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Shallow-water onlap model for the deposition of Devonian black shales in New York, USA

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ABSTRACT

Field relations, regional correlations, and sedimentological observations show that the organic-rich Middle to Upper Devonian Marcellus to Dunkirk black shales (eastern United States), commonly interpreted to have been deposited in deep, quiet, and permanently anoxic basins, were instead deposited in relatively shallow settings that at times had moving currents and oxygenated bottom water that supported benthic life. Traditionally interpreted to downlap onto a deep basin floor, regional wireline-log correlations linked to outcrop studies show that these black shales instead onlap unconformities on a tectonic high to the west. The basic elements of the proposed model are present in a range of other occurrences around the world, and this shallow onlap model should be considered as a viable hypothesis for the origin of any black shale succession.

INTRODUCTION

The origin of the Middle and Upper Devonian organic-rich black shales of the Appalachian Basin, eastern United States, has been the subject of lively debate for more than a century. The preferred interpretation in recent decades has been that the organic-rich shales were deposited in a deep, quiet, anoxic basin. This interpretation is based on geochemical attributes believed to be indicative of deposition in an anoxic water column, and the assumption that such fine-grained, organic-rich sediments could only accumulate in deep, low-energy settings like the modern Black Sea.

The observation that many black shales in the rock record directly overlie unconformities led some early workers to interpret a shallow-marine origin (e.g., Grabau and O'Connell, 1917). Conant and Swanson (1961) observed that the organic-rich Devonian Chattanooga Shale of the southern Appalachian Basin directly overlies a major unconformity and was time-equivalent to nearby areas of exposed land, which led to the interpretation that the shales could not have been deposited in any more than 30 m of water. Nonetheless, in many subsequent studies, deep-water interpretations were favored. Water-depth estimates for the deposition of black shales in the Devonian Appalachian Basin have ranged from 150 m (Kohl et al., 2014) to 200 m (House and Kirchgasser, 1993) to 300 m (Baird and Brett, 1991) and even 900 m (Lundegard et al., 1985).

Regional correlations of the black shales in New York show very similar field relations to those found by Conant and Swanson (1961). Close examination of these black shales reveals a number of features that indicate reworking and bedload sediment transport by waves and currents consistent with a shallow-marine interpretation. The presence of fossils and bioturbation within the black shales (McCollum, 1988; Wilson and Schieber, 2015) show that the water column could not have been permanently anoxic. The objectives of this paper are (1) to show that these black shales onlap unconformities developed on a tectonic high to the west, and (2) to present a model of shallow-marine deposition for the Devonian black shales of the northern Appalachian Basin.

OBSERVATIONS

The study area is in the northern Appalachian Basin in central and western New York State (Fig. 1A), which was bounded to the east by the active Acadian orogenic front and to the northwest by the Findlay-Algonquin arch during the Middle and Late Devonian. Thrust-loading to the east led to subsidence along the thrust front to the east and uplift on the Findlay-Algonquin and Cincinnati arches to the west. This produced a major decrease in stratal thickness from east to west and the development of unconformities on uplifted tectonic highs (Ettensohn, 1994). The Devonian Catskill Delta complex is composed of the sediments sourced from the uplifted Acadian Mountains which include nonmarine sediments and marine sandstones, siltstones, and organic-poor gray shales to the east and time-equivalent organic-rich black shales and limestones farther to the west (Fig. 1B). There is a vast array of names assigned to these units, but to simplify this for this brief paper, the focus is on the seven prominent organic-rich black shales (Fig. 1B). From oldest to youngest these are the Marcellus, Levana, Geneseo, Middlesex, Rhinestreet, Pipe Creek, and Dunkirk Shales. The Dunkirk Shale is equivalent to the basal part of the Ohio and Chattanooga black shales, which overlie and onlap unconformities farther to the west. Total organic carbon (TOC) measurements and regional correlations show that each of these black shales displays a consistent pattern: they thin, become more organic-rich, and onlap and pinch out on unconformities developed on the tectonic highs to the west (Smith, 2013). These well-documented unconformities are recognized by sharp-based shale packages, missing section, thin lag deposits, and low-angle truncations (Schieber, 1998; Over, 2007). These sharp discontinuities can also be recognized in the subsurface using wireline logs (Smith, 2013) where there are sharp contacts and missing section. For the sake of brevity, we focus the discussion on the characteristics of the Geneseo Shale where the onlap is very clear (Fig. 2), noting that the other black shales mentioned

