

# Evidence for Possible Late Paleozoic Alleghenian Deformation Structures in the Devonian Rocks of Erie County, Ohio, USA

MOHAMMAD D. FAKHARI<sup>1</sup>, D. MARK JONES, and MARK T. BARANOSKI (retired), Division of Geological Survey, Ohio Department of Natural Resources, Columbus, OH, USA.

**ABSTRACT.** Partially exposed bedrock beneath Pleistocene glacial till in Erie County (north-central Ohio) displays unusual structural deformation in the Devonian Berea Sandstone, Bedford Shale, and Ohio Shale. These folded and faulted units are exposed in creeks as anticlines and synclines. Past studies of this area proposed Pleistocene ice movement and soft-sediment deformation during the Late Paleozoic as the deformation mechanisms, but these hypotheses cannot explain the extent of layer displacement or the contradiction between the southwest travel direction of the ice sheet and the structural sense of motion on the folded units. A new interpretation using field data and constructing geologic profiles explains the development of these structures. This study investigated 17 anticlines that trend in different directions. Four of these anticlines are tightly folded with steep or overturned flanks and thrust-faulted Ohio Shale in their cores. Structural analysis of these folds shows that the incompetent shaly units of the Plum Brook–Ohio–Bedford and competent Berea Sandstone were folded above the Delaware–Niagara carbonates as a result of the compressional stress during the Late Paleozoic. Development of these tight or overturned folds, and change in trend of the anticlines, is caused by unusual stratigraphic thickness variations in the Berea and Bedford units. Preserved and undeformed fine sedimentary structures, and sharply faulted beds, in the Berea and Bedford indicate that soft-sediment deformation was not the cause of the regional structural deformation. Finally, the absence of physical features of glacially deformed bedrock demonstrates that Pleistocene glacial ice shove was not the cause of deformed bedrock units in the study area.

Publication Date: May 2022

<https://doi.org/10.18061/ojs.v122i2.8325>

OHIO J SCI 122(2):15-34

## INTRODUCTION

Unusual geologic structures near Chappel Creek in north-central Ohio have drawn the attention of geologists for many decades (Fig. 1). Unlike the horizontal to sub-horizontal sedimentary layers of most exposed bedrock in Ohio, formations in Chappel Creek are intensely folded, and in one case, overturned. At this location the Devonian Berea Sandstone strikes N-120°-E and is overturned 50° to 60° toward the southwest. Inverted ripple marks prove that structural overturning occurred. Upstream and downstream from these overturned beds, Berea Sandstone, Bedford Shale, and Ohio Shale layers are exposed on flanks of several small-scale folds. A smaller set of overturned beds and low-relief folds are also found in the glen of Old Woman Creek.

Geologists investigating Berea Sandstone have studied the region since 1874, including Newberry (1874), Read (1878), Gilbert (1892, 1899) and

Prosser (1912). All noted a geometric deformation—in the form of small-scale folds—of the Devonian strata of the Chagrin, Cleveland, and Bedford shales and Berea Sandstone. These authors concluded that this deformation reflects shallow surficial structure caused by Pleistocene ice movement and post-glacial rebound, or by lateral stresses of unknown cause.

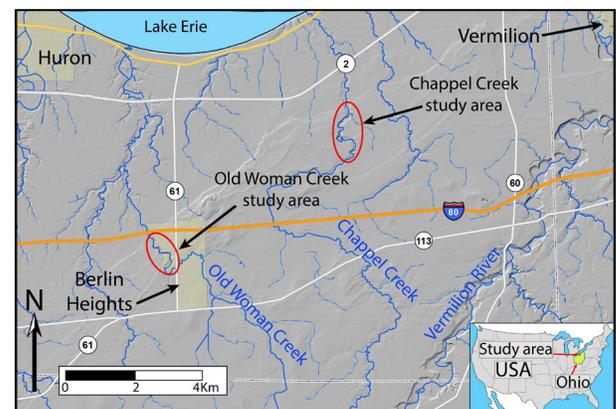


FIGURE 1. Location map of the study area. Chappel Creek and Old Woman Creek are in north-central Ohio, south of Lake Erie.

<sup>1</sup> Address correspondence to Mohammad Fakhari, Division of Geological Survey, Ohio Department of Natural Resources, 2045 Morse Road Building B-2, Columbus, OH 43229, USA. Email: [Mohammad.Fakhari@dnr.ohio.gov](mailto:Mohammad.Fakhari@dnr.ohio.gov)



Van Horn (1910) suggested pressure and volume increases during the alteration of iron sulfide to iron sulfate in the Chagrin Shale as the cause of deformation. Cushing et al. (1931) proposed that the folds formed during deposition, as semi-lithified sandstone layers slid on the soft, underlying, muddy shales, specifically in the vicinity of large channels. Wenberg (1938) described Devonian formations in Lorain County as having shallow folds, striking in different directions. He stated that these folds originated by ice movement or shortening by an unknown cause. Regionally, thrust faults and small-scale folds are reported along the southern shorelines of Lake Erie and Lake Ontario (Gilbert 1899; Hartley 1962; Jones 2000). Phillipson (2005) studied “Effects of Late Paleozoic Foreland Deformation on Underground Coal Mine Ground Instability, Illinois and Appalachian Basins.” Elizalde et al. (2016) authored “Thrust Fault Nucleation due to Heterogeneous Bedding Plane Slip: Evidence from an Ohio Coal Mine” and explained thrust faulting and folding in a coal mine in northeast Ohio.

Overtured Berea Sandstone at Chappel Creek was studied by Herdendorf (1963, 1966, 1973, 1977); Murphy (1974), and Wolfgang and Gardner (1977). During geological investigations for a proposed nuclear power plant, researchers—using drill cores, geophysical lines, and geologic profiles—reported that horizontal Berea layers were pushed down to the southwest and overturned at the creek level by Pleistocene ice movement (Wolfgang and Gardner 1977).

Pashin and Etensohn (1995) explained that the deformed beds at Chappel Creek and Old Woman Creek were due to soft-sediment deformation processes, similar to Holocene mud diapirism, thrust faults, and overturned beds within the Mississippi Delta (Morgan 1961; Morgan et al. 1968). Jones (2000) concurred with the soft-sediment deformation hypothesis and stated that the sense of rotation on Berea layers at Chappel Creek ruled out glacial deformation. Following the hypothesis of Pashin and Etensohn (1995), Baird (2017) reviewed Old Woman Creek outcrops and structures. He suggested multiple overthrusts with many repetitions of Cleveland Shale and pervasively mobilized fluidized gray Bedford with diapirs and abundant ball-and-pillow structures controlled by sediment loading.

For the current study, new field data were collected to determine how and when deformation of the layers took place and which units are deformed. The study addresses the reasons for the different trends of deformation, and how deeply deformation extends into the subsurface. Finally, this study presents a new hypothesis to explain the deformation and fold trends.

## METHODS AND MATERIALS

Researchers visited outcrops at Chappel Creek and Old Woman Creek and collected geologic data to prepare precise geologic maps and cross sections. Most of the region is covered by glacial till or glacial lake deposits; however, bedrock is exposed along the creeks, where there is generally little scree or alluvial deposits except at point bars and areas of slow-moving water.

