Subsurface Relationships between the Sebree Trough and Carbonate-Siliciclastic Mixing in the Upper Ordovician Lexington-Trenton and Point Pleasant-Utica Intervals in Ohio, USA, using Multivariate Statistical Well Log Analysis

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ABSTRACT. The Upper Ordovician (lower Katian; upper Chatfieldian-lower Edenian) Lexington-Trenton limestone and Point Pleasant-Utica shale intervals are important subsurface stratigraphic units across Ohio as they are the sources of significant conventional and unconventional hydrocarbon resources. However, both units exhibit anomalous distributions across the state and heterogeneous relationships, especially in areas where they intertongue. The limestone units show a peculiar SW-NE thinning trend across Ohio, whereas the overlying shale units show an anomalous thickening along the same trend—a trend associated with the poorly understood Sebree Trough, a supposed Late Ordovician paleobathymetric low related to the coeval Taconic Orogeny. To explore relationships among Lexington-Trenton carbonates, Point Pleasant-Utica shales, and the presumed Sebree Trough, multivariate statistical analysis was used to compare geophysical well logs across the state with well logs referenced to the mineral content of 4 Lexington-Trenton-Point Pleasant-Utica cores. Comparing well-log responses with the mineral content of the reference cores allowed the discernment of 10 electrofacies, keyed to lithofacies in the cores. Software analysis of many other well logs across the state then made electrofacies assignments by comparing well-log responses from the other wells with well-log responses from the reference cores preset into the software. Electrofacies responses were color-coded, mapped in wells at 0.6 m (2 ft) resolution, and used to make section lines and isopach maps of similar electrofacies. Isopach maps and cross sections confirm the presence of the Sebree Trough across Ohio, with trends that parallel existing and projected basement structures. This suggests that the Sebree Trough in Ohio was a bathymetric low, which was, at least in part, controlled by reactivation of basement structures due to far-field Taconic stresses.

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INTRODUCTION

The Point Pleasant Formation and Utica shale are Upper Ordovician (Katian; uppermost Mohawkian–lowermost Cincinnatian) shale-rich units that occur largely in the subsurface of northeast-central parts of the United States (Hickman et al. 2015a). Although the unit names vary by state (Fig. 1), in Ohio the "Utica shale" is considered to be an informal unit corresponding to upper organic-rich parts of the Point Pleasant Formation and overlying organic-rich parts of the Kope Formation (e.g., Larsen 1998), and the 2 units are commonly included together as the Utica shale/Point Pleasant Formation; in this paper, the term Utica shale is used in its informal sense. Aside from naming issues, the units have become increasingly important as source rocks (Cole et al. 1987; de Witt 1993; Laughrey and Baldassare 1998; Ryder 2008, 2014) and unconventional resources (Ryder 2008; Lavoie et al. 2014; Hickman et al. 2015a; Patchen and Carter 2015; Riley 2015; ODOGR 2017), which have in places been included as parts of the "Trenton" (Nuttall 1996), fractured carbonate (Wickstrom 1996), Utica Shale (Patchen and Carter 2015; Geary and Popova 2017; Popova 2017; Blondes et al. 2020), and Point Pleasant/Utica Shale (Enomoto et al. 2019a, 2019b) plays. The unit also has potential importance as a low-permeability seal for CO_2 injection and storage (Wickstrom et al. 2005; Ryder 2008; Gupta et al. 2020).

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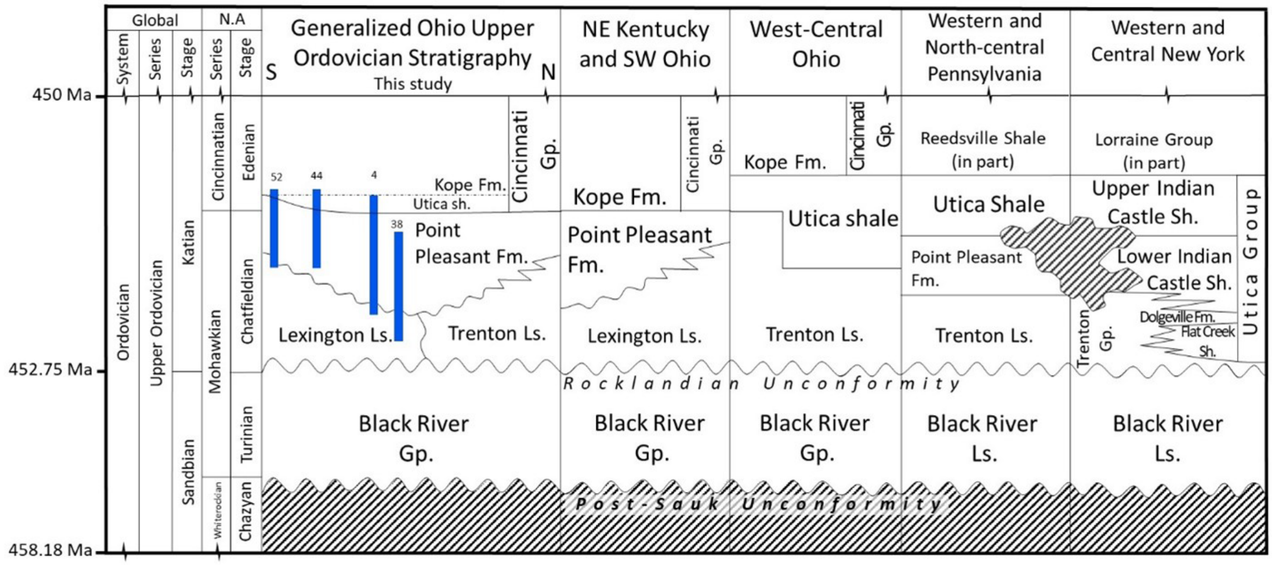

FIGURE 1. Generalized stratigraphic chart for Upper Ordovician (Sandbian–Katian; Mohawkian–lower Cincinnatian) strata from the study area in Ohio (far left) and nearby areas. The relative stratigraphic intervals present in the numbered cores chosen for study, and their locations relative to each other, are shown in blue. Based on Wickstrom et al. (1992); Larsen (1998); Hickman et al. (2015a).

The Point Pleasant and Utica are partially equivalent to, and intertongue with, the Trenton and Lexington limestones in Ohio and northern Kentucky (e.g., Cressman 1973; Wickstrom et al. 1992; Ettensohn et al. 2002), but some of the intertonguing and other important lithologic changes appear to occur along structural features associated with the controversial Sebree Trough. The Sebree Trough—an apparent paleobathymetric low—has been variously interpreted to have formed through submarine channel erosion (Schwalb 1980), flexure on a structural hinge line (Rooney 1966), extension of the Reelfoot Rift (Kolata et al. 2001), back-bulge isostatic adjustment (Bergström and Mitchell 1994), or far-field reactivation of basement structures (Ettensohn and Cecil 1992; Wickstrom et al. 1992). However, exactly how the intertonguing occurs in relation to structures associated with the Sebree Trough, and how it relates to the distribution of organic-rich shales that comprise the infill material, is largely unknown.

The current study focuses on large-scale regional and local controls that are primarily concerned with tectonics during the Late Ordovician Katian Stage (Chatfieldian–Edian) in Ohio. Although far from crustal loading in the Taconic orogenic belt to the east, which is interpreted as producing the flexural accommodation in the foreland basin (Ettensohn et al. 2002), the regional stratigraphic and lithologic data presented here suggest both local and regional structural controls on Late Ordovician deposition. Structure and isopach maps document changes in the limestone-dominant (Trenton and Lexington) and shale-dominant (Utica and Point Pleasant) formations. Multivariate analysis of well log data, coupled with core data, detail lithological changes in these formations and highlight the variability in electrofacies and carbonate abundance across the state and through Late Ordovician time. Facies mapping within the carbonate and shales identify patterns and influences not discernible from structure maps or isopach maps. Collectively, these data build upon recent work demonstrating localized variations in lithology across the basin (Solis 2015a, 2015b, 2015c, 2016; Gupta et al. 2020). This data also helps interpret the structural controls on Late Ordovician deposition in Ohio, likely produced by the reactivation of Precambrian basement structures by far-field tectonic stresses.

Late Ordovician Geologic Framework

The Point Pleasant Formation, Utica shale, and underlying Lexington and Trenton limestones are parts of a major sequence of rocks deposited in a broad, epicontinental sea across north-central parts of Laurentia. Deposition occurred at about 20° S latitude in what was then the subtropical trade-wind belt (Ettensohn 2010; Scotese 2014) during the Taconic tectophase of the Taconian Orogeny (Ettensohn 1991; Ettensohn et al. 2019). Prior to this phase of orogeny, a vast, shallow-water, carbonate platform, called the Blackriverian carbonate platform, spread across north-central Laurentia (Figs. 1 and 2A). The platform was characterized by relatively pure, muddy carbonates with characteristic fauna that suggest warm-water deposition analogous to the recent, warm-water carbonate photozoan association of James (1997). However, by the Sandbian-Katian (mid-Mohawkian Turinian-Chatfieldian), or the Black River-Trenton, transition (Fig. 1), large parts of the Blackriverian Platform had collapsed; the widespread, warm-water, carbonate deposition was replaced with several facies belts characterized by temperate-water, heterozoan (e.g., James 1997) carbonates (Fig. 2B) (e.g., Patzkowsky and Holland 1993, 1996; Holland and Patzkowsky 1996, 1997; Pope and Read 1998; Kolata et al. 2001; Ettensohn et al. 2002; Pope and Steffen 2003; Pope 2004). Moreover, this change coincided with the development of the Rocklandian unconformity (Fig. 1) (Ettensohn 1991, 1994), and the coeval stratigraphic differentiation of facies belts exhibited a broadly geometric outline that was dominated by a linear low feature called the Sebree Trough (Figs. 2B and 3) (e.g., Keith 1989). Although bounding structures on the Sebree Trough are illustrated in Fig. 3 as straight-line faults, they were, in fact, fault systems consisting of numerous sub-parallel faults, each active over varying time spans.