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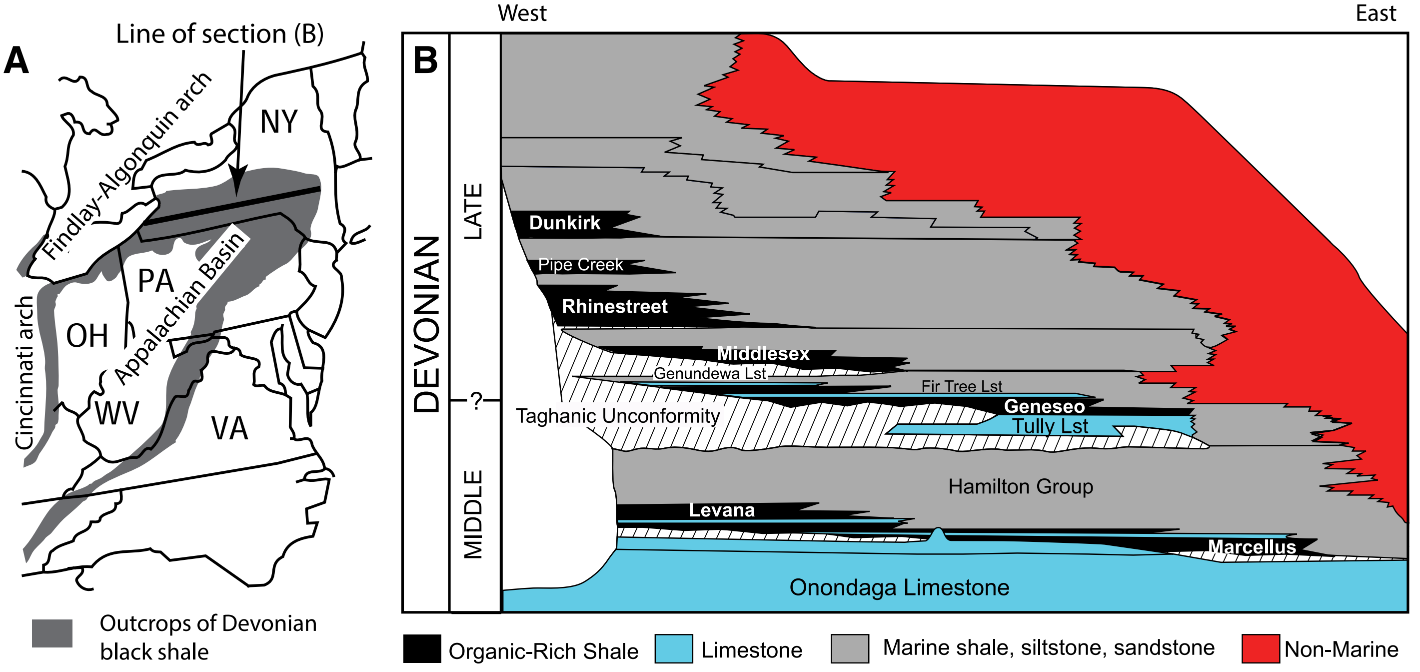

Figure 1. A: Map of Appalachian Basin, eastern United States. Study is focused on New York (NY). PA—Pennsylvania; OH—Ohio; WV—West Virginia; VA—Virginia. B: Middle to Upper Devonian stratigraphy for New York State. Basal ages of each successive black shale interval become progressively younger toward west as they onlap and pinch out (modified from Rogers et al., 1990). Lst—Limestone.

