

PS Far-Field Tectonic Controls on Deposition of the Ordovician Utica/Point Pleasant Play, Ohio Using Core Logging, Well Logging, and Multi-Variate Analysis*

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Search and Discovery Article #11233 (2019)**

Posted July 22, 2019

*Adapted from poster presentation given at AAPG 2019 Annual Convention & Exhibition, San Antonio, Texas, May 19-22, 2019

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Abstract

The Ordovician Utica shale is an extensive and important part of the Appalachian Basin subsurface, providing a source for hydrocarbon reservoirs, acting as an unconventional hydrocarbon reservoir, and of interest as in impermeable cap rock for carbon dioxide sequestration in Cambrian formations. The Utica shale and adjacent formations (Point Pleasant Formation, Trenton/Lexington Limestones) are a mixed siliciclastic-carbonate system that is mostly in the subsurface in areas of interest within the Appalachian Basin. Most outcrops are located to the east, in the Appalachian fold and thrust belt, and few public cores are available for study from key areas in the basin. Using a combination of core/well logging and multi-variate analysis with GAMLS software, lithofacies based upon mineralogical variations and sedimentology were extrapolated to electrofacies across the state of Ohio. These electrofacies were then mapped to identify controls on deposition during the Upper Ordovician time in Ohio. It typically is assumed that the primary control on regional deposition during this time period was the Taconic tectophase of the Taconian Orogeny; however, Precambrian basement structures appear to have localized influence on deposition also, such as the Waverly Arch, Utica Mountain Fault, and Harlem Fault. Also, the Sebree Trough has previously been reported to end in southwest Ohio, yet electrofacies mapping shows that the dark, calcite-poor shales that infilled the Sebree Trough continue towards northeast Ohio in a possible trough-like feature. These shales may have later timing compared to the Sebree Trough proper. Overall, lithofacies mapping combined with electrofacies mapping indicates that these Upper Ordovician formations are not homogenous rock types deposited across the state (such as layer-cake stratigraphy), but rather vary in mineralogy and thickness both horizontally and vertically across the region due to multiple controls on deposition.

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INTRODUCTION

The Upper Ordovician Point Pleasant Formation and Utica shale are fine grained sedimentary formations composed of shale and siltstone that are locally organic rich, calcareous, or interbedded with limestone and dolostone. They are recognized across

much of the Appalachian Basin (Figure 1), and of interest as a caprock for carbon sequestration, a source rock, and an unconventional reservoir, depending on location within the basin^{1,2,3}. The Utica shale and adjacent formations (Point Pleasant Formation, Trenton/Lexington Limestones) are a mixed siliciclastic-carbonate system (Figure 2) that is mostly in the subsurface in areas of interest. Most outcrops are located to the east, in the Appalachian fold and thrust belt, and few public cores are available for study from key areas in the basin. Using a combination of core/well logging and multi-variate analysis with GAMLs software, lithofacies based upon mineralogical variations and sedimentology were extrapolated to electrofacies across the state of Ohio. These electrofacies were then mapped to identify local controls on deposition during the Upper Ordovician time in Ohio.

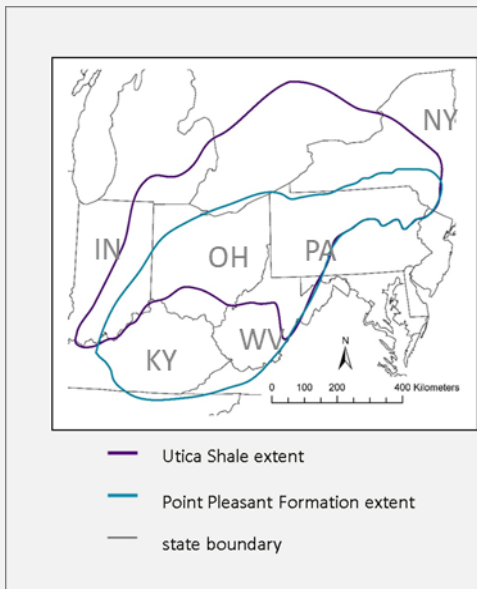


Figure 1. Extent of the Utica Shale and Point Pleasant Formation in the Appalachian Basin. Modified from^{3,4}.