The apparent paleobathymetric low known as the Sebree Trough had been recognized and named earlier by Schwalb (1980), who described it as a nearly 1,000 km long, linear trough or valley-like feature in which Trenton carbonates thinned and overlying Cincinnatian shales thickened (Fig. 4). Subsequent work by Kolata et al. (2001) and Ettensohn et al. (2002) recognized that the trough and related basinal areas paralleled basement structural features (Fig. 4). These basement structure features had probably been involved in trough formation. In fact, work by Ettensohn et al. (2002) showed that the structural and stratigraphic differentiation of the former Blackriverian carbonate platform (Fig. 2) was related to far-field reactivation of basement structures during the inception of the Taconic tectophase of the Taconian Orogeny. The Taconic tectophase represented island-arc collision at the New York promontory (Fig. 3, annotation N) near the Turinian-Chatfieldian transition (Ettensohn 1991; Ettensohn et al. 2002; Ettensohn and Lierman 2012, 2015), and much of the structural reactivation was apparently mediated by Taconic bulge moveout reflected in the Rocklandian unconformity (Fig. 1). Although Trenton and Lexington deposition on the Lexington Platform commenced after bulge-related unconformity development, reactivation of Keweenawan basement structures (Fig. 3) by growth faulting apparently created the downdropped, linear Sebree Trough north of the platform and opened it up to deep oceanic waters from the Ouachita Sea to the south (Figs. 2B and 3). It was the upwelling of deep, cold, oceanic waters from the Sebree Trough onto the adjacent Lexington Platform and the Galena and Trenton shelves (Fig. 2B) that was responsible for the temperate-water nature of Trenton and Lexington carbonates across the region (Ettensohn 2010). At the same time, the Lexington Platform blocked the influx of sediments from the rising Taconic mountains into the Sebree Trough, while

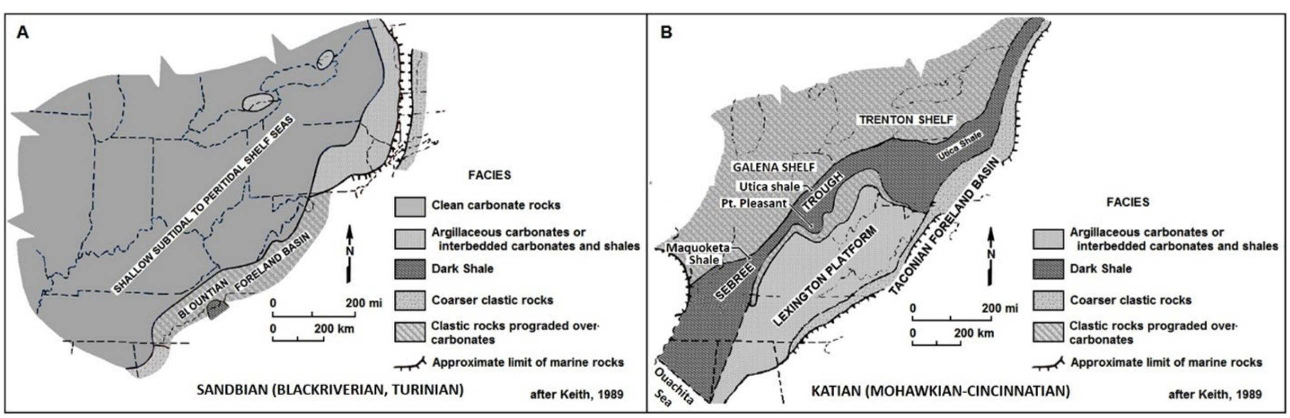

FIGURE 2. Reconstructions of north-central Laurentia before (A) and after (B) inception of the Taconic tectophase of the Taconian Orogeny. A) Northwest of Blountian foreland basin, facies reflect uniform shallow-subtidal to peritidal carbonates across the extensive Blackriverian carbonate platform. B) After Taconic tectophase, facies show major differentiation along basement structures (Fig. 3), especially the Sebree Trough (after Keith 1989; Ettensohn et al. 2002).

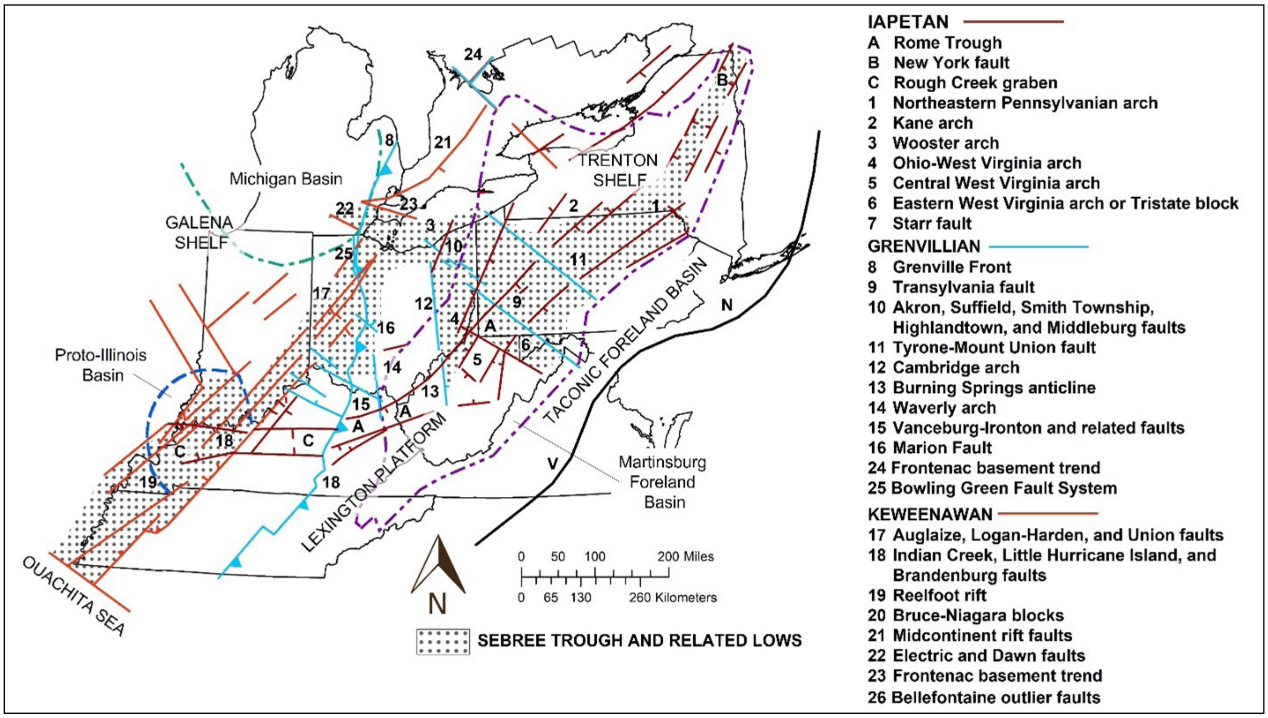

FIGURE 3. Map of north-central Laurentia showing approximate locations of Precambrian Iapetan (brown), Grenvillian (blue), and Keweenawan (orange) basement structures in the area of the Taconic foreland (purple outline), proto-Illinois (dark blue), and Michigan (green outline) basins relative to the New York (N) and Virginia (V) continental promontories. The above structures were reactivated during the Taconic tectophase, involving island-arc collisions at the New York promontory. The earlier Blountian tectophase was concentrated at the Virginia promontory and did not reactivate structures beyond its foreland basin (see Ettensohn 1991). The stippled area represents the black-shale infill (Utica shale and equivalents) of the Sebree Trough and adjacent Appalachian lows that connected the deep Ouachita Sea, to the south, with parts of the Appalachian Basin in the north (adapted from Ettensohn et al. 2002).

the upwelling of cold, phosphate-rich waters into the trough had a corrosive effect on the underlying Trenton and Lexington carbonates. This explained the thinned nature of the Lexington and Trenton limestones in the trough area (Fig. 4A), as well as the presence of a phosphorite and pyrite encrusted unconformity on top of the Lexington and Trenton limestones (Fig. 5) in the trough at least as far north as the Cincinnati area (Keith and Wickstrom 1993; Kolata et al. 2001; Ettensohn et al. 2002; McLaughlin and Brett 2007).

Corrosion and sediment starvation in the Sebree Trough persisted throughout most of middle Chatfieldian time. However, by late Chatfieldian (early-mid Katian) time, a global sea-level rise (Cooper and Sadler 2012; Goldman et al. 2020) along with large-scale, loading-related, tectonic subsidence and westward tilting across the Taconic foreland basin (Mitrovica et al. 1989; Ettensohn et al. 2002; Ettensohn and Lierman 2015) drowned the carbonate platforms (Trenton and Lexington carbonates) (Figs. 2B and 3). This allowed major, Taconic, fine-grained, clastic influx into the Sebree Trough, while severely dampening any further carbonate sedimentation. In the deepening seas, the presence of upwelling into—and the restricted nature of—the Sebree Trough generated epicontinental, quasi-estuarine circulation patterns that fostered the development of a stratified water column; the dysaerobic and anaerobic conditions being reflected in the dark, organic-rich shales of the Point Pleasant and Utica formations (Kolata et al. 2001; Ettensohn et al. 2002; Ettensohn 2010; Ettensohn and Lierman 2015). At the same time, coeval dark shales from the Martinsburg, Reedsville, and Antes formations, and from the Utica Group of New York, expanded across adjacent parts of the Appalachian foreland basin (Ettensohn 2008; Ettensohn and Lierman 2012). The nature and origin of the dark shales filling the Sebree Trough in Illinois, Indiana, Kentucky, and southwestern Ohio are relatively well-known (Kolata et al. 2001; Ettensohn et al. 2002; McLaughlin and Brett 2007; Young et al. 2016); however, in the rest of this paper, these relationships for the dark Point Pleasant and Utica shales will be examined throughout the remaining parts of Ohio.