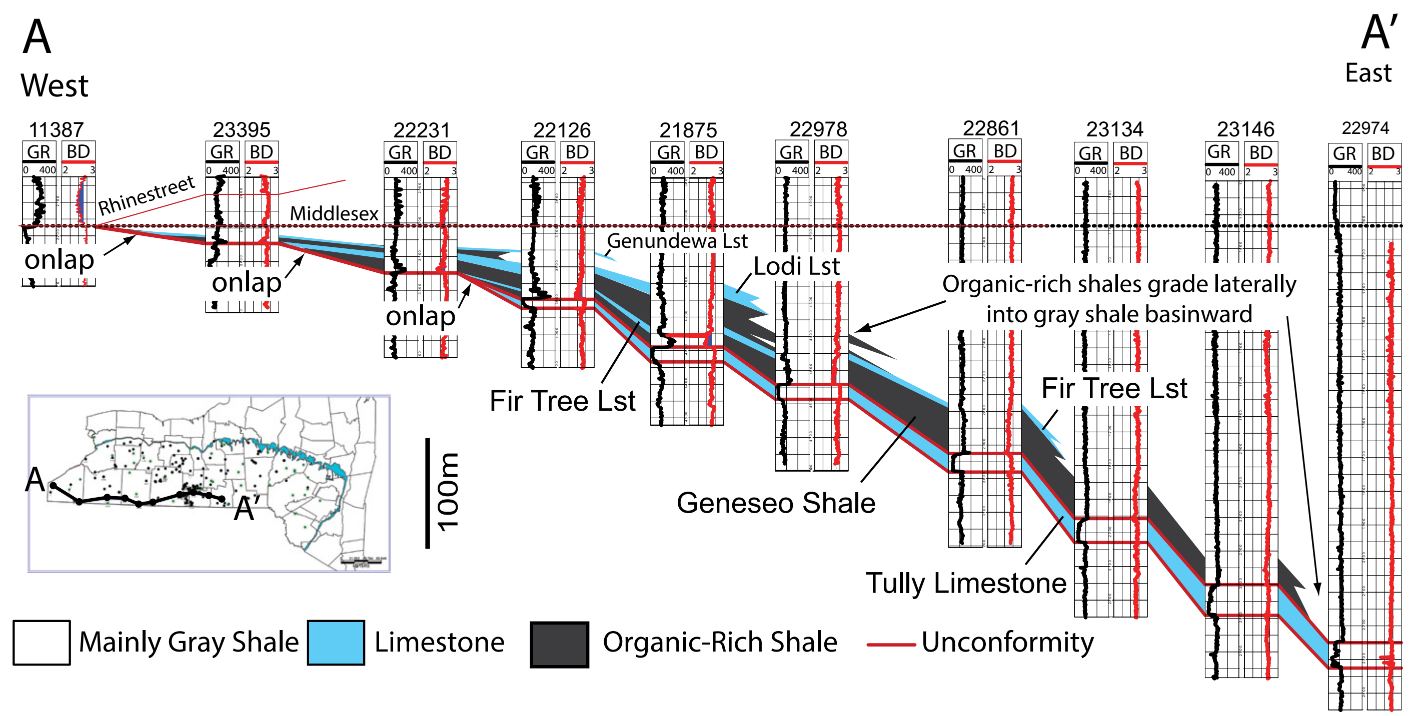

Figure 2. Wireline-log cross section of onlapping Tully Limestone to Middlesex Shale interval (Fig. 1) that extends from western to central New York (line A-A′; see inset). Datum for cross section is base of Middlesex black shale and interpreted equivalents to east. Logs are gamma ray (GR [API units]) and bulk density (BD [g/cc]). Cross section shows unconformities in red: one below Tully Limestone, one above it, and one at base of Middlesex Shale. Lst—Limestone.

above show a comparable pattern (see Fig. DR1 in the GSA Data Repository[1]).

Wireline logs provide continuous records of the stratigraphy rarely found in outcrop and are here used to interpret lithology and build a high-resolution stratigraphic framework. Figure DR2 shows the link between measured TOC and $CaCO_3$ content and wireline-log response. In the study interval, limestones have the lowest gamma-ray and highest bulk-density values, organic-rich shales have higher gamma-ray and low bulk-density values (due to the low density of organic matter and associated porosity), and organic-poor gray shales have intermediate density and gamma-ray values (Smith, 2013). These relationships are interpreted to occur throughout the study interval and are confirmed by outcrop observations and studies of well cuttings (Smith, 2013).

Figure 1B shows an erosional unconformity called the Taghanic unconformity (Johnson, 1970), which is developed to the west, that is overlain and onlapped by the Tully Limestone, Geneseo black shale, and overlying units. There is significant erosional relief on the unconformity (Baird and Brett, 1991), and there are two conodont zones missing in the far western part of the state in this interval (Huddle, 1981). The Tully is a marine limestone with corals and brachiopods that grades to sandstone to the east and pinches out to the west where it onlaps the unconformity. The overlying Geneseo Shale is subdivided into lower and upper members by the intervening Fir Tree Limestone. The lower Geneseo consists of gray shale in the east that becomes progressively more organic rich to the west where it thins, onlaps the unconformity, and pinches out (Fig. 2). The overlying Fir Tree Limestone grades laterally from siliciclastics in the east to a progressively cleaner limestone to the west until it too thins and pinches out. The overlying upper Geneseo also becomes progressively more organic rich to the west until it thins, onlaps, and pinches out. The overlying Lodi Limestone, Penn Yan Shale, and Genundewa Limestone all thin and onlap the unconformity to the west. Above that, the Middlesex Shale also becomes more organic rich to the west until it too onlaps and pinches out on an unconformity (Fig. DR1). The underlying Marcellus Shale also shows a similar pattern of increasing TOC, thinning, and onlap onto an unconformity on top of the Onondaga Limestone (Fig. DR1). All of strata below the Dunkirk onlap and pinch out on the Cincinnati arch farther to the west in Ohio.