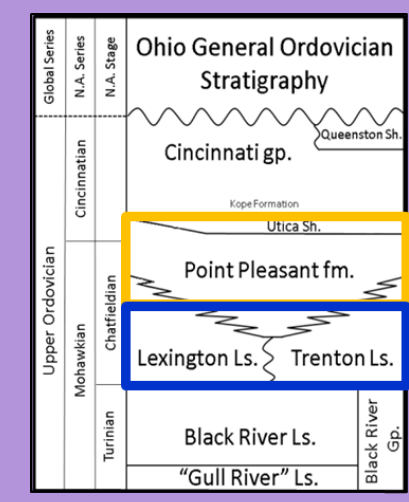


Figure 2. Ohio Ordovician stratigraphy. The Lexington and Trenton limestones are grouped together throughout this study, representing a period of primarily carbonate deposition (blue box). These two represent a period of cool-water carbonate deposition on an extensive platform that covered much of the Appalachian foreland basin. They are stratigraphically equivalent, and grade laterally into each other. The Trenton Limestone is marked with an abrupt contact with the overlying shale, representing a period of subaerial exposure, while the Lexington grades into the overlying unit. Overlying the carbonate platform, the Point Pleasant Formation consists of interbedded calcareous shales, siltstones, and limestone, primarily located within Ohio. It grades into the overlying Utica shale, decreasing in the amount of carbonate content upsection. The Utica shale consists of dark brown to black, predominantly shaley strata at the base of the Kope Formation; it is an informal term within the state of Ohio. The Utica shale and Point Pleasant Formation are grouped together throughout this study, representing a period of primarily shale deposition (orange box). Modified from^{5,3}.

METHODS

Digital well logs for 268 wells (Figure 3) were used to pick tops for the Lexington and Trenton Limestones, the Point Pleasant Formation, and the Utica shale across the state of Ohio following^{1,3,6,7,8} (Figure 4) in geoSCOUT software from geoLOGIC, Inc. Data was exported into ArcGIS for contouring isopach and structure maps.

Sixty-two wells were selected for multivariate analysis and clustering to identify electrofacies based upon well logs (gamma ray, neutron porosity, density, sonic, and photoelectric effect). Geological Analysis via Maximum Likelihood System (GAMLs) software was used to cluster well log data from the bottom of the Trenton/Lexington limestone to the top of the Point Pleasant Formation/Utica shale into modes with similar responses. Clustering in GAMLs was initialized "By Variable" with density (RHOB), with 10 modes, and a 0.01 convergence goal, producing 10 "modes", or electrofacies. Modes were interpreted based on their well-log responses and calibrated against core-based quantitative and qualitative lithologic composition in order to identify lithofacies, which were assigned to the well logs at 0.5 ft intervals. Four cores with corresponding LAS files were used for this comparison. The dominant electrofacies at a given depth was compared with calcite content, as determined either by direct measurement or by a reflectance-based estimate, providing lithofacies based upon mineralogy. Percentage of each lithofacies in each rock package (shale or carbonate platform) were calculated across the state, and dominate lithofacies for an area was assigned.

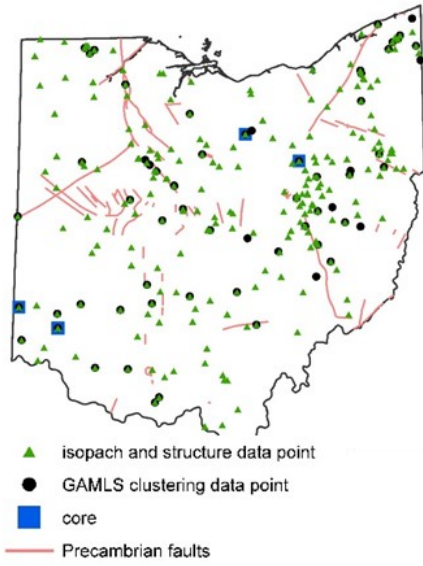


Figure 3. Well location for data used in GAMLs clustering, core locations, and well locations. Red lines are known or inferred faults that penetrate or influence Ordovician strata⁹.