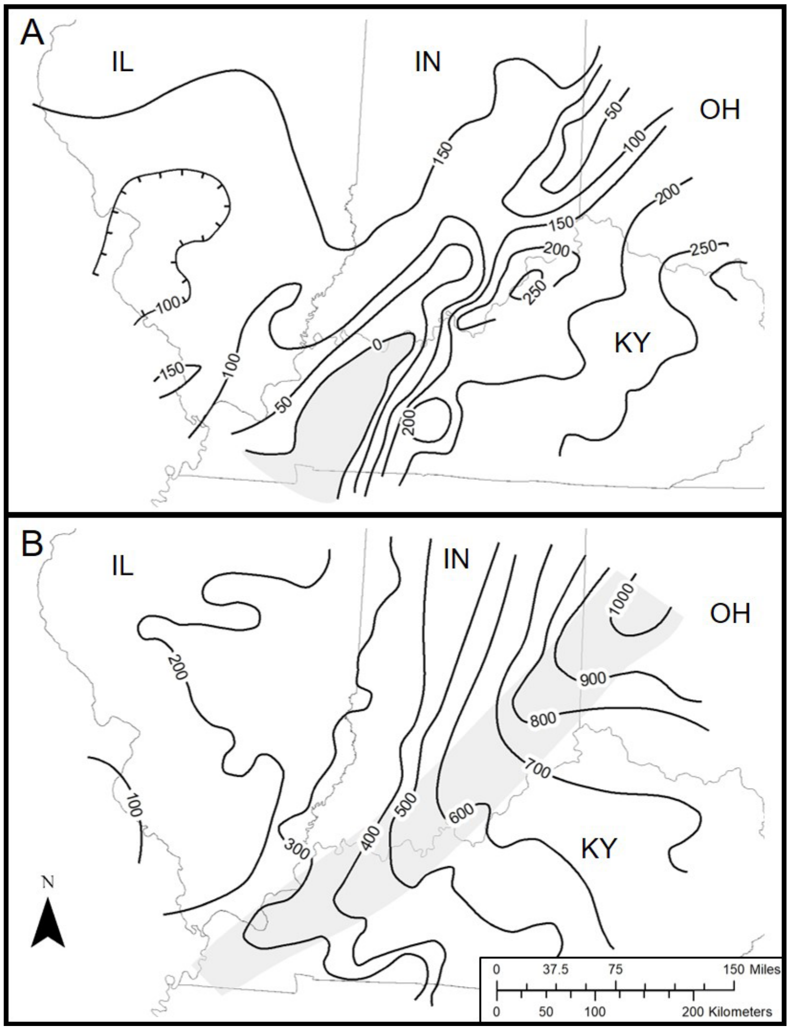

FIGURE 4. Isopach maps of the Lexington and Trenton limestones (A) and of the Maquoketa depositional sequence (B), which includes the Maquoketa, Kope, Clays Ferry, "Utica," Point Pleasant, and upper Lexington Limestone formations. Based on data from 571 wells and outcrops (Hohman 1998). A) Note the thin to absent (light gray) Lexington and Trenton carbonates (lower–Chatfieldian) along the NE-SW Sebree Trough corridor, and B) the overlying, thickened Maquoketa sequence (upper Chatfieldian–lower Edenian) following the same NE-SW trend of the Sebree Trough (adapted from Hohman 1998; Ettensohn et al. 2002).

Stratigraphic Framework

Upper Ordovician strata from the studied interval in Ohio include the Lexington Limestone, Trenton Limestone, Point Pleasant Formation, and Kope Formation; however, it is again important to note the informal use of the term "Utica shale" for organic-rich parts of the upper Point Pleasant and lower Kope formations (Fig. 1) (e.g., Larsen 1998). The Lexington Limestone in the study area disconformably overlies the Sandbian (Turinian) Black River Group. It is a lower Katian (upper Mohawkian; lower-middle Chatfieldian) shaley, fossiliferous limestone, consisting of argillaceous grainstone, packstone, and wackestone with localized phosphatic deposits (Cressman 1973; Ryder 2008). The Lexington Limestone is coeval with the Trenton Limestone (an argillaceous carbonate grainstone to packstone) to the northwest and the two grade laterally into each other (e.g., Wickstrom 1996). Locally, however, both Lexington and Trenton limestones may be dolomitized by later hydrothermal alteration along faults (Wickstrom et al. 1992; Wickstrom 1996; Ryder 2008). The top of the Trenton Limestone in much of the Sebree Trough is disconformable along a sharp corrosion surface (Fig. 1), a locally pyritized and phosphate-rich surface of non-deposition (Keith 1989; Keith and Wickstrom 1993; Kolata et al. 2001; Ettensohn et al. 2002). Along the margins of the trough and in northeastern parts of Ohio, upper parts of the Trenton Limestone grade into the shalier Point Pleasant and Kope formations; farther south in the Lexington, Kentucky, area, upper parts of the partially equivalent Lexington

Limestone are mid-Katian (latest Chatfieldian to early Edenian) in age and similarly intertongue with more shaly units (Cressman 1973; Ettensohn et al. 2002). In general, the shalier Point Pleasant and Kope formations are parts of a facies continuum with the Trenton and Lexington limestones such that the units become increasingly fine-grained and limestone-poor away from platform margins. Hence, the Trenton and Lexington limestones are predominantly coarser-grained limestones with a few shale interbeds (Fig. 5). The Point Pleasant is about 50% thicker-bedded, coarser-grained limestones and 50% calcareous shales; the Kope is about 70 to 80% shale with 20 to 30% thinner-bedded, finer-grained limestones (Weiss and Sweet 1964; Weiss et al. 1965; Cressman 1973). It is important to note, however, that what is defined as Point Pleasant Formation in the subsurface (Fig. 6B) and cores (Fig. 5) may be very different in lithology and thickness from what is defined as Point Pleasant Formation at its type section (e.g., Weiss and Norman 1960; Weiss et al. 1965).

In particular, the subsurface Point Pleasant Formation contains interbedded calcareous shales, even-bedded calcarenitic limestones, and occasional siltstones. The unit is primarily present in Ohio, with some extent into West Virginia, Kentucky, and Pennsylvania. These shales and siltstones are grey to brown to black (Fig. 5) and sparsely fossiliferous, consisting of occasional graptolite, brachiopod, or trilobite fragments—indicating a somewhat "deeper-water" depositional setting compared to the surrounding and underlying carbonate platforms of the Trenton and Lexington limestones (Kolata et al. 2001). The limestone beds are primarily light-grey to grey calcarenites (Fig. 5), consisting of a shell hash with brachiopod and crinoid fragments.

FIGURE 5. Core segments near Lexington-Point Pleasant contact (arrow), showing eroded and corroded nature of the contact with hematite (oxidized pyrite) coating the contact. Note the calcarenitic limestones and interbedded dark shales that comprise upper parts of the Lexington and the gray-brown shales that comprise the overlying Point Pleasant. Scale in centimeters. OGS core 2984, Butler County, southwestern Ohio, Well No. 52, at a depth of 158 m (517 ft) below the surface.

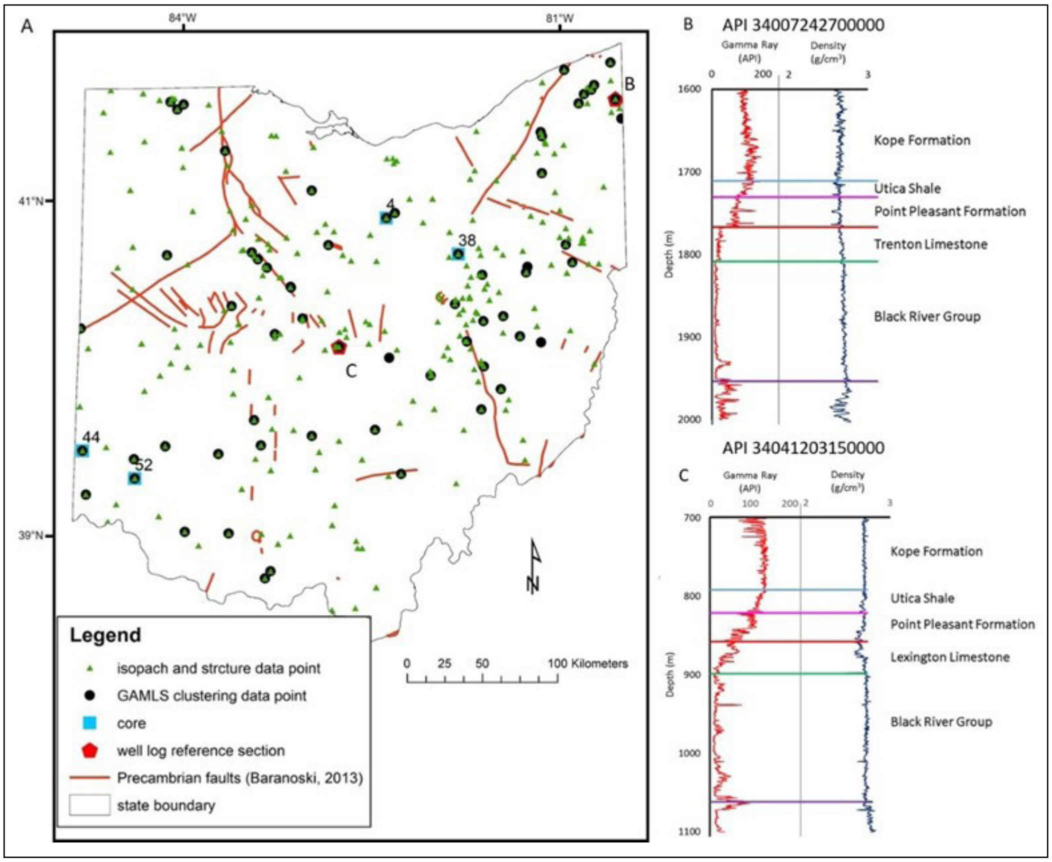

FIGURE 6. (A) Location map of well-log data for isopach and structure maps, GAMLS (Geological Analysis via Maximum Likelihood System) clustering analysis, location of cores used in this study, and the reference logs (B and C). The numbered wells are cores used in the study (Fig. 1). (B) Well-log reference examples for the Black River Group, Lexington and Trenton limestones, Point Pleasant Formation, Utica shale, and Kope Formation from Ashtabula County in northeast Ohio (API No. 34007242700000) and (C) Delaware County in central Ohio (API No. 34041203150000). (See supplemental data for a list of wells used in the study as well as the structural tops and unit thicknesses shown in Figs. 7, 8, 9, and 10.)

