outcrop of Tuscarora Sandstone.

Under the confining pressure of burial beneath thousands of feet of younger strata, even a rigid, brittle unit like the Tuscarora Sandstone can deform ductily. This exposure, associated with the Browns Mountain Anticline in Pocahontas Co., WV, illustrates this type of deformation. It has become visible once the overlying strata has been removed by erosion.

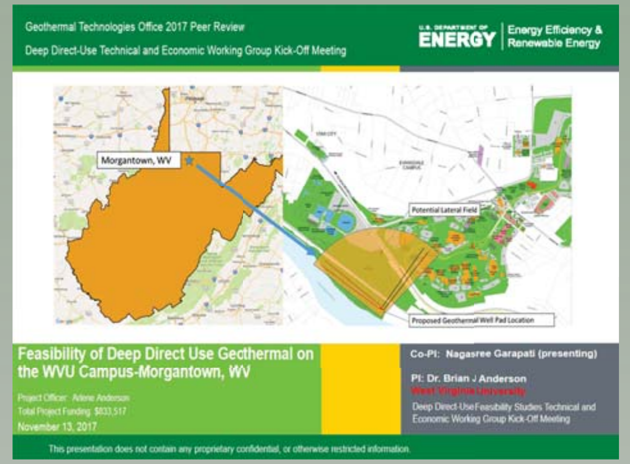
The Tuscarora Sandstone in the outcrop belt of eastern West Virginia, is marked by stylolitization - a sign of pressure solution and remobilization of silica which never bodes well for maintaining porosity and permeability. Previous attempts to identify and quantify permeability in outcrops of younger strata in eastern WV (McDowell, 2001) met with little success because remobilized silica had not traveled far before reprecipitating.

Stylolite surface in the Tuscarora Sandstone broken open exposing the "nooks and crannies" of the crenulated surface. Coin is 3 cm in diameter.

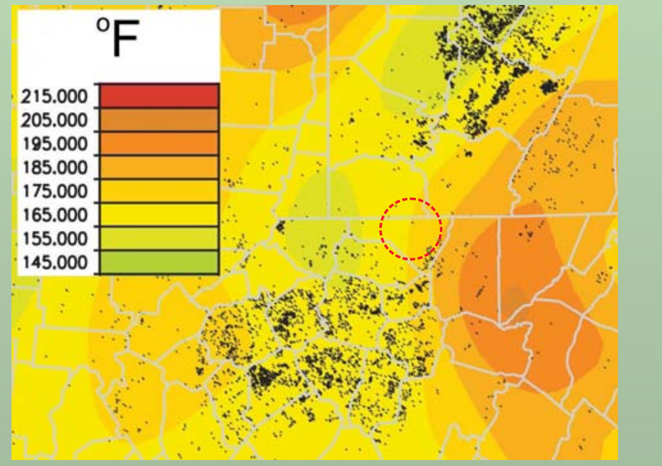


Previous outcrop permeability studies (McDowell, 2001) were foiled, in part, by the presence of thick quartz overgrowths which formed as mobilized silica from pressure solution precipitated on quartz grains partially or fully plugging original porosity. This example is from the Devonian Gordon Sandstone. Similar effects were expected for the Tuscarora in the outcrop belt . . . and possibly in the subsurface.

In 2017, WVGES became a participant in a geothermal feasibility study that sought to use formation waters of the Tuscarora Sandstone as a heat source in an engineered heat-exchanger system. WVGES' task was to investigate porosity and permeability in the Tuscarora in the subsurface.

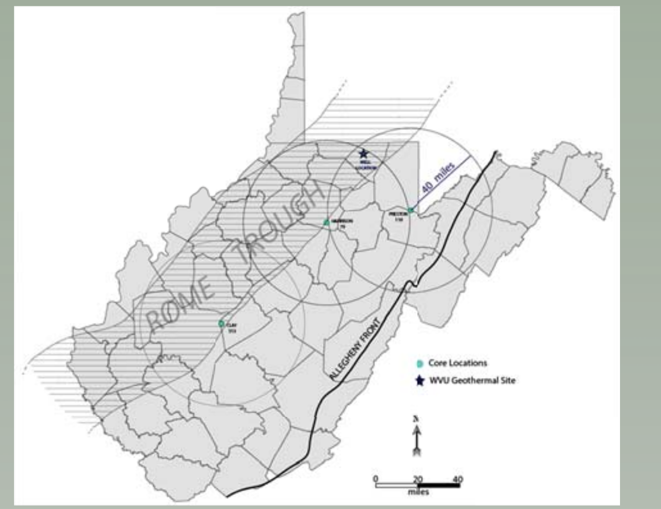


This Deep Direct Use (DDU) geothermal project proposes to use the formation waters of the Tuscarora Sandstone from a depth of ~10000 feet to produce steam to replace or augment the current coal-fired system on the West Virginia University campus.