CLUSTER ANALYSIS

Modes from GAMLs were assigned to each depth based on patterns among the values of log responses (Figure 4). GAMLs assigns initial electrofacies assignments based upon known, typical well log responses of rock types to the well log tool, preset in the program.

GAMLs provided a first assessment of lithologies, indicating five shale, three limestones, and two dolostones across the 62 wells. While GAMLs is able to identify several of each facies, they are still "vague", and are essentially end-member lithologies; the program does not identify mixed lithologies (i.e., shaley limestone, or sandy dolostone). These Upper Ordovician rocks are sometimes ideal end-members, such as shale (Figure 5), or limestone (Figure 6), but much of the formations consist of a mixture of these two end-members, either as a single bed consisting of a homogenous mixture of clay and carbonate (Figure 7), or interbedded lithologies (Figure 8). Also, GAMLs uses ideal mineralogical and facies values of well log measurements to identify these end-member facies, without taking into consideration specific circumstances of depositional environment or other potential mixing factors that could affect interpretation, or could make the interpretation more accurate (again, such as a mixed lithology). GAMLs interpretations, as with any program, needs the user to verify data and adjust as needed based upon previous knowledge of the study area, or core information.

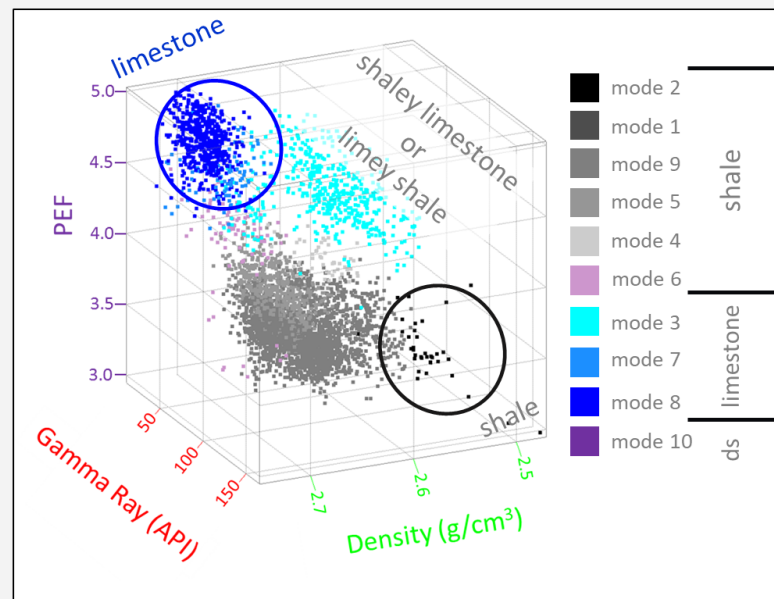


Figure 4. Example of clustering in GAMLs using Well No. 4 and 38. Blue circle is the region where it is limestone, and the black circle is the region of shale. Well log data plotted for three measured values and colored for electrofacies clustered based on the full suite of tools.



Figure 5. Image of dark shale from well no. 44, box no. 58 (180-183 m depth), mode 2. Ruler is in cm.

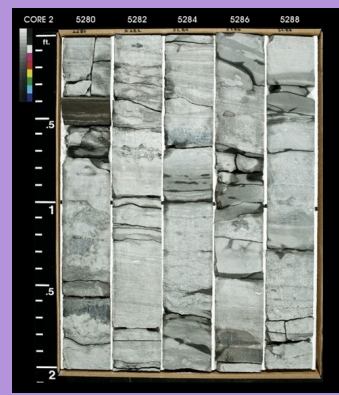


Figure 6. Image of the underlying limestone from well no. 38 (1609-1612 m), mode 8.¹¹

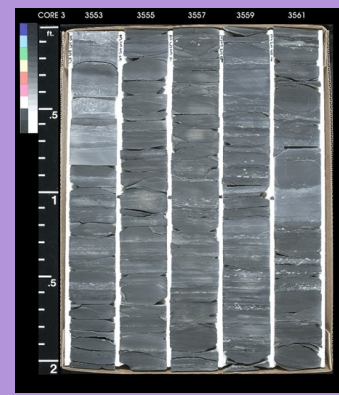


Figure 7. Image of light, calcareous shale from well no. 4, 1082-1085 m, primarily mode 5.¹¹



Figure 8. Shale (dark layers) interbedded with carbonates (light layers) at a cm scale in well no 38 (1557-1560 m), modes 5 and 3.¹¹

CALIBRATION OF ELECTROFACIES TO LITHOFACIES

Combined with core information, these electrofacies can be classified as lithofacies. Four of the analyzed wells had associated core and previously measured calcite content (Figure 9^{10,11}.