The geologic units (Fig. 2) were identified in the field and also in rare drilled cores. Ohio Geological Survey (OGS) cores #2739 and #734 were used, based on the “Generalized Column of Bedrock Units in Ohio” (Hull 1990), to prepare geologic maps and cross sections. In addition, authors identified

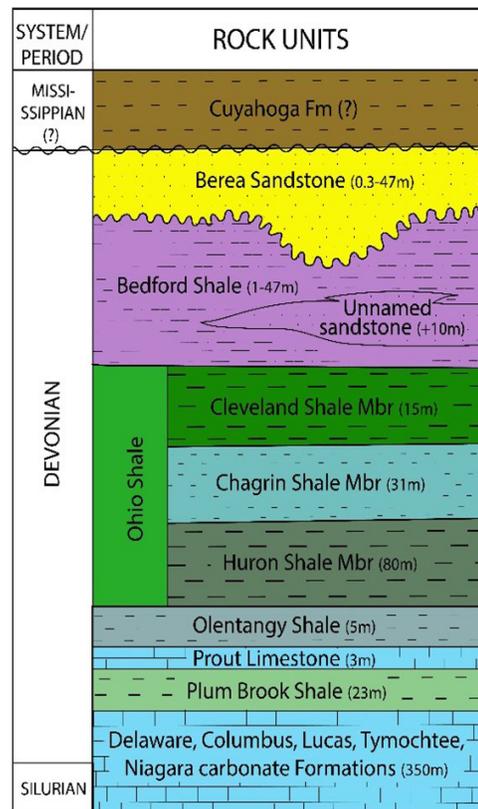


FIGURE 2. Stratigraphy of the study area (not to scale) based on Hull (1990) and Schumacher et al. (2013). Formation thicknesses are collected from well OHEE-2 (OGS core #2739) located 1.6 km south of Chappel Creek, and OGS core #734 from a well in the city of Huron (Baird 2013; Currie et al. 2014).

formation contacts, faults, and fold axes and recorded their locations using GPS. Geometric and structural data, including dip and strike of the layers, faults, and fold axes, were collected from limited outcrops. ArcMap 10.3.1 and Adobe Illustrator® software were used to create geologic maps, cross sections, and schematic drawings. Fault propagation fold geometry was used to create structural geologic sections and to estimate approximate detachment depth under anticlines.

### Stratigraphy

Glacial till covers most of the study area. Structurally deformed bedrock is exposed only in the creeks, deep roadcuts, and former Berea Sandstone quarries. Exposed units are the Berea Sandstone, the Bedford Shale, and the Ohio Shale (Cleveland Member and Chagrin Member) and possibly the Cuyahoga Formation under overturned Berea (Fig. 2). Stratigraphic information on the subsurface units was collected from well OHEE-2 (OGS core #2739) located 1.6 km south of Chappel Creek, and OGS core #734 from a well in the city of Huron (Baird 2013; Currie et al. 2014). These subsurface units include the Huron Shale, the Olentangy Shale, the Plum Brook Shale, and the Delaware, Columbus, Lucas, Tymochtee, and Niagara carbonate units (Fig. 2).

**Cuyahoga Formation (?).** The Mississippian Cuyahoga Formation is the youngest bedrock unit in the study area. It is an incompetent shaly unit and expected to be in the eastern bluff of Chappel Creek under the overturned Berea Sandstone.

**Berea Sandstone.** Below the Cuyahoga Formation, the Devonian Berea Sandstone is a fine- to medium-grained, light-brown, thin- to thick-bedded sandstone (Figs. 3, 4, and 10). Its thin-bedded lower layers preserve typical oscillation ripple marks (Fig. 3B). A zone of soft-sediment deformation is present within the basal part of the unit (Figs. 4A and 4B). The Berea is the most competent rock unit exposed in the study area.

**Bedford Shale.** The Bedford Shale is an interbedded shale, siltstone, and sandstone unit under the Berea Sandstone. It is composed of gray shale (“gray Bedford”) alternating with thin clayey siltstone beds at the base, and a red shale (“red Bedford”) composed of thin-bedded, purple, micaceous silty shales alternating with thin siltstone and sandstone beds. A thick, unnamed sandstone

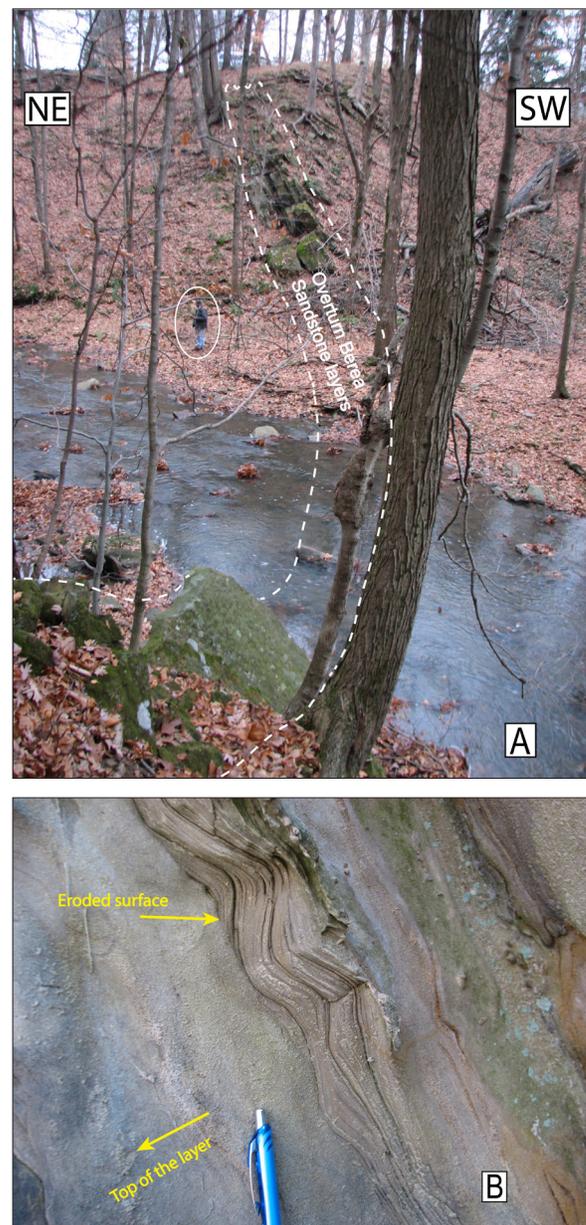


FIGURE 3. (A) Overturned Berea Sandstone in Chappel Creek, exposed at both banks and continuing under the creek bed (41° 21.198'N, 82° 25.360'W); 1.80 m tall person for scale. (B) Truncated ripple marks indicate beds are overturned.

layer with ripple marks (Fig. 5A) and remarkable soft-sediment deformation structures (Fig. 5B) is present in Old Woman Creek within the Bedford. The shaly Bedford is highly incompetent with significant tectonic deformation. The Bedford thickness variability resulted primarily due to erosion prior to Berea deposition and later tectonic deformation. In some localities almost all the formation was removed by erosion, with Berea deposited near the top of the Cleveland Member of the Ohio Shale. See Baird (2013) and Blood et al. (2019) for Bedford and Berea paleogeography and paleoenvironment.

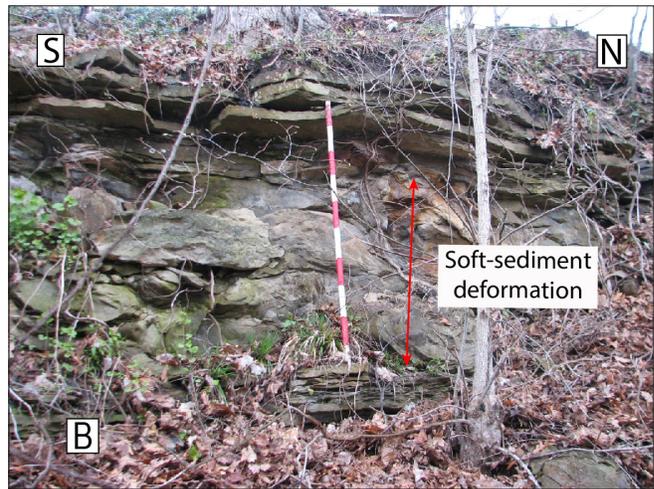


FIGURE 4. Soft-sediment deformation within Berea layers. (A) Chappel Creek east of Joppa Road bridge. (B) Furnace Road roadcut. Scale divisions are 15 cm. (See Fig. 7B.)