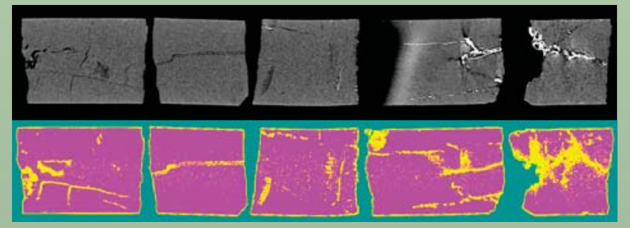
WVGES examined the Bottom Hole Temperatures (BHTs) for more than 1500 oil and gas wells drilled in West Virginia. Since almost all of these wells have no record of the time between end of circulation and taking of temperature, it was necessary to apply a correction technique developed at Southern Methodist University (Frone and others, 2015) to estimate "true" BHTs. Once this correction was applied to the WVGES data set, a geothermal gradient model was created for the state and maps of temperature-at-depth could be produced. Shown above is a portion of the West Virginia map of predicted temperatures at 10000 feet below surface. The Morgantown study area is circled.

Two Tuscarora fields, Indian Creek and Leadmine, currently produce gas from fractures in the sandstone reservoir. In addition, several individual wells in the western two-third of the state also produce gas from that formation (Avary, 1996).



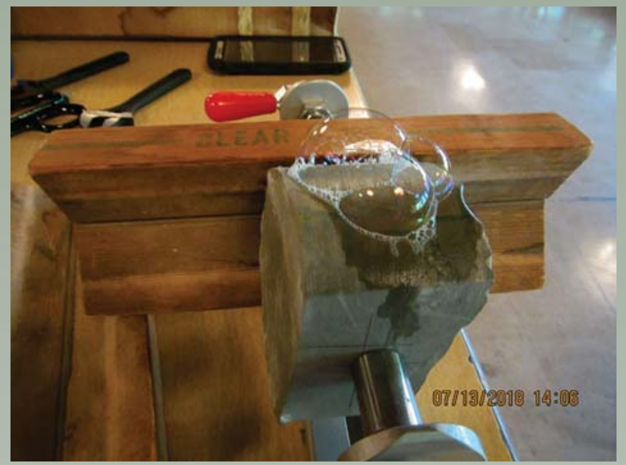
Three cored wells (Clay 513, Harrison 79, and Preston 119) were chosen because of their proximity to the Morgantown study area. Of the three, Preston 119 proved to have the most complete core material and it was subjected to a direct investigation of permeability. Clay 513 provided a suite of petrographic thin sections for examination.

Geophysical logs from 110 Tuscarora wells distributed across West Virginia were analyzed for comparison to depositional models proposed by Castle and Byrnes (2005). In general, the logs for Preston 119 appeared to be more marine/estuarine than fluvial. This is in agreement with the model of depositional environments proposed by Cotter (1983) for the Tuscarora.



The entire slabbed core from Preston 119 was scanned by a medical CT unit at the National Energy Technology Laboratory (NETL) in Morgantown, WV. The purpose of this procedure was to emphasize fractures in the core - the imagery was provided to WVGES. This imagery was used to identify core intervals especially relevant to permeability analysis of the fractures. In addition, the imagery proved suitable for computer image analysis that allowed estimation of 3D fracture volume for each core interval.

Air-injection permeability apparatus (CoreLabs PPP-250 Permeameter) was used to measure permeability of fractures and matrix material in the Preston 119 core.



Shaly interval from Preston 119 coated with a weak soap solution to allow the observation of air escaping from a horizontal fracture. This and similarly oriented fractures within the Tuscarora are assumed to be primarily the result of "unloading" or removal of the weight of lithologic overburden from the core after it has left the subsurface.

Top of core segment from Preston 119 showing the limbs of two vertical trace fossils - the marine dwelling trace *Arenicolites* sp. Both of the "u-tubes" have been filled with sand after being abandoned. Coin is 3 cm in diameter.