The calcite contents were then correlated with the corresponding single mode assignment assigned by GAMLs for each depth. Each mode number had general statistics run on the calcite content for all cores (mean, median, mode, standard deviation, maximum, minimum), and a general calcite content range was assigned based upon the mean and standard deviation (Figure 10). Lithofacies were assigned based upon calcite content and core observations (Figures 5—8, 10).

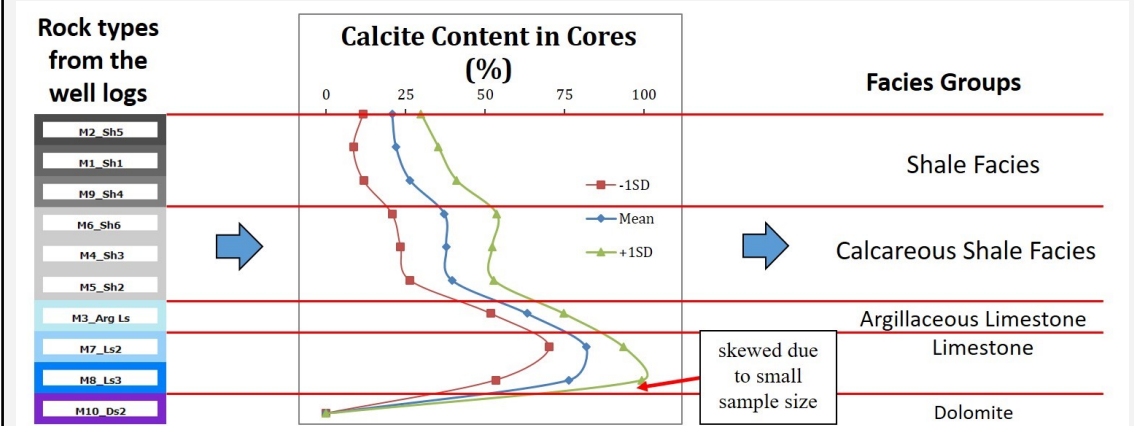


Figure 10. Calcite content within GAMLs assigned modes (electrofacies). Lithology descriptions are applied based upon average calcite content.

There are clear rock-type end members that can be designated (mode 2 as "shale"; modes 7 and 8 as "limestones"; mode 10 as "dolostone"). Modes 1, 9, 4, and 5 fall within a transition zone, from most shale-like (mode 1; black circle in Fig. 4) to more limestone-like (mode 5; blue circle in Fig. 4). Mode 3, initially classified as a limestone, is within this transition zone, bridging the transition between shale-like and limestone-like; a more accurate term would be "argillaceous limestone", or a muddy limestone. Finally, mode 6 was initially classified as a dolostone electrofacies by GAMLs, but after reviewing the average well log values, it also appears to be an argillaceous limestone or calcareous shale, and falls within this transition zone.