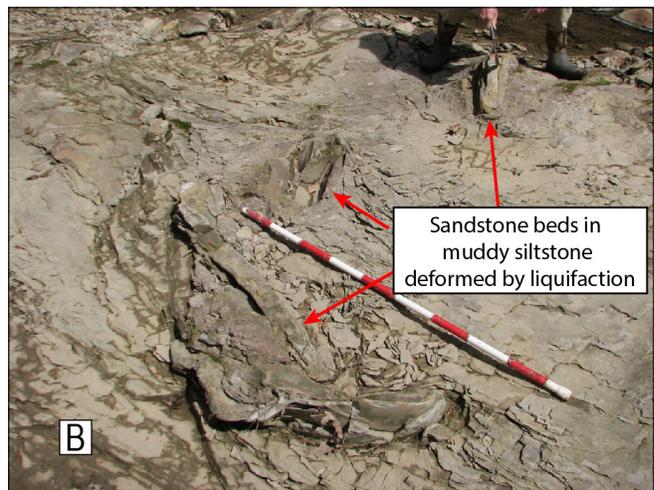


FIGURE 5. (A) Thick, unnamed sandstone layer with symmetric ripple marks ( $41^{\circ} 19.407'N$ ,  $82^{\circ} 30.099'W$ ). (B) Thick, lithified muddy siltstone with soft-sediment deformation ( $41^{\circ} 19.424'N$ ,  $82^{\circ} 30.140'W$ ) above undisturbed unnamed sandstone layer (5A) within Bedford. Scale divisions are 15 cm.

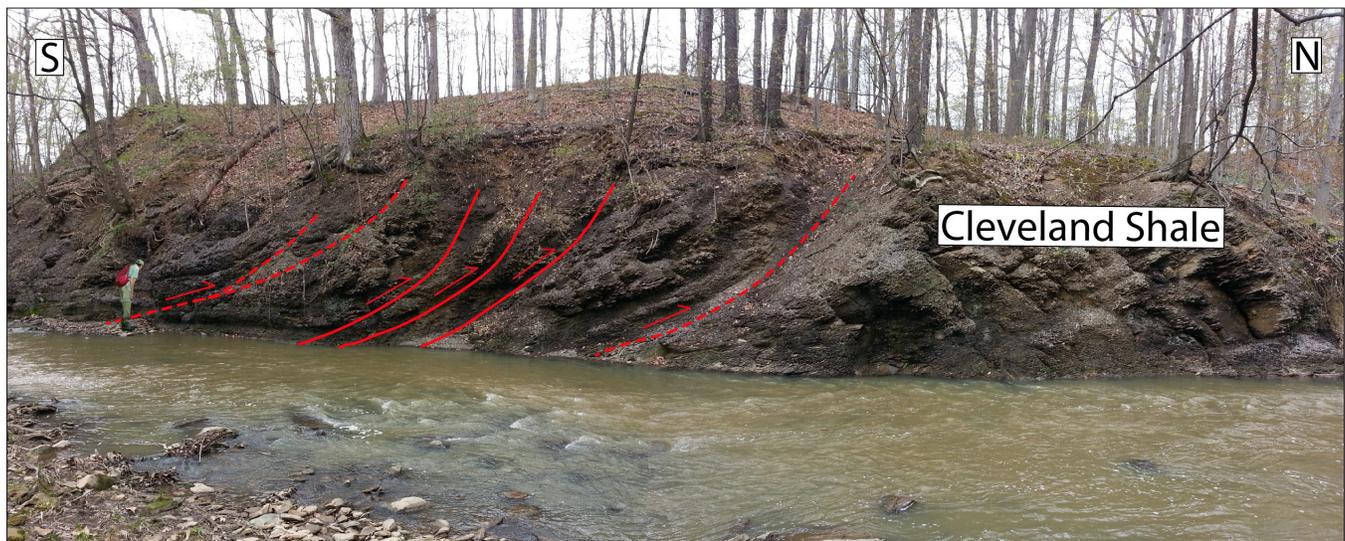


FIGURE 6. Cleveland Shale Member of Ohio Shale at the thrusted core of Chappel Creek anticline-4, west bank of Chappel Creek, ( $41^{\circ} 21.165'N$ ,  $82^{\circ} 25.396'W$ ). A 1.85 m tall person (left) for scale.

**Ohio Shale.** The Ohio Shale in the study area is composed of 3 distinct members. In descending order, they are the Cleveland Shale, the Chagrin Shale, and the Huron Shale. Units older than the Chagrin were identified in drilled deep wells.

The Cleveland Shale Member (Fig. 6) is a dark gray-brown to black, resistant, and fissile bituminous shale under the Bedford. The Cleveland's dark brown color and resistant lithology distinguish it from the red or light gray, soft, and less-resistant Bedford.

The Chagrin Shale Member is a greenish-gray and soft clayey shale with alternating thin limestone (cone-in-cone) beds. It is distinguished from the Cleveland by its clayey and non-resistant, slope-forming nature. The upper part of the Chagrin is exposed in the core of the northern anticlines at Chappel Creek and Old Woman Creek (Figs. 7 and 13).

The Huron Shale Member of the Ohio Shale is a resistant, fissile, and dark olive-brown shale similar to the Cleveland. The Huron in the study area is composed of 3 different lithologic units: The upper Huron is a fissile, dark brown shale. The middle Huron is a green and gray incompetent clayey shale with thin (5 to 10 cm) cone-in-cone beds and carbonaceous concretions. The lower Huron is a dark gray-brown fissile shale. The Huron is not exposed in the study area and was studied in drilled cores as were the following older units.

**Olentangy Shale.** The Olentangy Shale, equivalent to the upper Olentangy Shale in central Ohio, is a green-gray clayey shale with thin interbeds of dark brown-gray shale and pyrite-filled burrows. It is overlain by the Huron Shale and underlain by the Prout Limestone.

**Prout Limestone.** The Middle Devonian Prout Limestone is a thin limestone unit (OGS core #2739) that pinches out to the east. It is overlain by the Olentangy Shale and underlain by the Plum Brook Shale.

**Plum Brook Shale.** The Middle Devonian Plum Brook Shale is a blue-gray shale unit equivalent to the Olentangy Shale of central Ohio. The Plum Brook, Olentangy, and Chagrin shales are clayey, soft, and mechanically incompetent units. Although not exposed in the study area, they play a major role in the structural deformation of the region and the development of the folds in the study area.

**Delaware, Columbus, Lucas, Tymochtee, Niagara carbonates (Middle Devonian–Upper Silurian succession).** Devonian–Silurian Delaware and Columbus limestones, and Lucas, Tymochtee, and Niagara dolomite formations consist of about 350 m of carbonates below the Bedford–Plum Brook shale interval. The thick, competent carbonates of the Delaware–Niagara succession in the region experienced little or no deformation and acted as a resistant regional block below the folded formations. In contrast, the overlying incompetent Bedford through Plum Brook shales and overlying Berea Sandstone were folded and faulted into anticlines and synclines, which are partially exposed in erosion-carved creeks of the study area.

## GEOLOGICAL INVESTIGATION

### Chappel Creek Structures

The Ohio Shale, Bedford Shale, and Berea Sandstone are exposed in Chappel Creek. In contrast to the horizontal to sub-horizontal layering typical of Ohio bedrock, these formations are folded and faulted into conspicuous anticlines and synclines in variable trends along the creek. Nine small-scale anticlines with deformed bedrock units were studied along 4 km of the creek between Mason Road to immediately north of Darrow Road (Figs. 7A and 7B).

The southernmost upstream fold is the “Mason anticline” located north of Mason Road, 350 m southwest of the Joppa Road bridge (Fig. 7B). It is an asymmetric northeast-trending anticline. The Cleveland Shale is exposed in the faulted core of the anticline thrust over the Bedford Shale. Cleveland at the western flank dips 25° to 50° to the northwest and is sliced by westward-dipping thrust faults with variable strikes. A steeply dipping thrust fault truncates the eastern flank, and thrusts the Cleveland over the Bedford. The Bedford is sliced by minor faults and dips 10° to 80° in variable directions. Berea Sandstone at the west flank of the anticline is exposed upstream, dipping 10° to 13° westward.