The Utica shale is an informal formation name within Ohio, referring to the predominantly dark, shaley strata at the top of the Point Pleasant and base of the Kope Formation. The Utica shale extends throughout much of the Appalachian Basin; outside of Ohio, the Utica and equivalent units are recognized as formal units, comprising interbedded calcareous to non-calcareous shales, thin finer-grained limestones, and some siltstones. The Utica in Ohio is also sparsely fossiliferous and dark-brown to black, and as already mentioned, may be grouped together with the Point Pleasant informally as the Point Pleasant/Utica Formation (e.g., Wickstrom 1996; Enomoto et al. 2019a, 2019b). Locally, the contact between the Point Pleasant and Utica may be disconformable (Erenpreiss 2015; Smith 2015), but the contact in well logs (from which most of the data were obtained) is recognized by a decrease in the gamma-ray values—reflecting an increase in the carbonate content of the Point Pleasant compared to that of the Utica. The Utica shale also tends to be darker in color than the Point Pleasant.

The dark color and predominance of fine-grained rocks in the Utica have also been used to suggest a greater depth during deposition (e.g., Cressman 1973; Wickstrom 1996; Kolata et al. 2001; Ettensohn et al. 2002). However, the finer-grained nature of the Utica may merely reflect distance from the carbonate shelf and proximity to Taconic clastic sources at the time. The dark coloration, of course, reflects the presence of up to 3% TOC (Ryder 2008). But this could simply mean that more organic matter was generated by upwelling and/or that preservation of that organic matter was enhanced through the development of a stratified water column, associated with the upwelling of cold, nutrient-rich waters in the relatively closed, restrictive conditions of the Sebree Trough. Considering these conditions, Weiss et al. (1965) suggested that depths during the deposition of the Point Pleasant and Utica were not much greater than those across the adjacent shelves, perhaps on the order of 25 m total.

METHODS AND MATERIALS

Core and Well-Log Data

A combination of core and well-log data from 4 wells in Ohio were used to identify lithofacies and calibrate electrofacies for the study interval (Table 1). These 4 cores were selected based upon location and, during the time of the study, were the only publicly available cores containing the interval of study. Well No. 44 (API No. 34107600040000, OGS core 2982) and Well No. 52 (API No. 34017600110000, OGS core 2984) from Butler County in southwestern Ohio (Fig. 5) had downcore variations in calcite content estimated using visible derivative reflectance spectroscopy and calibrated by quantitative X-ray diffraction (Bloxson 2017). Reflectance spectroscopy was measured with a Konica Minolta® UV/VIS CM-2600d on each core at 1 cm (0.39 in) resolution and a 3 mm (0.12 in) spot size. The reflected-light intensity was measured at wavelengths from 360 to 740 nm at increments of 10 nm, along with the amount of light reflected (L*).

Quantitative X-ray diffraction (QXRD) was conducted on 30 samples from the 2 cores following the protocol in Eberl (2003). Each sample was analyzed on a Scintag X1 diffractometer with Cu-K-alpha radiation (39.5 mA, 44.5 kV) at 0.02° steps, from 5° to 65° 2 Θ, for 2 seconds per step. USGS RockJock software was used to analyze the samples for quantitative mineralogy, which integrates the intensities of peaks and compares them to a corundum standard using Chung's (1974) matrix flushing technique. A model is then created using measured standards and based upon the methodology in Smith et al. (1987). Calcite content was estimated throughout the cores based upon the correlation between L* measured with the spectrometer and calcite percent measured by QXRD. A non-linear regression between the data points was calculated in JMP® Pro 14 software. For full results, see Bloxson (2017).

The remaining 2 cores from north-central Ohio, including Well No. 4 (API No. 34005241600000, Eichelberger, Ashland County) and Well No. 38 (API No. 34169256690000, Hershberger, Wayne County), had calcite content measured by the New York State Museum as a part of the Utica Play Book Consortium (Smith 2015). In these cases, the amount of calcite was determined by the difference in sample weight pre- and post-dissolution of the carbonate by acidification. Unfortunately, it was not possible to cross-validate XRD and dissolution techniques for calcite content, but both techniques appear to have produced comparable results; results that, in retrospect, were typical of their respective locations. Previous studies on the mineralogy of the Utica shale and adjacent formations indicate that calcite content varies inversely with the clay-mineral content (Harper 2015; Bloxson 2017). Therefore, calcite content was used as a proxy for siliciclastic content as well as to indicate relative amounts of each to infer lithology.

Publicly available well logs (268 in total) (Fig. 6) obtained from the Ohio Department of Natural Resources, Division of Geological Survey were used to determine formation boundaries for the tops of the Black River Group, Trenton Limestone, Lexington Limestone, Point Pleasant Formation, and the Utica shale. These determinations followed the standards for boundary picks used by Wickstrom et al. (1992); Kolata et al. (1996); Patchen et al. (2006); Erenpreiss (2015); and Hickman et al. (2015b). Structure-contour maps and isopach maps were created by determining and

Table 1
Details for the cores used to calibrate the electrofacies. Information includes the well number assigned in this study, API (American Petroleum Institute) number, well name, and mineralogy data source.

Well No.	API No.	Well name	Mineralogy measured by
4	34005241600000	Eichelberger David	New York State Museum[1]
38	34169256690000	Hershberger	New York State Museum[1]
44	34107600040000	Izaak Walton League	Reflectance spectroscopy[2]
52	34017600110000	Davis Mickey	Reflectance spectroscopy[2]

[1]Reported in Smith (2015). [2]Reported in Bloxson (2017).

correlating formation boundaries in geoSCOUT software from geoLOGIC systems ltd., then exporting the data into Esri® ArcGIS® software for gridding and contouring. Gridding was done with ordinary Kriging, smoothed with a smoothing factor of 0.2, with errors of ±9.3 m (30.5 ft) (carbonate thickness), ±81 m (266 ft) (carbonate structure), ±11 m (36.1 ft) (shale thickness), and ±51 m (167 ft) (shale structure).

Multivariate Analysis

Sixty-two of the wells that pass through the Point Pleasant Formation, Utica shale, and underlying Lexington and Trenton limestones in Ohio were selected for multivariate analysis and clustering to identify electrofacies. The electrofacies were verified and "calibrated" using the core data. These wells were chosen because they contain all (or most) of the log types selected for analysis—gamma ray (GR), neutron porosity (NPHI), bulk density (RHOB), sonic (DT), and photoelectric effect (PEF). Geologic Analysis via Maximum Likelihood System (GAMLS) software from Eric Geoscience, Inc. was used to analyze well-log data—from the base of the Lexington and Trenton limestones to the top of the Point Pleasant Formation and Utica shale—and group them into clusters with similar log responses. GAMLS is a multivariate statistical program that can group large datasets into clusters based on similarities in their values, regardless of the number of variables. The program uses MLANS (Maximum Likelihood Adaptive Neural System) to group the data into "modes" (i.e., clusters) characterized by sets of typical log responses, the combination of which distinguish one mode from another (essentially pattern-recognition in multiple dimensions, creating subsets of data within a very large dataset that are similar) (Perlovsky and McManus 1991; Perlovsky 1993; Eslinger et al. 2000). Clustering in GAMLS was initialized "By Variable" with RHOB, with 10 modes and a 0.01 convergence goal. The Generalized Fuzzy Multilinear Model (GFMLM) within GAMLS was used to estimate formation responses and identify modes for well logs that were missing one of the selected log types, usually DT. GAMLS assigned initial electrofacies assignments based on known, typical, well-log responses of rock types to the well log tool (Fig. 6B) preset in the program: shale 1, shale 2, limestone 1, dolostone, etc. Ten electrofacies were assigned to the 10 modes (Table 2).

While both lateral and vertical heterogeneities can be shown in the well logs, it should be noted that the resolutions of many well logs are not at the centimeter-scale; such logs only have a resolution of approximately 0.6 m (2 ft) at best. In core, limestone laminae and beds can be observed, but well logs do not have the detailed resolution to determine these small-scale changes, especially in a mixed carbonate-siliciclastic environment.

Calibration of Electrofacies Model

Electrofacies modes were compared to the measured calcite content and mineralogy, core images, and descriptions of the 4 cores for verification and calibration. The electrofacies were grouped into 5 lithofacies based upon carbonate content and core descriptions (Table 2) including: shale, which has little to no calcite; calcareous shale, which is a mixture of shale and carbonate with more shale than carbonate; argillaceous limestone, which is a mixture of shale and carbonate with more carbonate than shale; limestone with very little interbedded shale or intermixed clay material; and dolostone. The percentage of a lithofacies at a given location was used to create lithofacies maps, rather than the total thickness (total footage), to reduce the effects of thickening and thinning of a formation and highlight the dominant lithofacies. These maps were hand contoured in ArcGIS. Finally, the major facies constituent at each location was identified, and its distribution mapped, to provide a generalized assessment of the distribution of facies and mineralogy across the state (within the studied stratigraphic interval). Although it is realized that the use of lithofacies can be problematic when trying to show high-resolution relationships, the statistical procedures used to generate them in this study were especially effective at analyzing large numbers of well logs, while providing results with sufficient resolution to make meaningful interpretations.