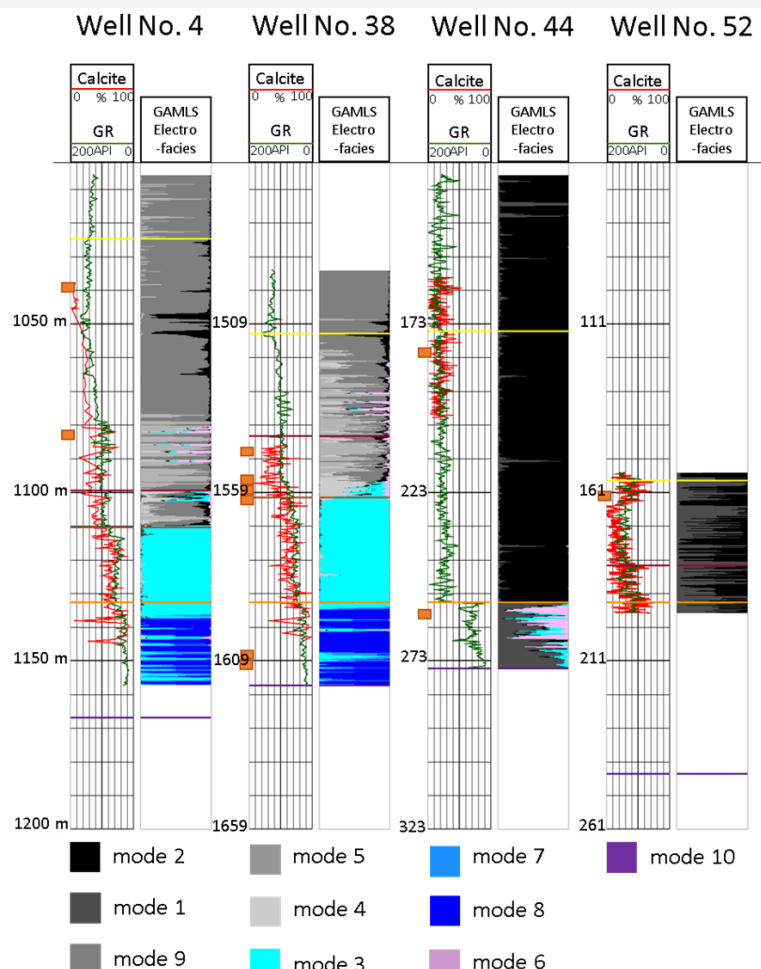


Figure 9. Comparison of measured calcite content (red line), gamma ray values, and GAMLs assigned electrofacies for four cores. Horizontal colored lines are tops of formations: purple- Black River Group; orange- Trenton or Lexington Limestone; dark red- Point Pleasant Formation; yellow- Utica Shale. Depths are all in meters from the surface. Orange boxes are locations of core images (Figures 5—8). There is an inverse correlation between GR and calcite content for each of the four cores.

LITHOFACIES VARIATIONS ACROSS OHIO

Cross Section A-A' (Figure 11) shows an increase in limestone thickness towards the east, with shale within wells 51, 45, and 50 having greater amounts of calcareous shales, followed by a decreased amount of calcite in the shale and grading towards greater amounts of calcite in wells 16 and 17 (west). The contact between the overlying shale and underlying limestone units is gradational, with increasing amount of calcite towards the east. Cross section B-B' (Figure 12) has greater amounts of calcite within the shale except within Well No. 46. There are several wells which have interbedded calcareous shale and shale (Well No. 61, 29, 58, 35). The contact between the shale and underlying limestone formations is sharp in the west (Well No. 46, 2), becoming more gradational towards the east (i.e., the blue limestone interfingers the gray shale). Cross section C-C' (Figure 13) shows a sharp contact between the shale (grey) and limestone (blue) in northeast Ohio (Well No. 11, 5, 27) but becomes gradational further south (Well No. 34, 29, 62). The shale also becomes lighter, indicating an increase in calcite content.

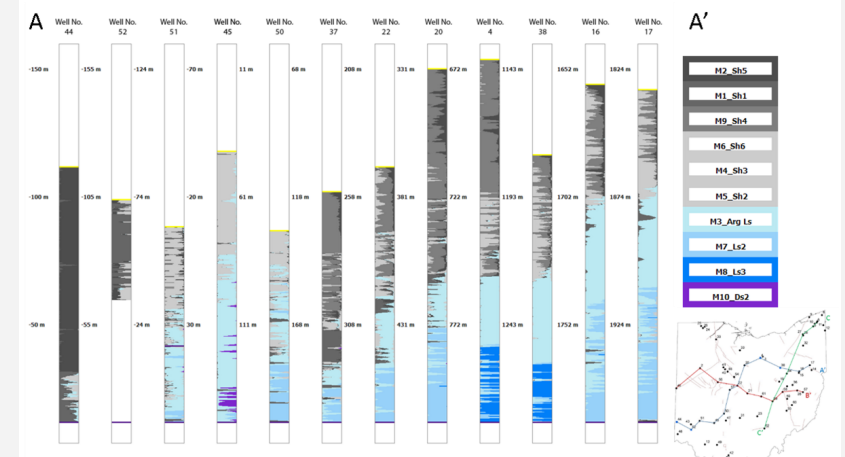


Figure 11. Cross section A-A'.