The “Joppa anticline” is located 200 m southwest of the Joppa Road bridge (Fig. 7B). This structure is an asymmetric, north-verging, tight anticline with the Cleveland Shale exposed in the core. The southern flank dips 33° to 45° southward, but the northern flank is truncated by a thrust fault developed in the core of the anticline. This



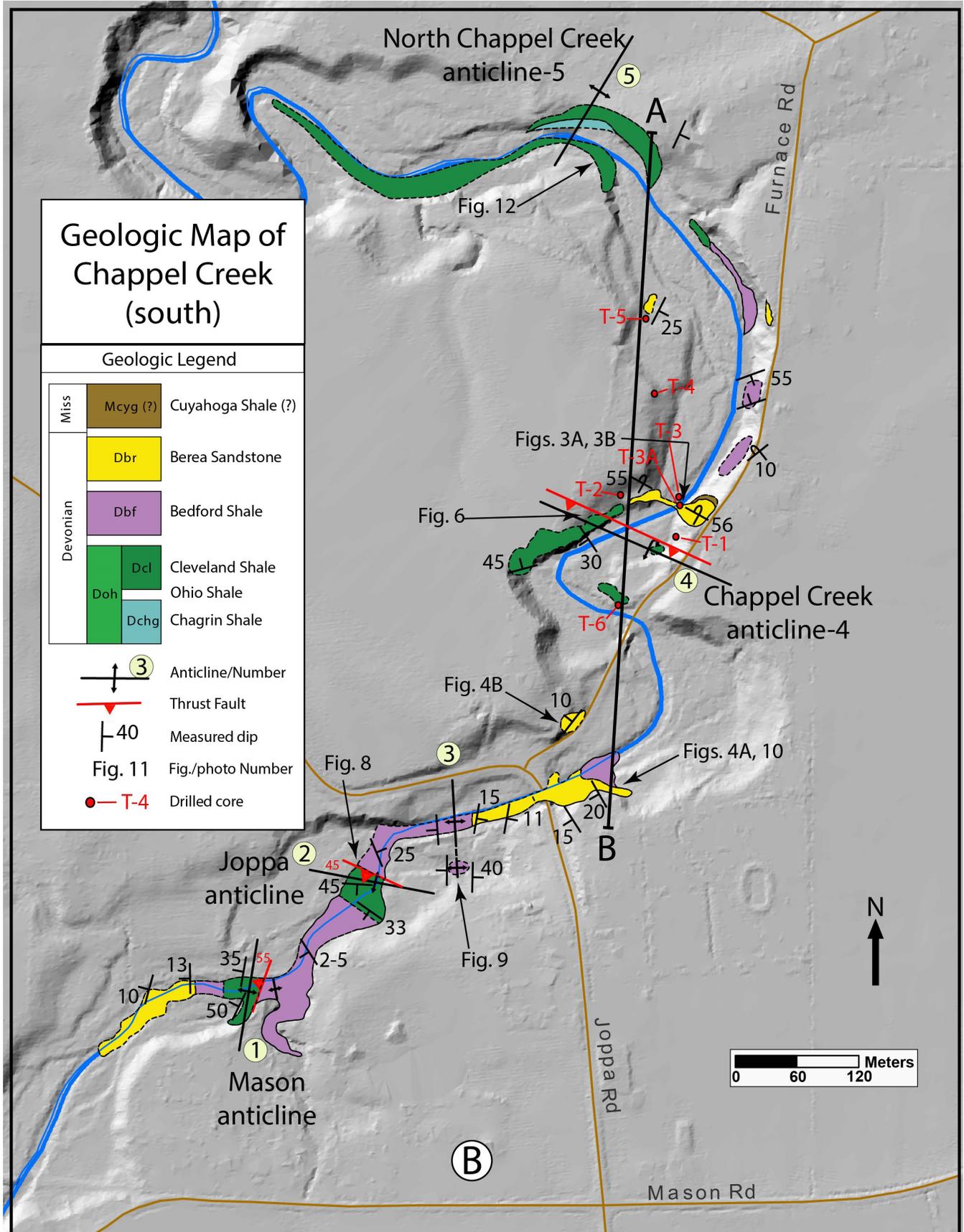


FIGURE 7B. Geologic map of Chappel Creek (south). Line A-B is the approximate location of the geologic profile on Fig. 11.

southeast-dipping  $35^\circ$  thrust fault has placed Cleveland Shale over the Bedford of the northern syncline (Fig. 8). Bedford layers dip between  $0^\circ$  to  $15^\circ$  in the syncline between the Mason and Joppa anticlines. Numerous soft-sediment deformational features occur within the clayey siltstone layers of the Bedford in this syncline.

A minor, north–south-trending anticline (anticline-3) (Fig. 7B) formed within the Bedford shales of the syncline north of the Joppa anticline. The south end is a gentle fold of 1 to 2-meter-thick sandstone layers (Fig. 9).

Further downstream, Berea Sandstone is exposed in a syncline under the Joppa Road bridge with flanks dipping  $11^\circ$  to  $15^\circ$  (Fig. 10) to the east and  $15^\circ$  to  $20^\circ$  to the SW overlying the Bedford at both flanks. An extension of the northeast flank

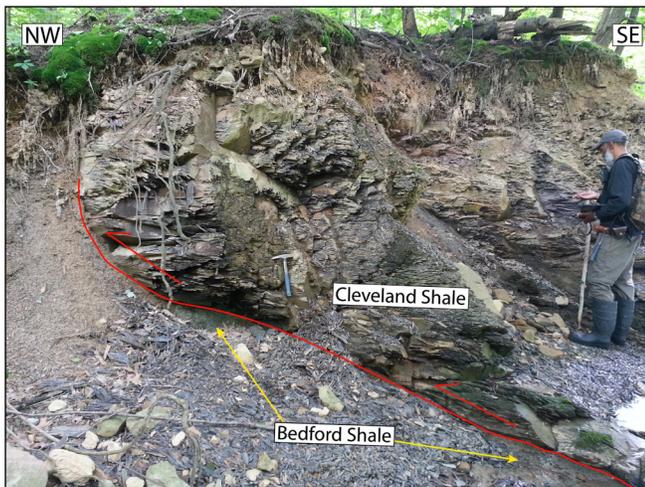


FIGURE 8. Cleveland Shale in the core of the Joppa anticline thrusts over Bedford Shale. Fault strikes  $N 60^\circ E$  and dips  $35^\circ$  to SW (see Fig. 7B).



FIGURE 9. Folded sandstone layer in Bedford, 100 m southwest of Joppa Road bridge (see Fig. 7B). Black-and-white bar is 1.4 m.

beds is exposed at the Furnace Road roadcut at the intersection of Joppa and Furnace roads (Fig. 4B). There are two 0.5 to 1.5 m convoluted sandstone beds (soft-sediment deformation) within the lower layers of the Berea Sandstone (Figs. 4A and 4B).

Further north (downstream), an extensive outcrop of the Cleveland Shale is exposed on the west side of the creek ( $41^\circ 21.165'N$ ,  $82^\circ 25.396'W$ ) (Fig. 6). Shale beds are horizontal south of the outcrop but dip  $45^\circ$  and  $25^\circ$  SW at the north end. The steep, dipping layers of the outcrop are sliced by 3 south-dipping stacked thrust faults, which repeat the shales several times and change the bedding strike (Fig. 6). This faulted Cleveland Member shale makes up the core of the overturned “Chappel Creek anticline-4.”