Table 2
Electrofacies (modes), assigned by GAMLS and user knowledge, then reclassified as lithofacies based upon calcite content and core descriptions. Rows are color-coded to match mode No./electrofacies classification color-coding in subsequent figures.

	Average well log values								
Mode No.	Grain density (g/cm³)*	GR (API)	RHOB (g/cm³)	NPHI (%)	PEF	DT (μsec/ft)	Electrofacies description	Core description	Average calcite (%)
2	2.61	133	2.58	16.2	3.53	73	Shale 1	Shale	20.7
1	2.35	96.2	2.49	18.0	3.83	83	Shale 2 (potentially organic-rich)	Shale with occasional carbonate bed	22.0
9	2.77	123	2.69	19.2	3.68	72	Shale 3	Shale with occasional carbonate bed	26.4
4	2.68	106	2.66	19.9	3.87	82	Calcareous shale 1	Shale with distal carbonate event beds	37.8
5	2.63	105	2.69	18.3	3.89	70	Calcareous shale 2	Shale with distal carbonate event beds	39.6
6	2.83	53.6	2.76	7.30	3.92	55	Calcareous shale or argillaceous limestones	Approximately equal amount of shale and carbonate event beds	37.2
3	2.69	39.2	2.65	8.00	3.97	60	Argillaceous limestone	More limestone than shale	63.2
7	2.72	17.7	2.70	1.40	4.77	50	Limestone 1	Proximal carbonate tempestites	81.8
8	2.72	20.1	2.71	1.30	4.74	51	Limestone 2	Proximal carbonate tempestites	76.3
10	2.84	21.0	2.76	6.60	3.12	50	Dolostone	Not found within the cores	--

Clay-rich
Gradational transition zone
Calcite-rich

*Grain density was calculated using RHOB and NPHI.

RESULTS

Structure and Isopach Maps

The top contacts of the combined Trenton and Lexington limestones and the combined Point Pleasant Formation and Utica shale exhibit similar, generalized, subsurface structural dips. Both surfaces show a high area in western Ohio (Findlay Arch during deposition and modern-day Cincinnati Arch) with deepening across the state: toward the northwest into the Michigan Basin by 400 m (1,312 ft) to 500 m (1,640 ft), and toward the east into the Appalachian Basin by more than 2,500 m (8,202 ft) (Fig. 7). Calculated bedding dips are approximately 0.6°, with local variations up to approximately 1°. The overall structural configuration of the basin was produced by later orogenic influences during the late Paleozoic time (e.g., the Acadian and Alleghenian orogenies) (Ettensohn et al. 2019).

Constructed isopach maps of the studied stratigraphic intervals (Fig. 8) indicate that the Trenton and Lexington limestones in Ohio range in thickness from 14 m (46 ft) to 89 m (292 ft), while the overlying Point Pleasant and Utica shale formations vary from 6.5 m (21 ft) to 113 m (371 ft) in thickness. However, isopach maps of both intervals display thickness trends that differ from the present-day structural grain of the basin and display variability between units (Fig. 8). For example, the Trenton and Lexington limestones thin along a southwest-northeast-trending band, extending from the southwest corner of the state toward north-central Ohio, whereas the Point Pleasant Formation and Utica shale thicken along the same trend. This southwest-northeast trend coincides with the previously defined trend of the Sebree Trough (Figs. 2B, 3, and 4) (Kolata et al. 2001; Ettensohn et al. 2002) and supports the northeastward extension of the linear, Late Ordovician, structurally controlled Sebree Trough into Ohio. The thinned nature of the Lexington and Trenton limestones (Fig. 8A), presence of a corrosional disconformity surface atop the Lexington and Trenton limestones (Fig. 5), and the thickening of dark Point Pleasant and Utica shales along the same trend (Fig. 8B) strongly suggest that the trend represented a Late Ordovician bathymetric low that limited carbonate deposition

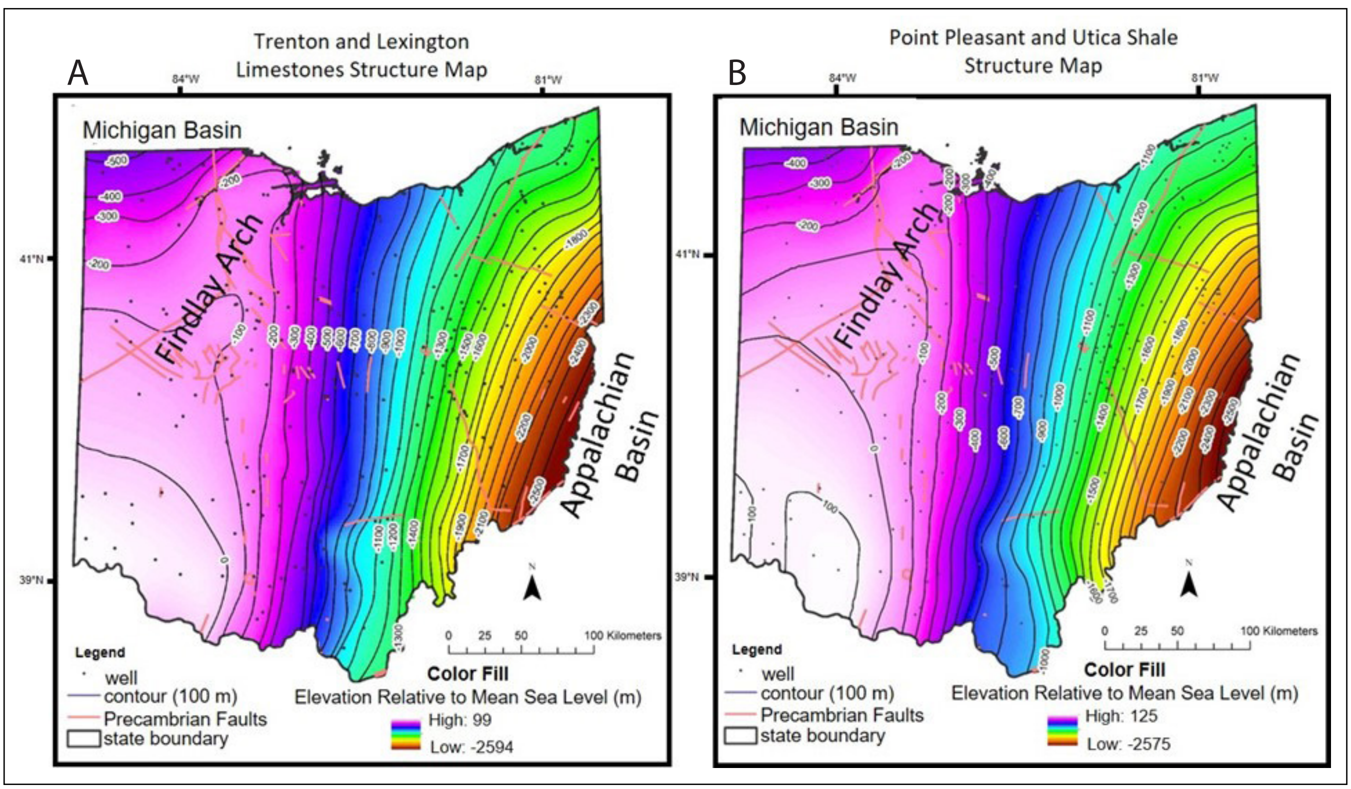

FIGURE 7. Structure contours on top of the (A) combined Trenton and Lexington limestones and on top of (B) the overlying Point Pleasant Formation and Utica shale with prominent structural features labeled. On the Trenton-Lexington map, the large, structurally flat area north and northeast of the Cincinnati area reflects the separation of the Cincinnati Arch into the Kankakee Arch (Wickstrom et al. 1992) and Carntown-Moscow Anticline (Potter 2007), forming a broad area called the Indiana-Ohio Platform (Wickstrom et al. 1992).