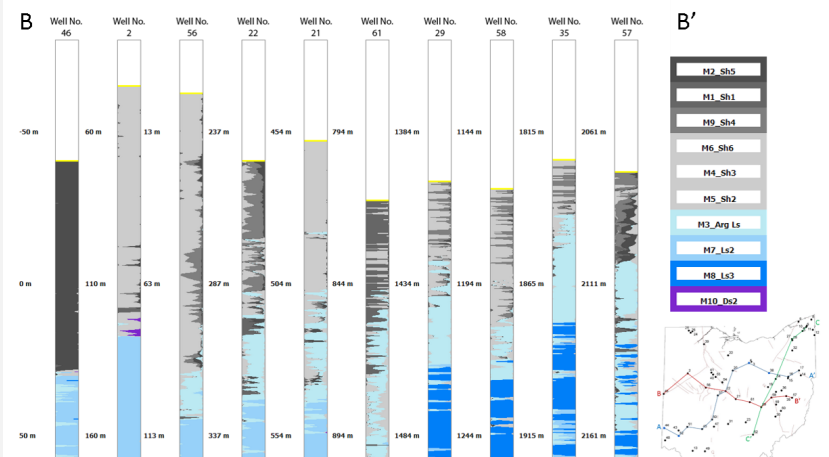


Figure 12 Cross section B-B'.

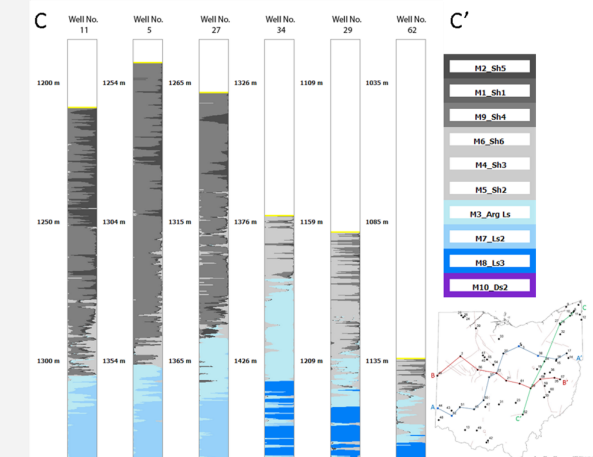


Figure 13. Cross section C-C'.

LITHOFACIES WITHIN THE UTICA/POINT PLEASANT

The highest percent of shale with little to no calcite content (facies 1, 2, 9) of the Utica shale and Point Pleasant Formation (Figure 14) mostly lie within a linear channel trending from southwest to northeast Ohio which corresponds to the thick linear feature on the isopach map (Figure 15), and another basin-like feature in eastern Ohio. The calcareous shale, mainly occupies the edges of the linear feature (Figure 16), and the argillaceous limestone is situated mainly in the southeastern half of the state (Figure 17). There are very few limestone beds limestone that were detected by well logging, at most occupying 4% of the shale formations, but the majority of the well locations contained no limestone beds. (i.e., thick enough for well logs to detect a true carbonate value).

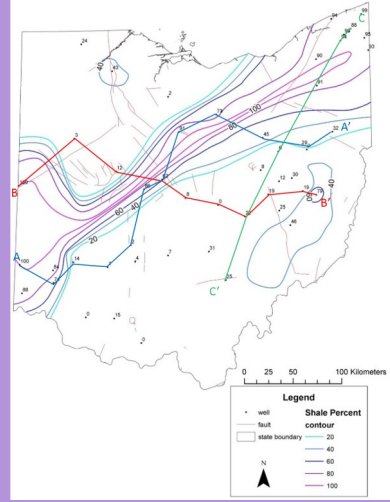


Figure 14. Percent of shale in the Utica/Point Pleasant.