The Chappel Creek anticline-4 has a normal-dipping southwest flank and an overturned northeast flank. The overturned Berea layer dips  $56^\circ$  to the southwest ( $41^\circ 21.198'N$ ,  $82^\circ 25.360'W$ ). The upside-down symmetrical ripple marks and a paleoerosion surface (Figs. 3A and 3B) demonstrate the overturned flank of the anticline. Bedford Shale between the Cleveland and the Berea is very thin or absent, having been eroded prior to Berea deposition. Berea in the south flank of the anticline is covered by scree or eroded out, and only a remnant of its southern limb is exposed at the Furnace Road roadcut and east of the Joppa Road bridge (Figs. 4 and 10). The wavelength of the Chappel Creek anticline-4 is about 200 m and its estimated amplitude is about 80 m (Fig. 11). A geologic cross section (Fig. 11) along the creek explains the structural geometry of the overturned layers at Chappel Creek.

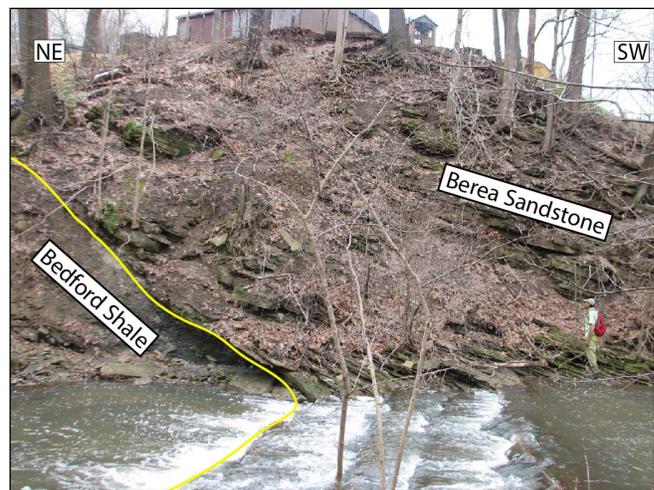


FIGURE 10. Berea Sandstone at the northeast flank of the syncline under the Joppa Road bridge and southwest flank of Chappel Creek anticline-4 (Fig. 7B). A 1.85 m tall person for scale.

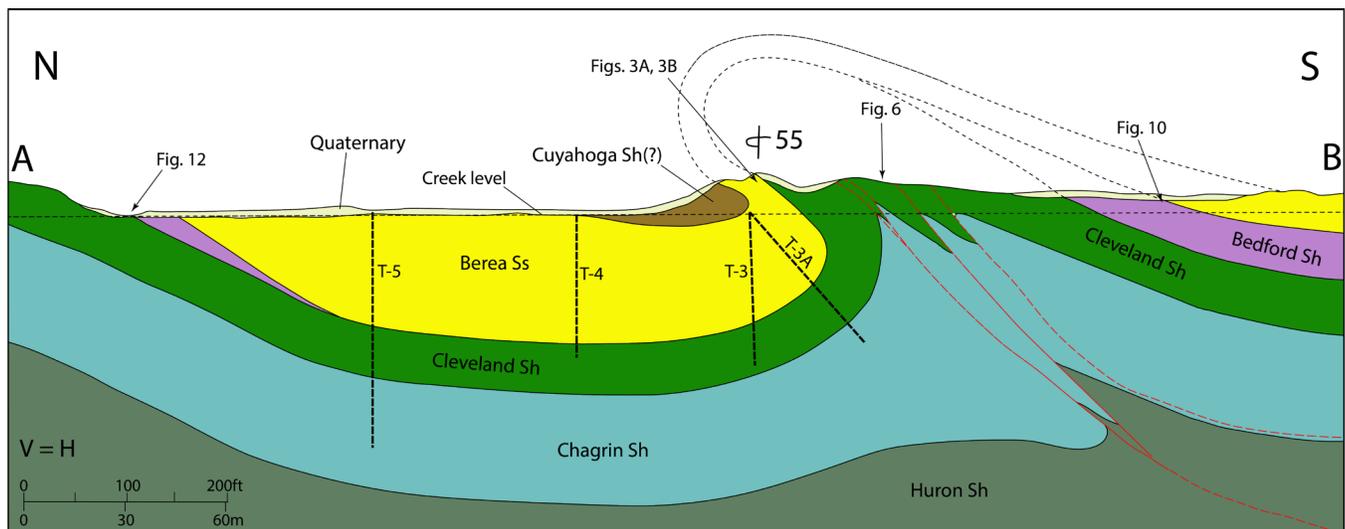


FIGURE 11. Projected geological cross section on Chappel Creek anticline-4 perpendicular to anticlinal axis along the creek. Field data and Berea thickness in the syncline are projected from limited outcrops and Ohio Edison Co. (1973) core drilling information (T-3 to T-5). Geometry of the overturned anticline prior to erosion is shown by dashed lines. Thick Berea is deposited in a paleovalley on the Cleveland Member of the Ohio Shale, where Bedford Shale was eroded. See Fig. 7B for approximate location.

Berea beds of the northern flank of the overturned syncline are exposed in the creek, dipping 25° southeast (Fig. 7B). These beds form the southern flank of the North Chappel Creek anticline-5, with the Cleveland Member of the Ohio Shale exposed at the core (Fig. 12).

At least 4 more anticlines are exposed in the creek within the study area, including East Bailey, West Bailey, South Darrow, and North Darrow anticlines (Fig. 7A). Cleveland and Chagrin Shale members of Ohio Shale are exposed in the core of these anticlines. These anticlines are gently folded, and their axes trend NE–SW.



FIGURE 12. Cleveland Member of the Ohio Shale at the south flank of the North Chappel Creek anticline-5. Scale divisions are 15 cm. (Fig. 7B).

### Old Woman Creek Structures

Berea, Bedford, and the Cleveland and Chagrin Members of the Ohio Shale are exposed in the glen of Old Woman Creek, between the south end of the village of Berlin Heights and the Interstate 80 overpass to the north (Figs. 13A and 13B). There are 8 anticlinal structures “OWC 1 to 8” (Old Woman Creek 1 to 8) in the Ohio Shale along the creek, either partially exposed on the creek bed or on the banks (Figs. 13A and 13B). They are asymmetric NE–SW-trending anticlines verging northwest. Most of these anticlines are low relief with flanks dipping 5° to 30°; only OWC-2, OWC-5, and OWC-6 have very steep or faulted flanks. OWC-1, OWC-3, and OWC-4 (Fig. 13B) with Cleveland Shale exposure, and OWC-7 and OWC-8 (Fig. 13A) with Ohio Shale (Cleveland and Chagrin) outcrops, are gently folded, low-relief folds.

Anticline OWC-1, located south of Berlin Heights and west of State Route 61 (Fig. 13B) is a low-relief anticline dipping 10° E at the southeast flank. The northwest flank dips 10° to 15° NW where the Bedford is very thin and deeply eroded prior to deposition of the Berea. The Berea forms a tighter syncline sitting near the top of the Cleveland Member of the Ohio Shale.

Anticline OWC-2 is an asymmetric anticline verging northwest, with Cleveland Shale exposed in the core (Fig. 13B). The southeast flank dips 20° and the northwest flank dips more than 45°.

Bedford Shale at the northwest flank on the creek bed is internally folded with beds dipping 45° to 70°. The sandstone beds of the Bedford at the higher level of the north bank are strongly folded, overturned, and faulted.

Anticline OWC-3 is a gentle structure with a flat crest and Cleveland Shale exposure. The structure is located east of (upstream from) the Berlin Road overpass (Fig. 13B).

Anticline OWC-4 is also a low-relief structure at the Cleveland Shale Member level and located west of Berlin Road (Fig. 13B). The southeast flank dips about 10° to 15° toward SE. The northwest flank is exposed only at the crest of the fold and

dips 5°. A gray Bedford outcrop in the west bluff of the creek above the anticline is about 15 m thick and is internally folded and faulted (Fig. 14). Berea at the top of the bluff dips 5° to 10° to the northwest. Thin siltstone beds within the Bedford are asymmetrically folded and verging to the northwest. These minor folds are sliced with several southeast-dipping small thrust faults (Fig. 14). The tops of the minor folds at the contact with the Berea are cut off by a bigger, horizontal to low-angle thrust fault (Fig. 14). The sense of motion along this fault indicates that the overlying Berea was displaced toward the northwest by horizontal compressional stress from the southeast.