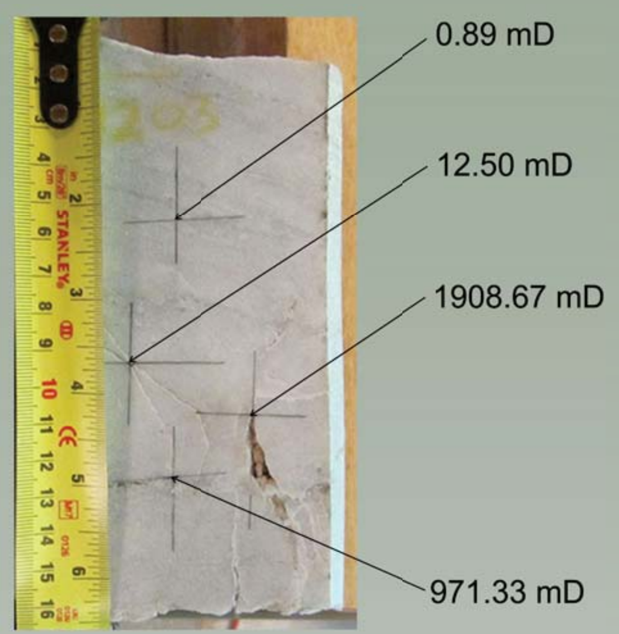
Examples of bioturbation in core segments for Preston 119. On the left, well-defined "u-tube" *Diplocraterion* sp. from a depth of 7438'. On the right, crossbedding and unidentified trace fossils from a depth of 7415'. Coin is 3 cm in diameter.

Core segment from Preston 119 from a depth of 7321.5' showing voids left from the dissolution of sedimentary clasts (probably shale). Coin is 3 cm in diameter.

Deformation observed in core segments from Preston 119. On the left, nearly vertical stylolite from a depth of 7199'. On the right, large, open void from a depth of 7192'. Coin is 3 cm in diameter.

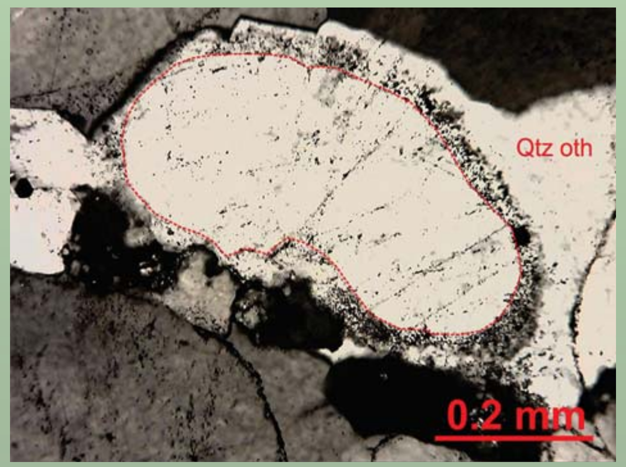
Two core segments from Preston 119 illustrating brittle deformational features. On the left, a large, healed fracture filled with sandstone breccia from a depth of 7165'. On the right, an oblique fracture, partially open and partially filled with crystalline quartz cuts across a stylolite at a 90° angle.

A database of more than 2000 permeability readings, together with measurements of fracture lengths and relative fracture orientation, were assembled and illustrated with core photographs as the WVGES part of this project.



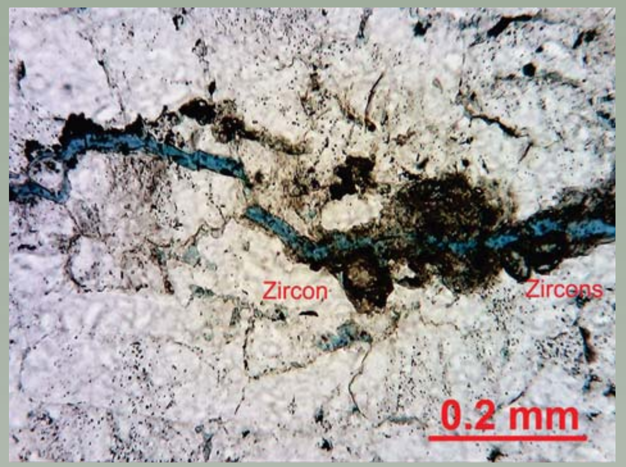
Examples of measurements of fracture permeability on core from Preston 119 (7203' depth). No Klinkenberg corrections have been applied to these measurements. Matrix permeability in this segment was less than 1 mD.

A suite of thin sections from Clay 513 were examined to supplement information obtained from the Preston 119 core. Particular attention was given to remaining porosity visible in the sections.