DISCUSSION AND PROPOSED MODEL

Field Relations

Any depositional model for this interval must account for the preferential development of erosional unconformities and black shale on tectonic highs such as the Findlay-Algonquin and Cincinnati arches and the presence of what was likely exposed land nearby during deposition. This was the main reason that Conant and Swanson (1961) interpreted the Chattanooga black shale to have been deposited in <30 m of water, and the same reasoning applies here. It has been suggested that these unconformities are entirely submarine in origin, formed during long periods (up to millions of years) of nondeposition and submarine erosion to the west while deposition continued to the east (Baird and Brett, 1991). While there may have been a relatively brief period of nondeposition during the initial flooding for each shale, that interpretation is difficult to support given the preferential development of the black shales and unconformities on what were tectonic highs during deposition and throughout much of the Paleozoic.

Sedimentological Aspects

Sedimentological studies of these black shales document a range of sedimentary features such as scour surfaces, reworked lag deposits, bed amalgamation, current, wave, and combined-flow ripple cross lamination, and both normal and inverse grading (Wilson and Schieber, 2014; Lash, 2016). Collectively, these features suggest a dynamic, storm-influenced setting in which bottom currents carried fine-grained clastics in bedload westward rather than a still, quiet basin.

Slumps, submarine-fan complexes, mass-transport deposits, and derivation from canyon-fed point sources typically dominate deep-water environments along a clastic shelf (e.g., Posamentier and Kolla, 2003). If the northern Appalachian Basin was truly 150 m deep, at least some of these features, along with clinoforms visible on seismic data, should be present, but none have been reported. The lack of these features and the presence of the aforementioned sedimentary structures suggest instead a broad deltaic system and a shallow, storm-dominated clastic depositional model (*sensu* Mutti et al., 2003).

Paleobiological Aspects

In the Middle and Upper Devonian black shales of the Appalachian Basin, brachiopods, ostracods, agglutinated benthic foraminifera (McCollum, 1988; Schieber, 2009), benthic fecal pellets (Wilson and Schieber, 2015), cryptobioturbation caused by meiofauna (Schieber, 2003; Pemberton et al., 2008), and in some cases even corals occur within the most organic-rich intervals (Baird et al., 1999). These occurrences suggest that, although seasonal anoxia is plausible, there were extended periods of at least dysoxic conditions.

Geochemical Aspects

Water-column anoxia is not necessary for deposition and preservation of organic-rich shales (Bohacs et al., 2005). Geochemistry-based studies to assess redox conditions for the depositional setting of these shales (Sageman et al., 2003;