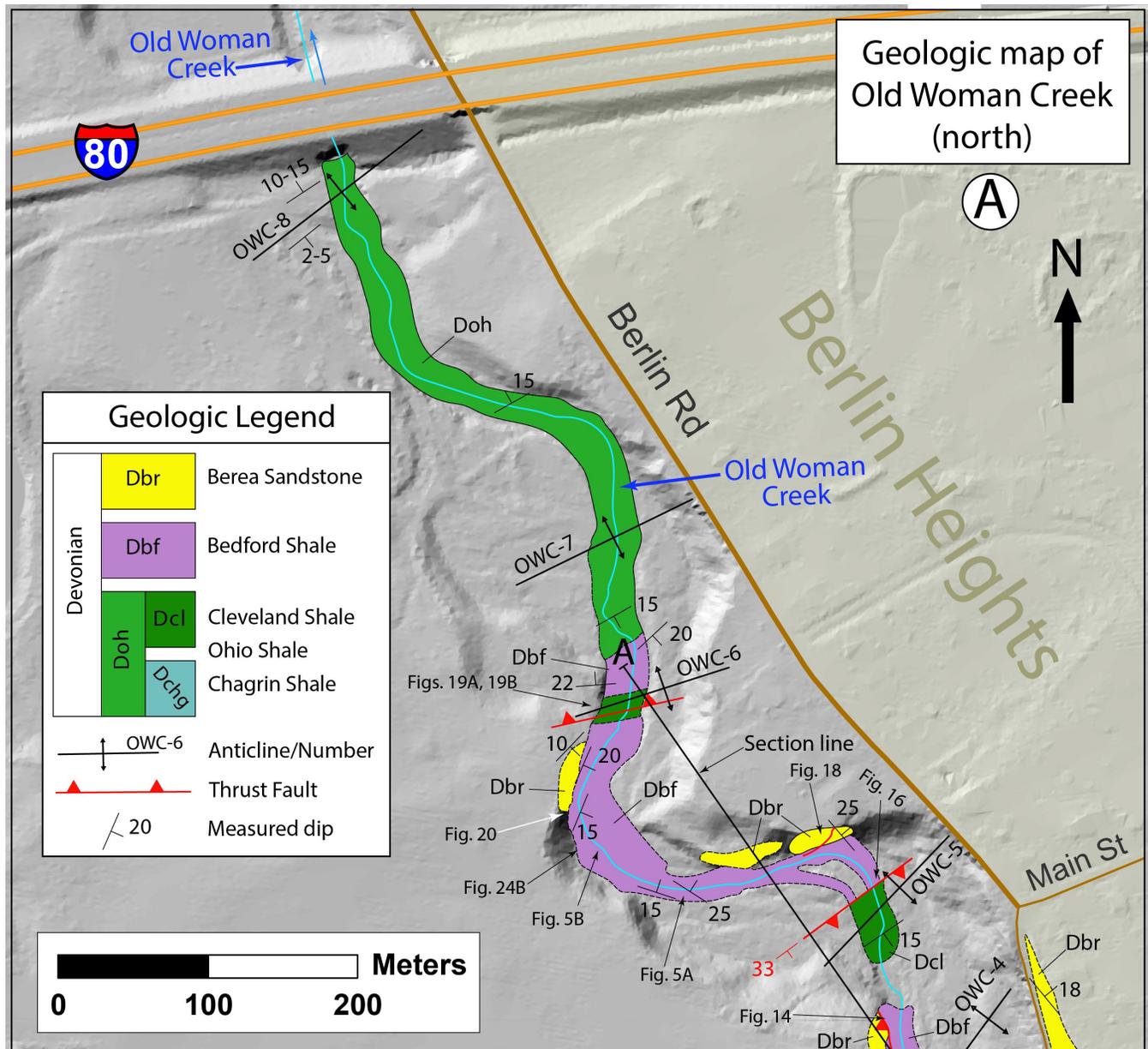


FIGURE 13A. Geologic map of Old Woman Creek (north). The black A-B line partially drawn on A and B maps is the approximate location of the Old Woman Creek geologic cross section (Fig. 17).

The Cleveland layers at the top of the anticline at creek level are not horizontal, having an angular contact with the overlying Bedford. There are several angular Cleveland blocks (Fig. 15) within the Bedford just north of the anticline axis. They indicate that the Cleveland layers at the anticline's apex were truncated by a horizontal thrust fault, removing the top of the anticline and relocating broken blocks within the Bedford on the north flank. Incompetent Bedford between the Cleveland Shale and the Berea acted as a décollement zone, allowing massive competent layers of the Berea

Sandstone to deform independently of the Cleveland Shale during folding.

Anticline OWC-5 (Fig. 13A) is partially exposed just north of OWC-4. It is an asymmetric anticline with a thrustured core. Cleveland Shale at the southeast flank dips 15° to 30° toward SE. The north flank of the anticline is absent due to a southeast-dipping thrust fault developed at the crest of the fold, moving the Cleveland of the southeast flank over the Bedford on the northwest flank (41° 19.409'N, 82° 30.016'W) (Figs. 16 and 17). This thrust fault originated within incompetent Chagrin