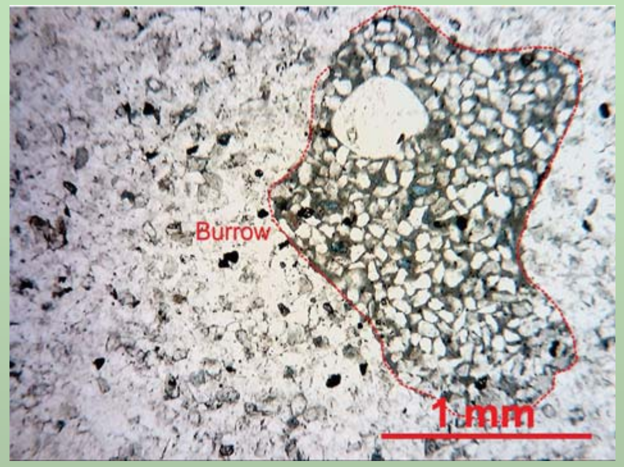


Thin-section photomicrograph from Clay 513 (7466.83' depth) showing thick quartz overgrowth. Original grain surface is marked by a dashed line. Polarized, transmitted light.

Thin-section photomicrograph from Preston 119 (7332' depth) showing relatively large, open pores (blue epoxy). Thick quartz overgrowths are visible on a number of grains but do not occlude all pore space. The lining of framboidal pyrite in several of the pore suggests bacterial degradation of pre-existing hydrocarbons that may have kept silica from completely filling pores. Plain, transmitted light.



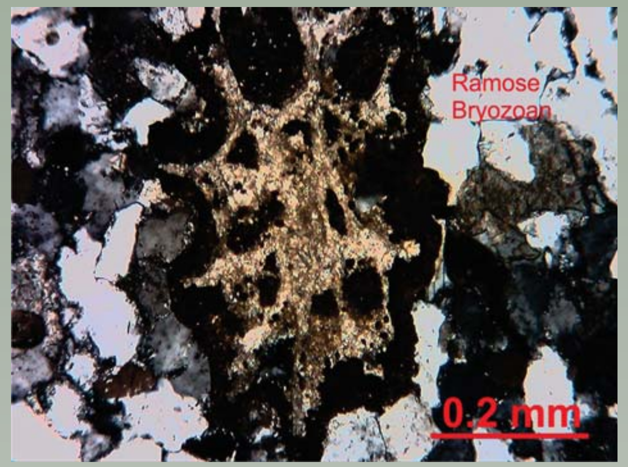
Thin-section photomicrograph from Clay 513 (7436' depth) showing porosity (blue epoxy) along a horizontal stylolite. This porosity may have developed due to "unloading" after the core was removed from reservoir conditions. Notice the heavy minerals (zircons) concentrated along the stylolite. Plain, transmitted light.



Thin-section photomicrograph from Clay 513 (7490.42' depth) showing a burrow (dashed line) filled with quartz silt retaining a small amount of porosity. The matrix is "tight." Plain, transmitted light.

Thin-section photomicrograph from Clay 513 (7483.42' depth) showing a large sedimentary rock fragment (dashed line) and several relatively large open pores (blue epoxy) that appear to be formed from the dissolution of other grains. Plain, transmitted light

Same slide as previous but taken in plain, reflected light to show the contents of the large sedimentary rock fragment have been partially replaced by limonite.



Thin-section photomicrograph from Clay 513 (7497.0' depth) showing a cross-section cut through an unidentified ramose bryozoan. The presence of marine fossils reinforces the interpretation of a marine depositional environment for this portion of the Tuscarora. Polarized, transmitted light.

DISCUSSION

Can the Tuscarora Sandstone in the Morgantown study area work as a reservoir for geothermal circulation purposes? - Based on an examination of core and thin section materials from proxy wells chosen for their proximity to the area, it appears that there is remaining porosity connected by a network of at least partially open fracture. Our prediction is that this fracture network should provide pathways for removal and reinjection of formation fluids.

It appears, unlike the Tuscarora in outcrop to the east, quartz overgrowth resulting from mobilization of silica during pressure solution has not fully occluded porosity (and permeability). It is possible that the presence of hydrocarbons in pore spaces may have diminished or reduced the precipitation of silica on existing quartz grains.

Concurring with facies analyses of geophysical logs, core and thin section observations of trace fossils and rare body fossils supports the importance of marine depositional influence in the Tuscarora Sandstone in western West Virginia.

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