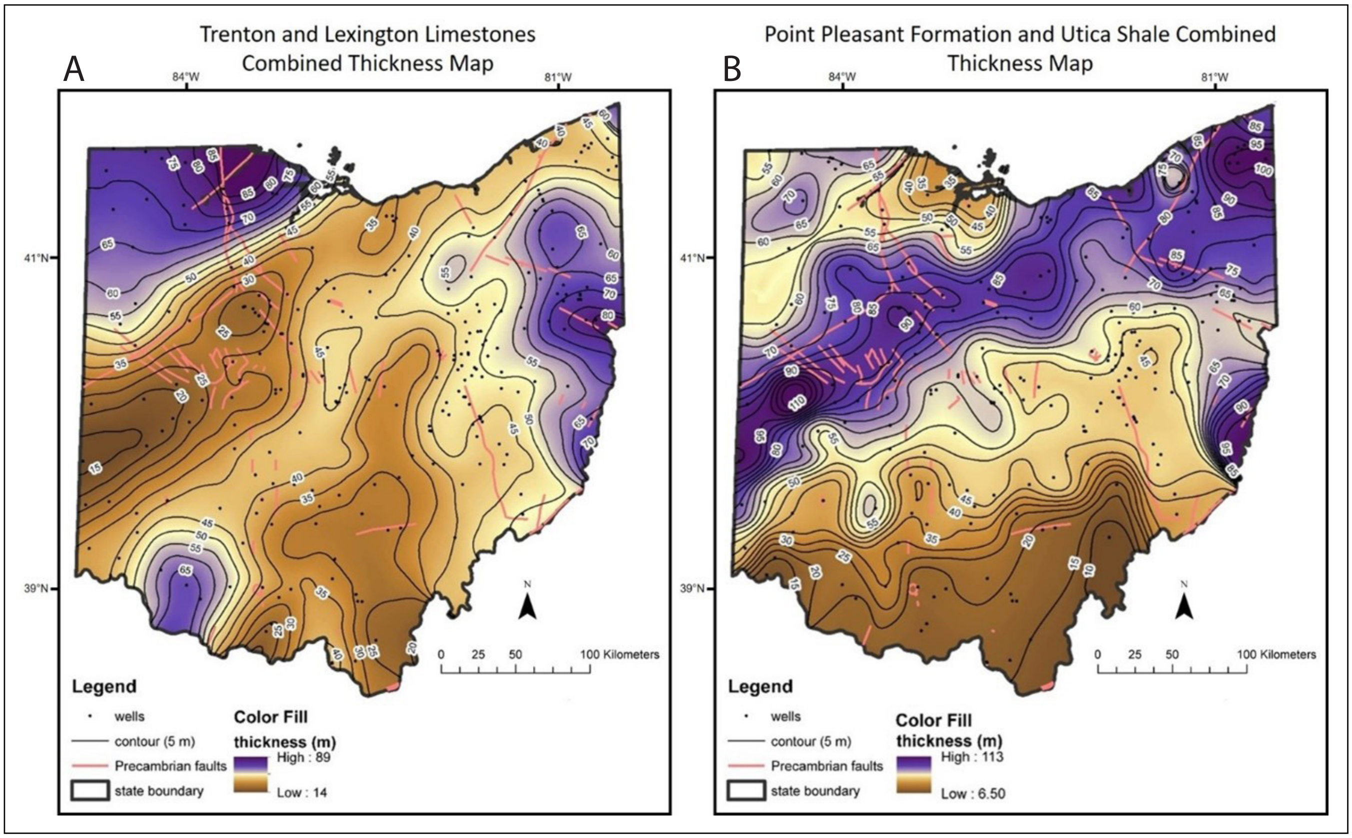

FIGURE 8. Isopach maps for (A) the combined Trenton and Lexington limestones, showing noticeable thinning from southwestern through northeastern Ohio, and (B) for shales in the overlying Point Pleasant Formation and Utica shale, which exhibit noticeable thickening along the same southwest-to-northeast trend in Ohio. These thinning of the limestones and thickening of the overlying shale units suggest an extension of the Sebree Trough throughout northeastern Ohio (see Figs. 2B, 3, and 4).

and allowed for the preferential accumulation of deeper-water, fine-grained siliciclastics as indicated by Kolata et al. (2001) and Ettensohn et al. (2002). It is suggested here that periodic growth faulting along the bounding structures created the accommodation space necessary for the greater accumulations of Point Pleasant and Utica shales (Fig. 8B), while at the same time generating depths great enough to facilitate upwelling and the preservation of organic matter in the accumulating muds.

The isopach maps also reveal other trends. The Trenton and Lexington limestones, as well as the Point Pleasant and Utica shales, both thicken toward the east into the foredeep of the Taconic foreland basin (Fig. 8) (Ettensohn et al. 2002). Similarly, the Trenton and Lexington limestone interval thickens to the northwest toward the Trenton Platform at the southeastern edge of the Michigan Basin (Patchen et al. 2006). In this same area, however, the overlying Point Pleasant and Utica shale interval displays variable thicknesses, but these variable thickness trends all roughly parallel basement structures (Figs. 3 [structures 17, 25], 8B), suggesting synsedimentary activity during deposition. South of the interpreted Sebree Trough, the total thickness of the shale-dominated units thins toward the south as shale deposition lapped up onto the uplifted northern margin of the Lexington Platform (Figs. 2B, 8B). In the same area, the thickness of the Trenton and Lexington limestones is somewhat variable, again probably related to synsedimentary activity on structures like the Carntown-Moscow Anticline (Potter 2007, Fig. 34) and the Waverly Arch (Woodward 1961; Rudman et al. 1965; Dever et al. 1977).

Facies Heterogeneities

As described above, the grouping of similarities between the 10 interpreted electrofacies modes resulted in the classification of 8 lithofacies (Table 2). However, both the Trenton and Lexington limestone and the Point Pleasant Formation and Utica shale display both lateral and vertical facies heterogeneities throughout Ohio (Figs. 9, 10). From southwest to northeast Ohio (Fig. 9), cross-

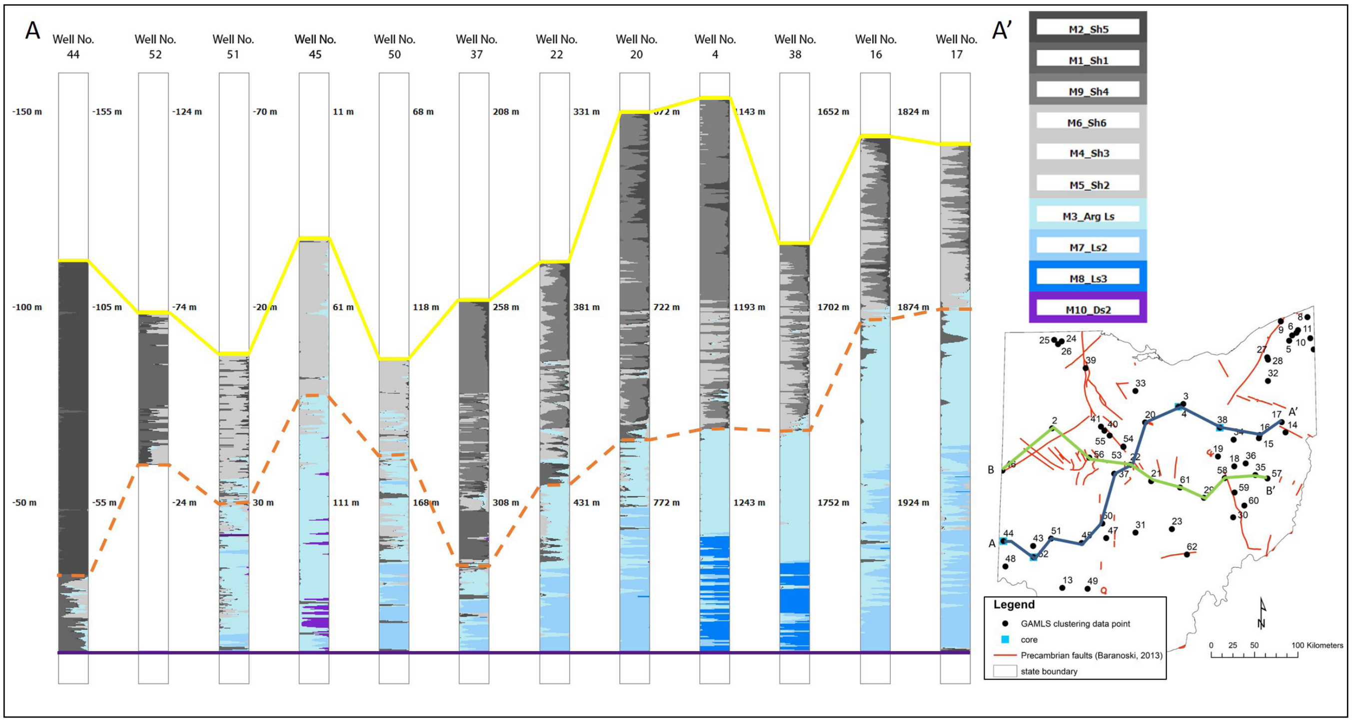

FIGURE 9. Cross-Section A-A′ trending southwest to northeast. The yellow line marks the top of the Point Pleasant and Utica shales; the brown dashed line marks the approximate top of the Trenton and Lexington limestones; and the purple line is the datum, marking the top of the Black River Group. Modes are numbered and color-coded to reflect the lithofacies interpreted in Table 2. Depths are relative to sea level.

section A-A' shows the thickening of limestones comprising the underlying Lexington carbonate platform (Fig. 2B), showing up-section variations in calcite content from limestones at the base into intervals of argillaceous limestone. Further up-section, the underlying carbonate platform either gradually transitions into calcareous shale or exhibits an abrupt transition from argillaceous limestone to either calcareous shale or shale. The first transition (e.g., Fig. 9, Wells 51, 45, 50) represents the Lexington Limestone grading into the overlying Point Pleasant shales; however, Wells 4 and 38 (Fig. 9) to the east show a sharp, clear demarcation between Trenton Limestone on the platform and the overlying Point Pleasant Formation.

Cross-section B-B' is approximately west to east (Fig. 10), cutting through the center of Ohio. The Point Pleasant Formation and Utica shale also display vertical and lateral variations with changing amounts of calcareous shale, shale, and sometimes argillaceous limestone beds (e.g., Well 21), some of which may reflect small-scale structural influence. Overall, the Point Pleasant and Utica intervals display an up-section decrease in calcite content as lithologies transition from dominantly calcareous shale to shale. The spatial variability is great, however, with areas of predominantly calcareous shale (e.g., Well 21) and others of entirely shale with low calcite content (Well 46). The section also shows that the Point Pleasant-Utica shale interval thins to the east, especially from around Well 22 eastward, as shale deposition apparently moved out of the trough and onto the higher Lexington carbonate platform. The section also shows that the electrofacies, in general, become more carbonate rich in an eastward direction until Well 57, at which point the section line moves off the Lexington Platform into the deeper Appalachian Basin (see Fig. 8B).

Statewide Facies Variations and Depositional Influences

The electrofacies determined from well logs and mapped across the state were then combined into similar lithologies to create generalized facies maps: one for a time representing mostly Trenton and Lexington limestone carbonate-platform deposition (Fig. 11A), and a second for a subsequent time of platform drowning during deposition of the Point Pleasant Formation and Utica shale (Fig. 11B) (see Supplemental Information for the full set of maps depicting individual facies percentages).