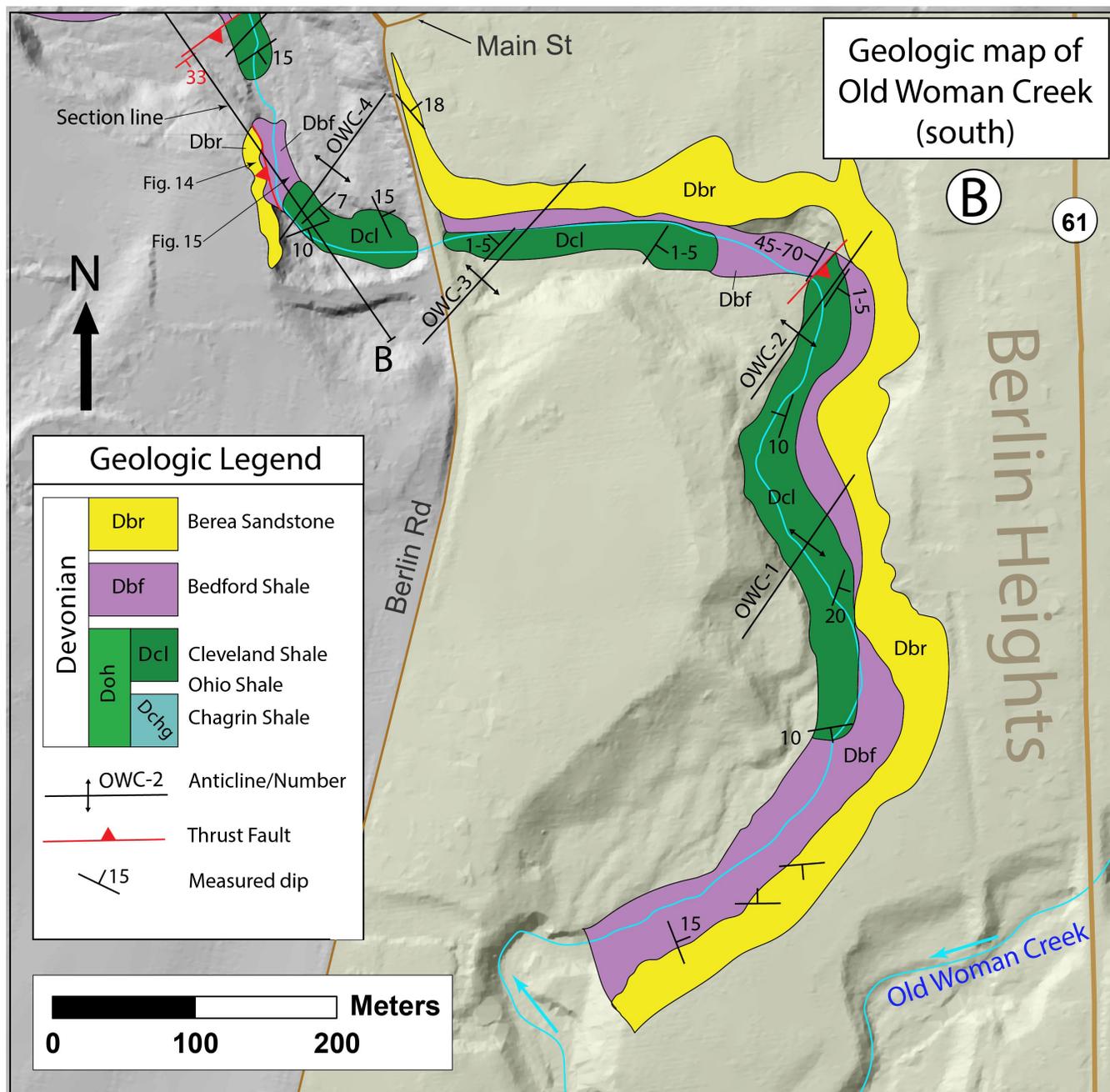


FIGURE 13B. Geologic map of Old Woman Creek (south). The black A-B line partially drawn on A and B maps is the approximate location of the Old Woman Creek geologic cross section (Fig. 17).

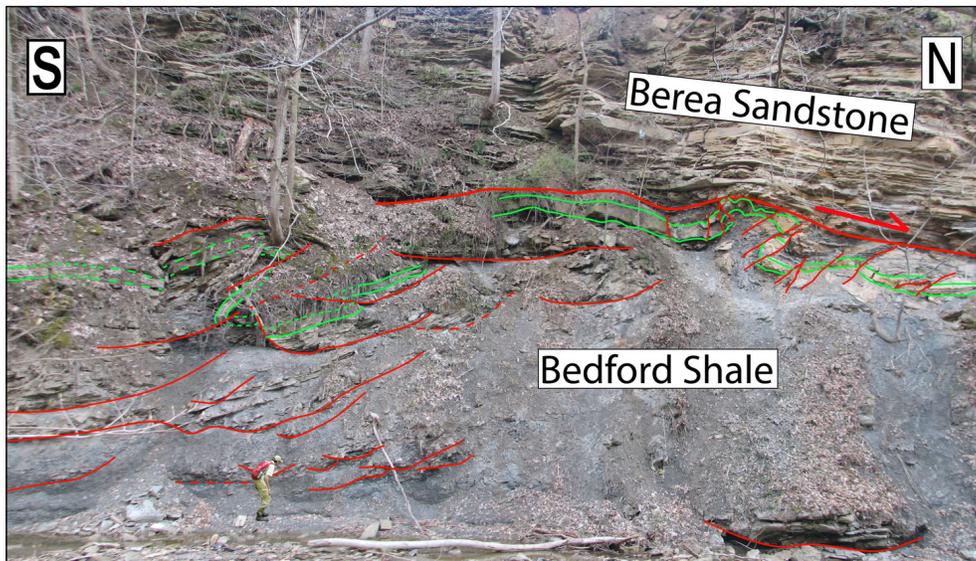


FIGURE 14. Bedford Shale and Berea Sandstone layers at the west bluff of Old Woman Creek (41°19'21.16"N, 82°30'0.49"W). Bedford layers are folded and displaced by small horizontal southeast-dipping thrust faults. Asymmetrically folded thin beds of the Bedford (green) at the right are truncated by the movement of Berea to the northwest along a low-angle thrust fault (see Fig. 13B for location). Reverse and low-angle faults are red. A 1.85 m tall person (bottom left) for scale.

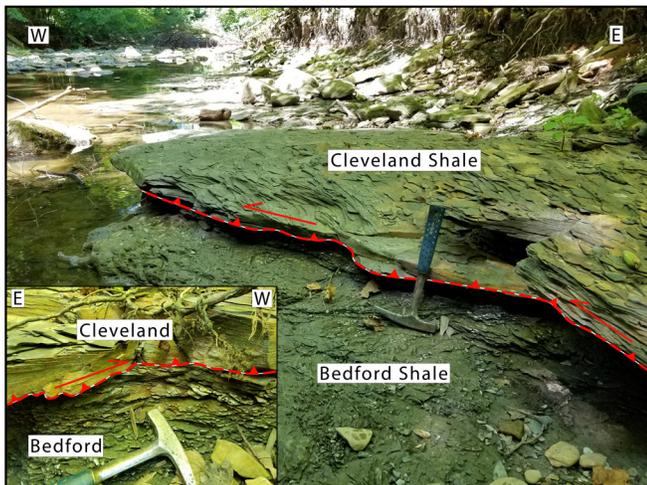


FIGURE 15. Cleveland Shale block sliced from the apex of OWC-4 anticline and imbedded within Bedford Shale. Inset: close-up image of the Bedford and Cleveland contact.

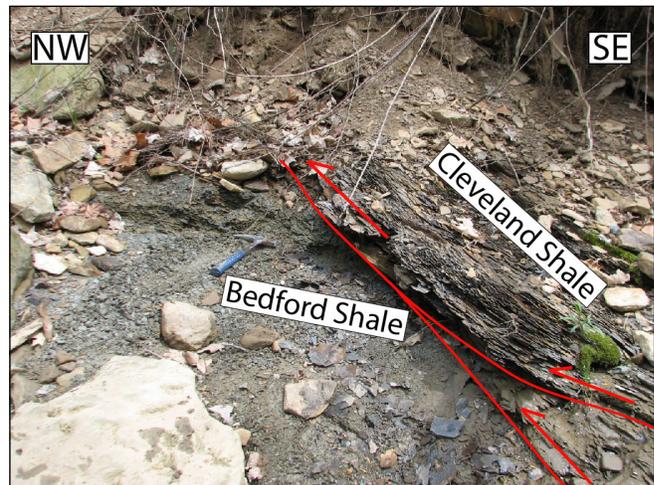


FIGURE 16. Cleveland Shale of the southern flank of OWC-5 anticline thrust over Bedford at the core of anticline (Fig. 13A)

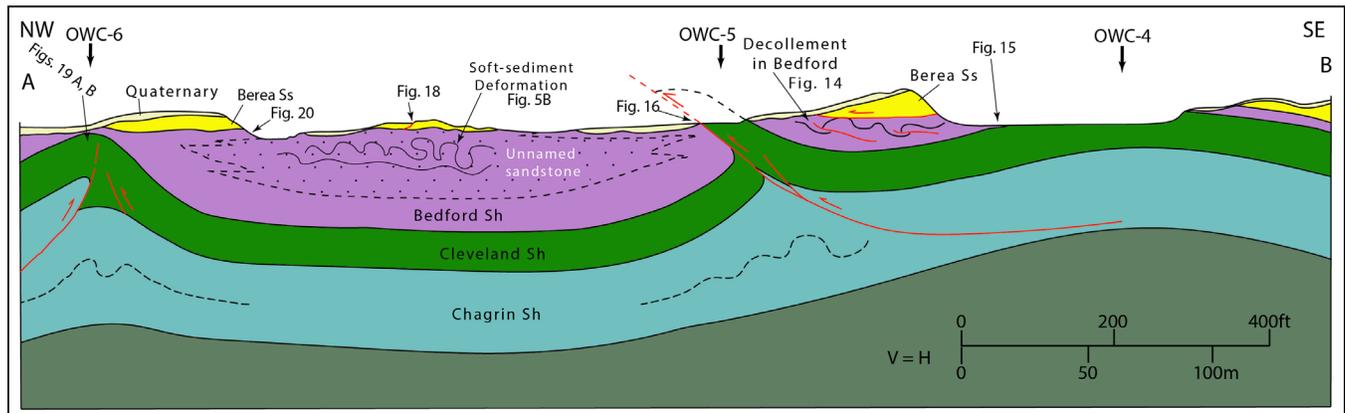


FIGURE 17. Projected geological cross section through Old Woman Creek anticlines OWC-4, OWC-5, and OWC-6. See Figs. 13A and 13B for approximate location.

under the Cleveland Member (Fig. 17), or deeper within Huron and lower incompetent layers, during horizontal compressional stress from the southeast. A thick sandstone layer with symmetric ripple marks (Fig. 5A) and a thick lithified muddy siltstone unit with abundant soft-sediment deformation (Fig. 5B) is present within the Bedford northwest of OWC-5. Berea is exposed to the north and east of the creek banks overlying the Bedford without noticeable folding. A big block of the Berea is downthrown by gravity sliding along a curved normal fault (41° 19.414'N, 82° 30.082'W) (Fig. 18) at the east bank, north of OWC-5. It most likely developed much later in the Quaternary following regional erosion and valley creation.