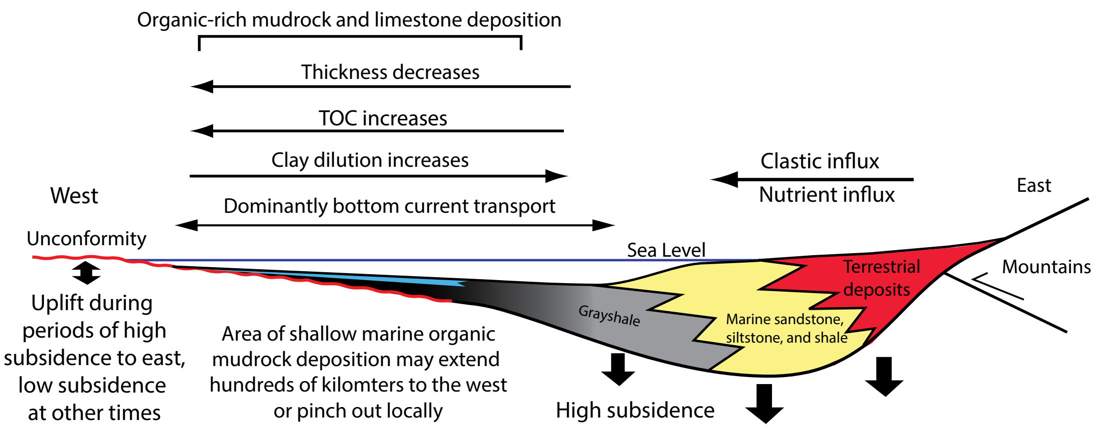

Figure 3. Conceptual depositional model for black shale deposition in the Appalachian Basin and adjacent areas. Color change from gray to black indicates increase in total organic carbon (TOC) to the west. Limestone (blue) only forms on the western side of the basin.

[1]GSA Data Repository item 2019078, Figures DR1 (log cross section of Middle and Upper Devonian strata in New York State), and DR2 (logs and core description from Beaver Meadows #1 well, Chenango County, New York State), is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

Formolo and Lyons, 2007) presumed that enrichment of some redox-sensitive trace elements was indicative of water-column anoxia, comparable to conditions in the modern Black Sea (Algeo and Rowe, 2012). Studies of modern environments have shown, however, that sedimentary enrichment of redox-sensitive trace elements does not require water-column anoxia, and instead may occur where oxygen is present in bottom waters, provided the redox boundary is close to the sediment-water interface (Elbaz-Poulichet et al., 2005). Under those conditions, molybdates, for example, can diffuse into the porous muddy sediment and be sequestered and enriched in pyrite-forming, reducing pore waters (Vorlicek et al., 2004). The latter process provides a mechanism for enrichment of redox-sensitive trace elements that is consistent with sedimentologic observations and stratigraphic studies and can occur in shallow-marine conditions.

Based on the above considerations, a model for the Middle and Upper Devonian organic-rich shales of the Appalachian Basin is proposed in Figure 3. Organic-rich shale deposition was largely confined to the western, cratonward side of the basin away from the clastic source. The thickest part of the basin fill is to the east and composed of marine sandstone, siltstone, and gray, organic-poor shale. The increase in TOC to the west of the basin axis is largely a function of decreasing dilution by siliciclastic material sourced from the east. The black shales and associated limestones are likely transgressive deposits up to the zone of maximum TOC, and then regressive above that as TOC decreases and organic-rich shales grade upward into limestone or gray shale. Limestone deposition is also largely confined to the western side of the basin, away from the clastic source. Water depths in the area of organic-rich shale deposition were probably on the order of a few meters to a few tens of meters and shallowed to the west where TOC is higher. There was likely exposed land on nearby tectonic highs farther to the west during deposition (Fig. 3; Conant and Swanson, 1961). Land-plant fragments are abundant in these black shales, and while they may have been sourced from the east, it is possible that some of them were sourced from the high to the west (Conant and Swanson, 1961). Seasonal anoxia driven by algal blooms may have contributed to the development of the black shales, but there were also extended periods when bottom waters could support life and the seafloor was colonized by benthic organisms. The black shales were likely reworked by storms, which may have eroded some of the accumulating organic-rich sediments, but over time, enough were preserved to produce an organic-rich shale deposit.

Process sedimentology and paleobiology support the basic functionality of the proposed model, but it is the physical context provided by our detailed stratigraphic reconstruction (Fig. 2; Fig. DR1) that provides powerful validation for a "shallow-water onlap" over a "deep-water downlap" model (Fig. 4). Figure 4 shows two cross sections of the same stratigraphy, one using a datum below the interval of interest (Fig. 4A) and one using a datum above (Fig. 4B). The datum for the cross section in Figure 4A (modified from House and Kirchgasser, 1993) is the base of the Tully Limestone and interpreted equivalents to the east and west. This choice of datum below the shales of interest creates the illusion that the shales are downlapping and amalgamating in a deep basin, even though the observed stratigraphy and sedimentological features contradict this notion. Figure 4B, with the datum above the shales of interest, more accurately captures the syndepositional differential subsidence, the development of unconformities, and deposition on the tectonic high and the onlapping nature of the stratigraphy. Greater accuracy can be achieved through construction of individual cross sections for each black shale and associated facies with the datum chosen just above the interval of interest (Fig. 2).