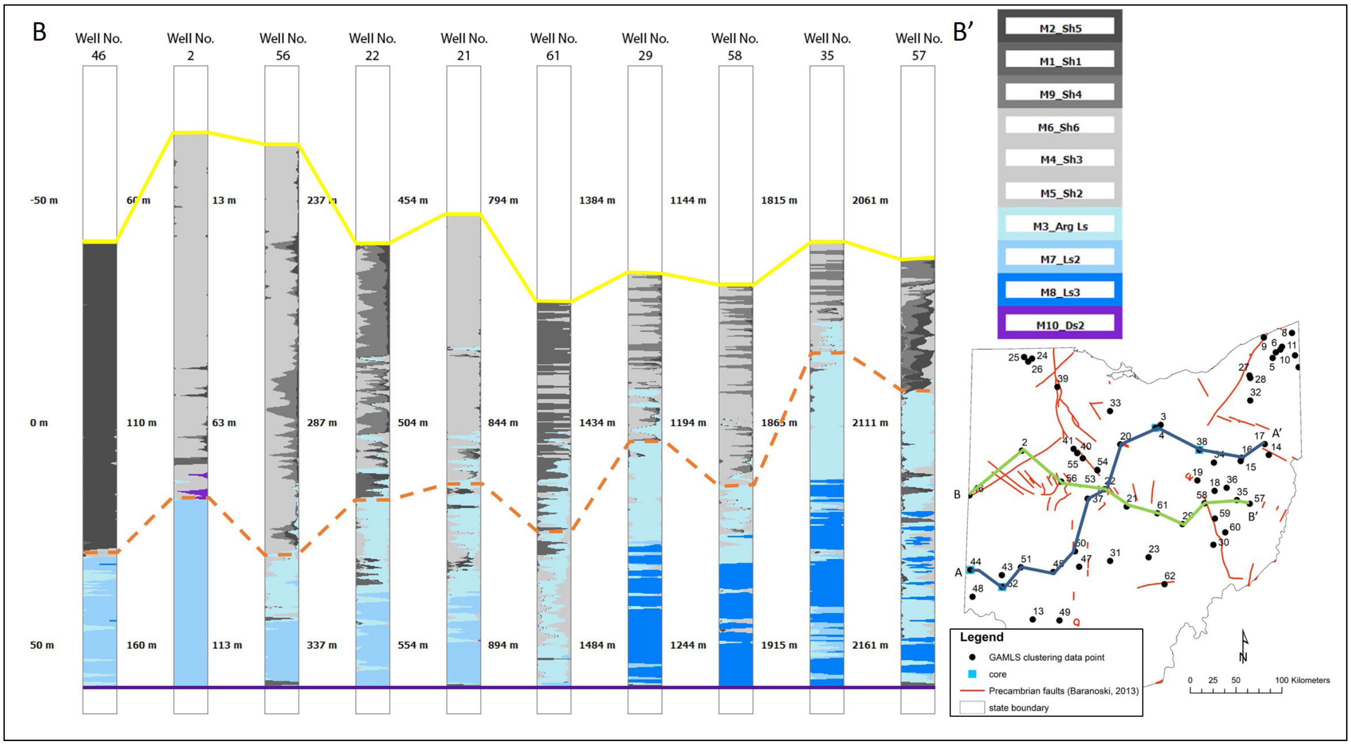

FIGURE 10. Cross-section B-B' trending west to east. The yellow line marks the top of the Point Pleasant and Utica shales; the brown dashed line marks the approximate top of the Trenton and Lexington limestones; and the purple line is the datum, marking the top of the Black River Group. Modes are numbered and color-coded to reflect the same lithofacies interpreted in Table 2. Depths are relative to sea level.

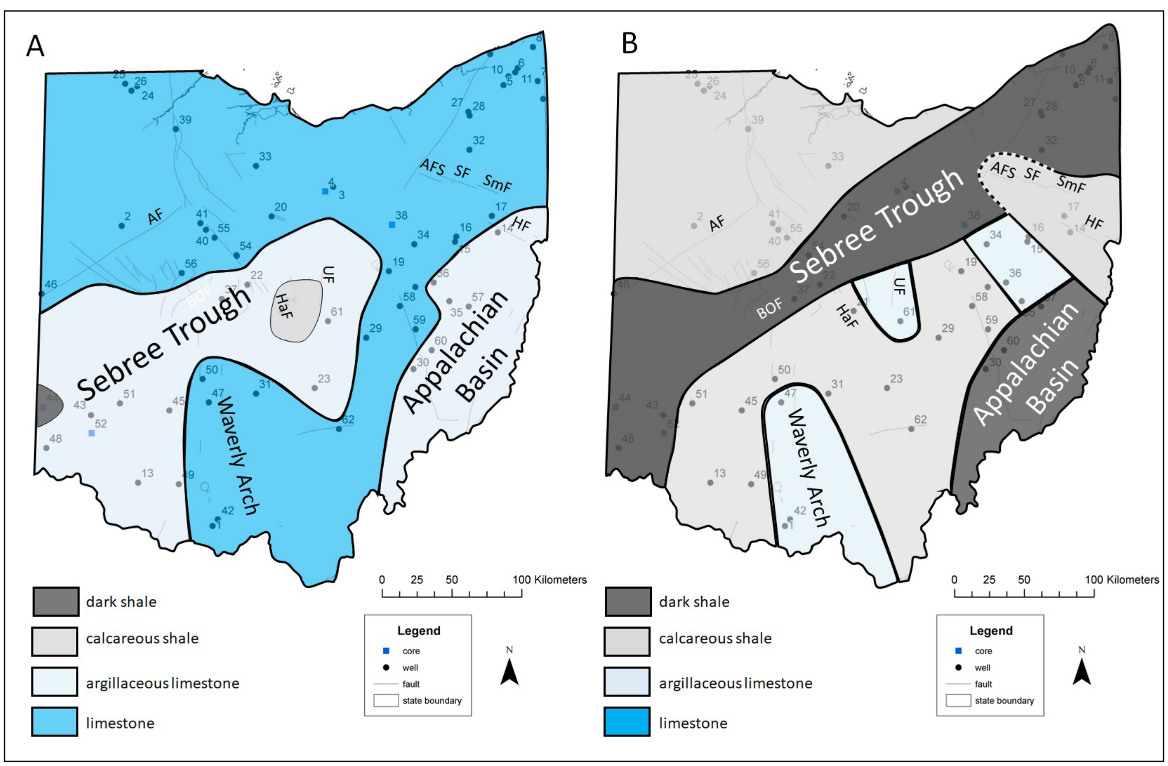

FIGURE 11. Generalized facies distribution across the state using GAMLS facies assignments and core comparison (Table 2) for (A) the Lexington and Trenton limestones and (B) the Point Pleasant Formation and Utica shale. The designated facies at a given location was assigned based upon the facies to which the most beds were assigned. Prominent features that likely influenced facies distribution are labeled. The maps used to create these bulk facies maps are located in the Supplemental Information provided. AF: Auglaize fault; AFS: Akron fault system; BOF: Bellefontaine Outlier faults; HaF: Harlem fault; HF: Highlandtown fault; SF: Suffield fault; SmF: Smith Township fault; UF: Utica Mountain fault. Note: the Akron fault system, Suffield fault, and Smith Township fault are often combined in literature, and also here, as the Akron-Suffield-Smith Township fault system due to their close proximity.

The most conspicuous feature on the generalized shale facies map is a linear zone, approximately 60 to 100 km wide, that trends across the state from the southwest toward the northeast and is dominated by dark, low calcite shales (Fig. 11B). This same area corresponds to the area of thickening of the Point Pleasant and Utica shales (Fig. 8B) and thinning of the Trenton and Lexington limestones (Fig. 8A) that is interpreted to be the northeastward extension of the Sebree Trough (e.g., Kolata et al. 2001; Ettensohn et al. 2002; Ettensohn 2010).

Also apparent on both facies maps is a linear, north-south-trending feature in south-central Ohio (Fig. 11). In this region, the Point Pleasant/Utica shale consists of argillaceous limestones facies (Fig. 11B), which overlie relatively pure limestones of the Trenton and Lexington interval (Fig 11A). This area approximately corresponds to the Waverly Arch (Fig. 3, No. 14), a Precambrian, low-relief, topographic high that has been distinguished through the surficial and subsurface mapping of Precambrian through the Carboniferous rocks (Woodward 1961; Ettensohn 1980; Cable and Beardsley 1984; Ettensohn and Cecil 1992; Dever 1999; Baranoski 2013). During the deposition of these Upper Ordovician strata, uplift of the Waverly Arch did not produce enough relief to significantly influence the overall structure of the present-day basin. Yet, facies mapping (Fig. 11A) and slight thickening of carbonates along the structure (Fig. 8A), indicate it was likely active at the time.

Finally, both the carbonate facies map and the shale facies map locally show places with either increased clay deposition or carbonate deposition, respectively. These localities are typically near known structures within the state, such as the Bellefontaine Outlier faults, Harlem fault, and Utica Mountain fault in central Ohio, or the Akron-Suffield-Smith Township faults in northeastern Ohio (Fig. 11). Like the Waverly Arch, sufficient offset to detect these faults is not present on structure contour maps, nor is well density great enough to determine thinning or thickening on isopach maps. However, facies discrimination via electrofacies analysis is sufficiently detailed to distinguish subtle differences in carbonate or siliciclastic deposition that seem to be coincident with certain structures, thereby suggesting their pre- or synsedimentary influence on deposition.