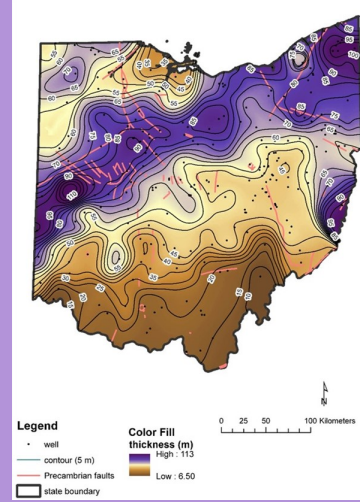


Figure 15. Isopach map of the Utica/Point Pleasant.

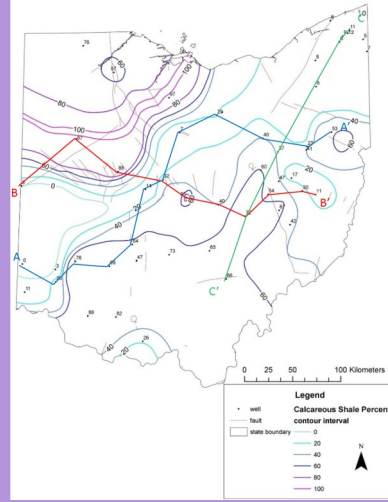


Figure 16. Percent of calcareous shale in the Utica/Point Pleasant.

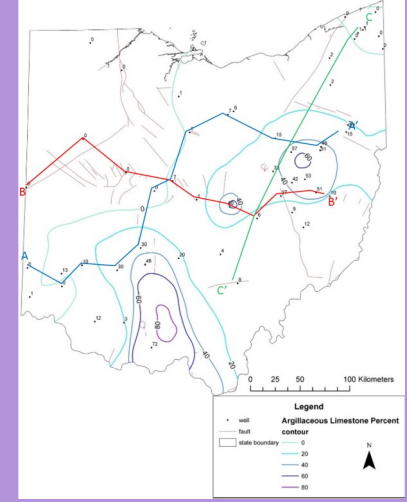


Figure 17. Percent of argillaceous limestone in the Utica/Point Pleasant.

LITHOFACIES WITHIN THE LEXINGTON/TRENTON LIMESTONES

Within the carbonate units, there is generally very little shale content overall for either shale or calcareous shale; as a result these two facies were combined to create the shale percent map (Figure 18). The two notable locations with very high shale percent are in the middle of the state and at the southwestern edge of the state. Argillaceous limestone is mostly located towards the southwestern portion of the state (Figure 19). The northwest corner of the state has no to very little (on the order of just a few percent maximum) of argillaceous limestone, eventually increasing towards the east and southeast. Dolostone and limestone were combined to create the limestone percent map, as dolostone represents still a "clean" carbonate unit. The dolostone within the carbonate platform also is a result of localized hydrothermal alterations from fault zones, particularly the Bowling Green Fault Zone in northwest Ohio (Wickstrom et al., 1990). Limestone is mainly found in northwest Ohio and southeast Ohio, with central Ohio containing less amounts of "pure" limestone (Figure 20). There are also several locations of very little to no "pure" limestone present in the carbonate platform, focused in central Ohio and southwest Ohio, such as the area of argillaceous limestone at the eastern edge of the state.

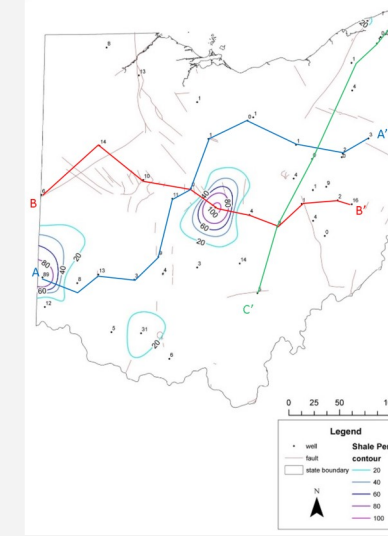


Figure 18. Shale percent in the limestone formations.

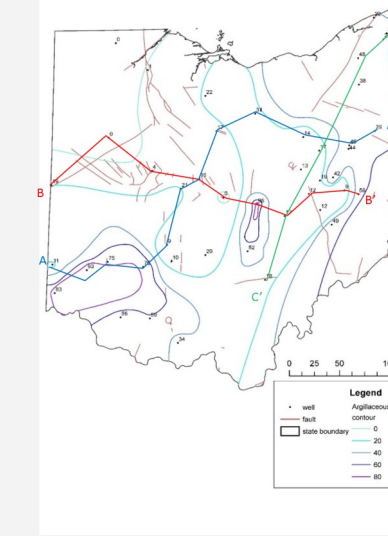


Figure 19. Argillaceous limestone percent in the limestone formations.