The proposed shallow-water onlap model should be considered as a viable hypothesis for the study and interpretation of other organic-rich shale successions. There are many other black shales in North America and around the world that were likely deposited in similar conditions, but there are also some that were clearly deposited in deeper-marine settings. A shallow-marine origin is likely when black shales onlap and overlie unconformities and are preserved on tectonic highs. Shales deposited in deeper-marine conditions are found at the base of clinoforms visible on seismic profiles and should have associated deepwater facies such as slumps, submarine fans, and other gravity-driven deposits.

"*Black shales…should not be assigned to any general condition but each black shale should receive interpretation on the basis of the characteristics of that black shale formation*"—Twenhofel (1939, p. 1197).

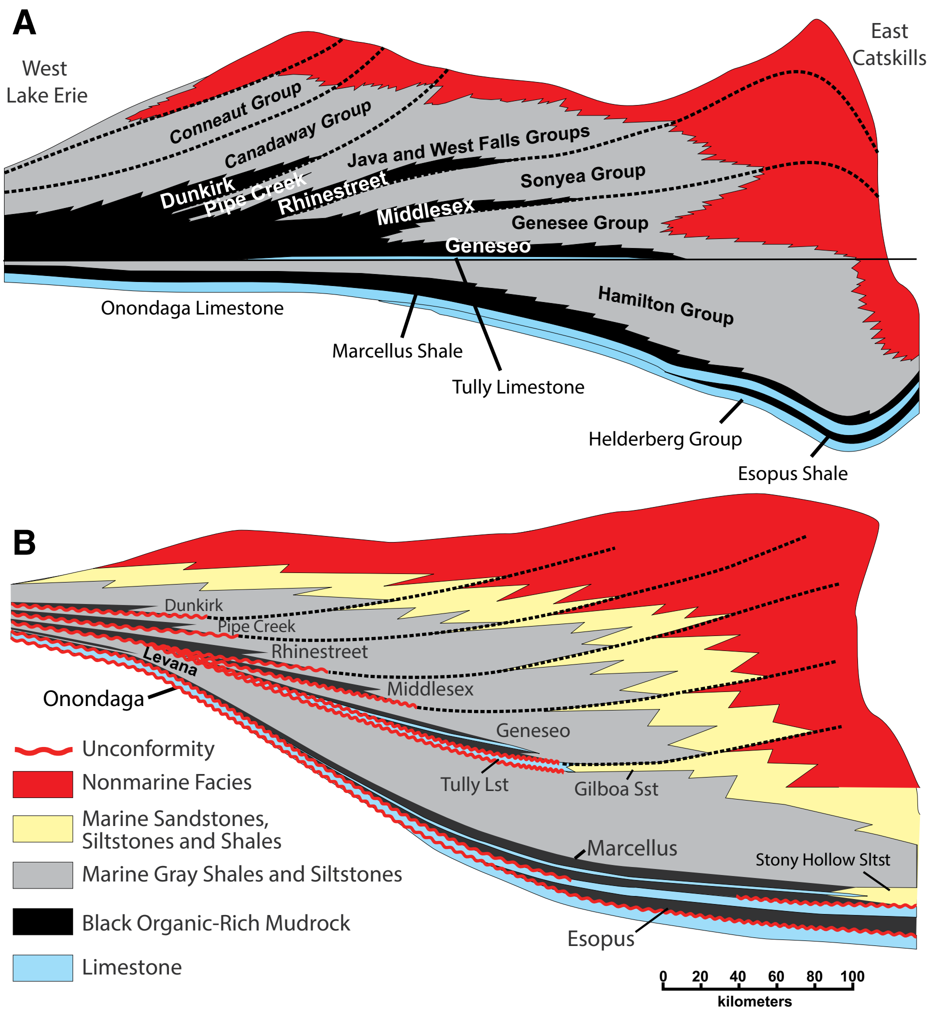

Figure 4. A: Interpretive cross section redrawn from House and Kirchgasser (1993) of Middle and Upper Devonian stratigraphy of central and western New York that shows black shales downlapping and amalgamating in deep basin. B: Interpretive cross section of same interval using model presented in this paper, showing black shales onlapping unconformities to west. Lst—Limestone; Sst—Sandstone; Sltst—Siltstone.

CONCLUSIONS

- Devonian black shales of the Appalachian Basin were deposited in relatively shallow-water conditions that, at least at times, had moving currents and supported benthic life.
- The shallow-water model is consistent with the long-established observation that marine black shales overlie and onlap unconformities on tectonic highs to the west.
- The proposed shallow-water onlap model should be considered as a viable hypothesis for the study and interpretation of similar organic-rich shales around the world.

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