DISCUSSION

This study of complexly intertonguing Upper Ordovician (Katian; upper Mohawkian–lower Cincinnatian) carbonates and shales demonstrates the utility of electrofacies in discriminating subtle differences in lithology that reflect noticeable changes in structure, thickness, and facies within carbonate formations (Trenton and Lexington limestones) and overlying shale formations (Point Pleasant Formation and Utica shale). Changes on relatively large scales, such as the thinning of carbonates and thickening of the shales across the center of the state, reflect the presence of the Sebree Trough (Figs. 8, 9, and 10). Smaller-scale variations in carbonate and argillaceous content across areas like the Waverly Arch and several smaller fault zones (Fig. 11) are apparently heterogeneities in these formations that suggest structural controls on deposition. While eustasy is known to have influenced deposition at this time (e.g., McLaughlin et al. 2004; Ettensohn 2010), the fact that most variations in lithology are small-scale and associated with structures suggests that eustasy was not a controlling factor. Clearly, however, larger-scale events like the filling of the Sebree Trough and the westward influx of clastic sediments must have had major eustatic components.

The carbonate content of the Utica shale is primarily attributed to storm-bed deposits from a relatively shallow carbonate shelf (<30 m), as indicated by "shell hash" beds throughout the formation. Although the shales probably reflect depths greater than those on the carbonate shelf (e.g., Weiss et al. 1965), sedimentary structures and the presence of algal laminae, certain acritarchs, and alginate in the shales have suggested that accumulation occurred at depths no greater than 50 m (Obermajer et al. 1999; Smith 2013). Minor amounts of calcite (micritic mud) also occur within the shale itself, and quantitative mineral analysis of the shales indicates that the shales exhibit much lower calcite concentrations than the shell hash beds. Overall, the calcareous shale facies and argillaceous limestones facies within the Utica shale are associated with shallower, storm-frequented areas that are interpreted to have been paleobathymetric highs. In contrast, shale facies with little calcite content are attributed to deeper, more protected areas interpreted to have been paleobathymetric lows—sites where little primary carbonate deposition occurred, and where less carbonate material was swept into deeper areas by storms. Localized changes in water depth may be attributable to far-field tectonic influences throughout the state, as further discussed below.

Far-Field Tectonic Controls

Both the Lexington-Trenton and Point Pleasant-Utica intervals in Ohio deepen in the subsurface as they enter the Michigan Basin to the northwest and the Appalachian Basin to the east (Fig. 7), and they thicken in the same directions (Fig. 8). Both trends, at least in part, reflect subsidence, deposition in deepening conditions, and thicker sediment accumulation related to deformational loading in the Taconic orogen to the east (Ettensohn 1991; Howell and van der Pluijm 1999; Ettensohn and Lierman 2015). Along with deformational loading, far-field tectonics (i.e., compressional reactivation of structures at a distance from the orogen) (Klein 1994) will typically reactivate basement structures within and beyond the foreland basin. The most important way to discern such reactivation is by observing abrupt facies changes near the structures (e.g., Ettensohn et al. 2002, 2004; Ettensohn 2010). Similarly, several noticeable, localized facies changes coincide with known faults (i.e., Harlem fault and Utica Mountain fault in central Ohio and the Akron-Suffield-Smith Township fault system in northeast Ohio) (Fig. 11). Although the study area is located far from the locus of deformational loading, the current study suggests that Taconic stresses reactivated basement faults in the region (Fig. 3) on both the Lexington Platform and Sebree Trough during deposition. This created paleobathymetric highs and lows that likely allowed preferential carbonate and siliciclastic deposition, respectively. For example, the Harlem fault in central Ohio appears to have formed part of a topographic low during deposition of the Trenton and Lexington limestones, supporting preferential deposition of fine-grained siliciclastic content (Fig. 11A). On the other hand, the nearby Utica Mountain fault formed part of a bathymetric high during deposition of the shale units (Fig. 11B), supporting the continued deposition of carbonates during Point Pleasant time. The similar reactivation of faults at this time appears to have occurred in other places as well, including the Bellefontaine Outlier faults and the Akron-Suffield-Smith Township fault system (Fig. 11). Higher-resolution structure and isopach mapping of the area could provide more insight into the structural features, their extent, relative motion, and timing of reactivation.

Sebree Trough

Based on the isopach map of Point Pleasant and Utica shale (Fig. 8B), the accumulation of thick dark shales and thin, argillaceous limestones extended from southwest Ohio toward its northeast corner (Fig. 8A). This expanse of shale coincides with the known limits of the Sebree Trough in southwest Ohio, and its extension through northeast Ohio, connecting to the subsiding Appalachian Basin. The upwelling of cold, anoxic, phosphatic-rich waters (originating from further south along the failed Reelfoot Rift) within the Sebree Trough corroded existing limestones (Fig. 5) and largely halted carbonate production within this low. With continued subsidence, continental tilting, and sea-level rise, starvation in the trough was followed by the eventual deposition of fine-grained siliciclastics eroded from the Taconic highlands (Kolata et al. 2001; Ettensohn et al. 2002; Ettensohn 2008, 2010). Based on graptolite and conodont biostratigraphy (Sweet 1979; Mitchell and Bergström 1991; Mitchell et al. 1994; Ettensohn et al. 2002; Ettensohn and Lierman 2015), infilling of the trough in Ohio with dark shales and argillaceous limestones began in early Katian (latest Chatfieldian) time (Fig. 1).

As already noted in this study, the overall trend of carbonate thinning (Figs. 8A, 9, and 10), with a similar trend of thickening in overlying fine-grained clastics (Figs. 8B, 10), extends the trend of the Sebree Trough northeastward into Ohio (Figs. 4, 11). Moreover, the fact that the Sebree Trough in Ohio largely coincides with known structural fabrics of the area, which similarly trend northeast-southwest (Wickstrom 1990; Baranoski 2013; Solis 2015a, 2015b, 2015c, 2016), suggests that the trough was at least in part controlled by basement structures reactivated through growth faulting at depth. For example, the Auglaize fault in western Ohio runs roughly parallel to the northern boundary of shale thickening (Fig. 8B), and the Bellefontaine Outlier fault and several unnamed faults run along the southern boundary of the trough in western Ohio (Figs. 3, 8B, and

11) (e.g., Wickstrom 1990; Hansen 1991; Steck et al. 1997; Baranoski 2013). However, early Katian (early Chatfieldian) carbonate corrosion, sediment starvation, and sea-level rise probably also contributed to the development of a bathymetric low along the trend of the Sebree Trough in Ohio.

Conclusions

1. This current study highlights a relatively new procedure—using a combination of core mineralogy and well log analysis—to map the large-scale, regional distribution of lithofacies interpreted from well-log responses.

2. The Upper Ordovician (lower Katian; upper Chatfieldian-lower Edenian) Lexington-Trenton limestone and Point Pleasant-Utica shale intervals in Ohio were deposited during the major Taconic tectophase of the Taconian Orogeny to the east, during a time of tectonic subsidence, reactivated basement structures, continental tilting, and eustatic sea-level rise. The transition between the Lexington-Trenton limestones and the Point Pleasant-Utica intervals reflects the change from a shallow-water, carbonate-platform to widespread deepening across the Appalachian Basin and adjacent intracratonic areas. This was especially prominent in a linear, SW-NE trending low behind the Lexington Platform called the Sebree Trough.

3. The Upper Ordovician rocks being analyzed reflect a highly heterogeneous, mixed carbonate-siliciclastic system. In the current study, the percentage of calcite and, in the absence of calcite, siliciclastics were used to map the distribution of 10 Upper Ordovician lithofacies in the Lexington and Trenton limestones and in the Point Pleasant and Utica shales.

4. By comparing the calcite content from 4 reference cores with corresponding geophysical logs from the same wells, patterns of well-log responses were compared with corresponding calcite contents and statistically grouped into clusters with similarities. Using a multivariate statistical program (GAMLS), clusters with similar log responses were used to identify 10 modes, or electrofacies. Then, by examining well-log responses from many other wells in the area, the statistical program made electrofacies assignments by comparing well-log responses from the other wells with well-log responses from the reference cores preset into the program. Electrofacies responses were color-coded, mapped in wells at 0.6 m (2 ft) resolution, and used to make section lines and isopach maps of similar electrofacies.

5. The 3 calcite-rich electrofacies (>60% $CaCO_3$) were combined as parts of the Lexington and Trenton limestones; an isopach map of the unit showed a prominent NE-SW thinning trend across central Ohio that was previously interpreted to represent the trend of the Sebree Trough. A dolomite-rich electrofacies rarely occurred in the cores and was included with the Lexington and Trenton limestones.

6. Six calcite-poor (<40% $CaCO_3$), siliciclastic-rich electrofacies were combined as parts of the Point Pleasant and Utica shales; an isopach map of the unit showed a prominent NE-SW thickening trend across central Ohio that was previously interpreted to represent the trend of the Sebree Trough. The same isopach map shows a roughly rectilinear area of thinned shales in southern Ohio that corresponds to the northeastern edge of the Lexington Platform.

7. Isopach maps of both the Lexington-Trenton and Point Pleasant-Utica intervals in Ohio show expected thickening trends into the Michigan Basin to the northwest and into the Appalachian Basin to the northeast.

8. The isopach maps and cross sections confirm the continuation of the Sebree Trough across central Ohio, with trends that parallel existing and projected basement structures. This suggests that the Sebree Trough in Ohio was a bathymetric low, which at least in part reflected the reactivation of basement structures by far-field Taconic stresses. Periodic growth faulting on these structures apparently generated accommodation space for the increased thicknesses of Point Pleasant and Utica shales and the depths necessary to support upwelling and preservation of organic matter. Other factors contributing to trough formation probably included the thinning of underlying carbonates by erosion and corrosion, early sediment starvation behind the Lexington Platform, and major sea-level rise at the time.

9. Localized thickening and thinning trends of both carbonate and shale intervals near structures, like the thinning carbonates atop the Waverly Arch, suggest that reactivation of these structures also influenced deposition.

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SUPPLEMENTAL MATERIAL

Supplemental material to accompany this report is available at: http://hdl.handle.net/1811/102379