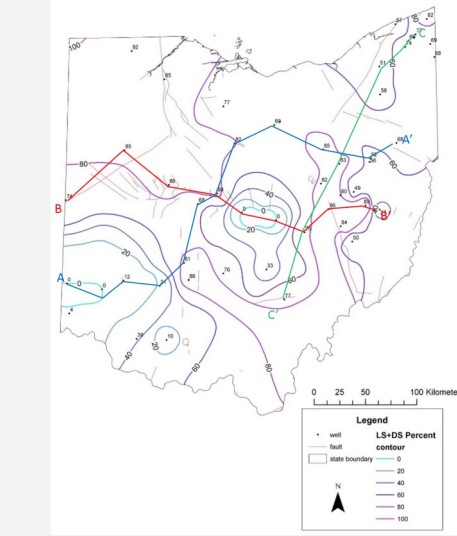


Figure 20. Limestone/dolostone percent in the limestone formations.

DISCUSSION AND CONCLUSION: CONTROLS ON DEPOSITION

There are several prominent features that appear when dominant lithofacies are mapped across Ohio (Figure 21). First, the Sebree Trough, containing predominantly calcite-poor shales and corresponding to thickening of the shales and thinning of the carbonate platform, appears to extend across the state rather than terminate in SW Ohio^{9,12,13}. The Waverly Arch appears to have been a low-relief, topographic high that persisted from the Precambrian into the Ordovician^{14,15}. Although moving throughout time, suggesting a migrating peripheral bulge, it has affected rates and types of deposition. To the east, the Appalachian Basin was influencing deposition by providing a source of siliciclastics and deepening waters. Finally, there are several, smaller regions where reactivation of Precambrian faults appear to have created localized uplift (such as the Utica Mnt. Fault, promoting carbonate deposition) or down-dropping (such as the Harlem Fault, promoting siliciclastic deposition) in central Ohio^{9,16}.

Overall, the mineralogy and facies distribution of the lower Upper Ordovician in Ohio is controlled by two basins formed to the east (Appalachian Basin) and northwest (Michigan Basin), and structures that are prominent or reactivated during deposition within the Precambrian basement.

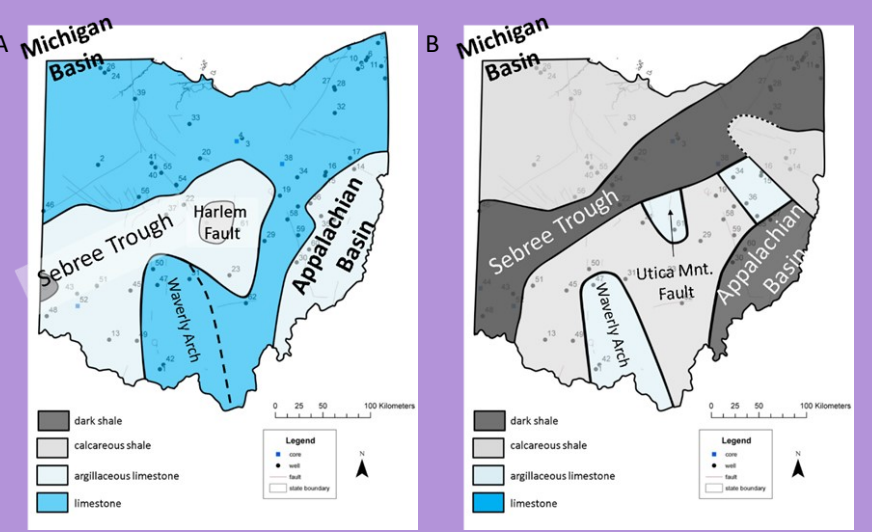


Figure 21. (A) Carbonate platform and (B) shale formations major facies composition across the state using GAMLs facies assignments and core comparison. Major facies at a location was assigned based upon which facies had the most beds assigned to it.

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