Anticline OWC-6 contains exposed Cleveland Shale at the core. This structure is located 450 m south of the Interstate-80 bridge, west of Berlin Road (Fig. 13A). The core of the structure is sliced

by several small thrust faults in different directions, but mainly dipping northwest (Figs. 19A and 19B). Thick, unnamed sandstone layers of the Bedford in the syncline between OWC-5 and OWC-6 (Fig. 17) acted as a barrier. This could explain the irregular movement of the layers during the folding, resulting in development of the northwest-dipping back thrusts to compensate spatial shortening.

Bedford with thick unnamed sandstone beds and Berea on the southeast flank of OWC-6 are exposed on the steep bluff on the west side of the creek (Figs. 13A and 20).

Anticlines OWC-7 and OWC-8 are located to the north and downstream from OWC-6, just south of Interstate-80 and west of Berlin Road. Chagrin Shale is exposed in the core of these NE–SW-trending low-relief anticlines with flanks dipping 10° to 20° (Fig. 13A). The syncline between OWC-7 and OWC-8 is a very shallow saddle between the anticlines.



FIGURE 18. Southeast-dipping Berea downthrown by northwest-dipping curved normal fault, formed by gravity sliding toward eroded open valley to the west (Fig. 13A)

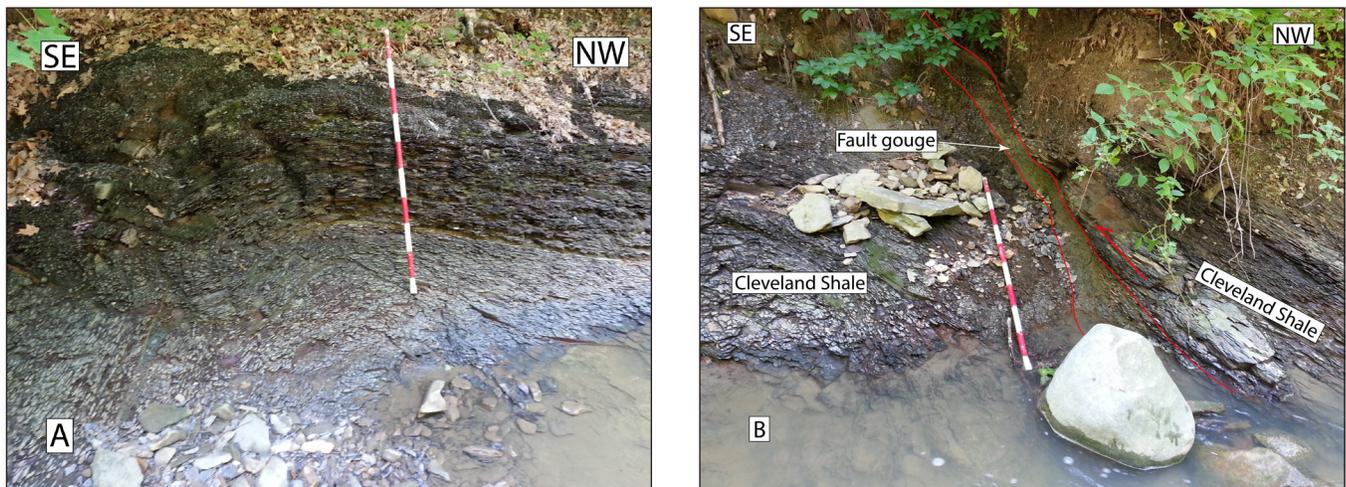


FIGURE 19. (A) Cleveland Shale at the core of OWC-6 anticline. (B) Thrust fault at the north flank of the anticline. Scale divisions are 15 cm.

## DISCUSSION

A geometric analysis of the Chappel Creek and Old Woman Creek anticlinal structures and limited thrust faults indicates that most trend northeast to southwest. Comparison of structures suggests that the Chappel Creek fold axes are more random than those of Old Woman Creek. Two geological cross sections were constructed through the intensely deformed anticlines along the creeks (Figs. 11 and 17). Considering lithostratigraphy and geometry of the exposed deformed layers, the methods of Busk (1929), De Sitter (1964), Dahlstrom (1969), and Ragan (1984) were utilized for making cross sections. The sections are approximate due to significant stratigraphic thickness changes in the Bedford and Berea, and limited outcrops to collect stratigraphic and structural data on the folded layers.

Interpretation of the geologic structures shows that variation in stratigraphic thickness of the Berea and Bedford is the main reason for the development of variable geometric structures and the more random trends at Chappel Creek. Changes in orientation of the layers on the folds are the result of the variation of compressional shear stress (Fig. 21), and accommodation of layers with different stratigraphic thicknesses in a fold or between folds.

The results of field observations, interpretations of geological structures, and analyses of the cross sections are summarized below:

- Most of the major anticlines in Chappel Creek and Old Woman Creek trend northeast to southwest. Only the Chappel Creek and Joppa anticlines trend NW–SE.

- The estimated wavelengths and amplitudes of the anticlines indicate that these are shallow structures, and the detachment level (De Sitter 1964) should be above the Columbus and Delaware Limestones.

- The steep NW flanks of the anticlines (in comparison to SE flanks) show that the folds are asymmetric and verging NW, indicating that the folds formed by horizontal compressional tectonic stress from the SE.

- The Bedford and Berea in the region are characterized by significant lithostratigraphic variation and dramatic, short-distance thickness changes. For example, the Berea's thickness ranges from 3 m at the overturned Chappel Creek outcrop (Herdendorf 1963) to more than 35 m (Wolfgang and Gardner 1977) immediately to the north under

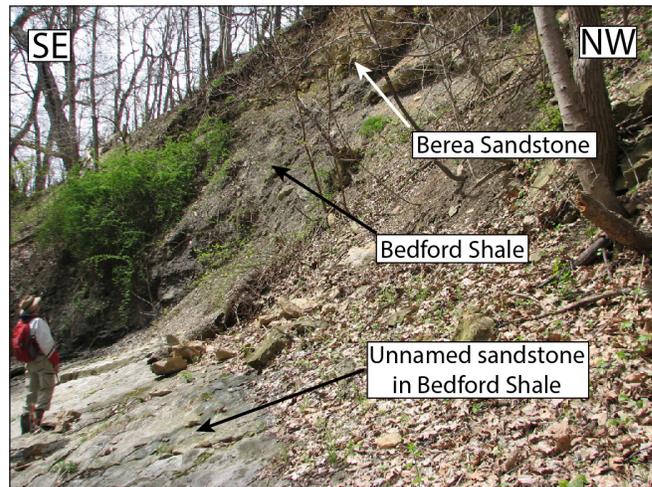


FIGURE 20. Southeastern flank of OWC-6 anticline (Fig. 13A)

Chappel Creek (Figs. 11 and 22). This massive Berea body hidden under the creek served as a stratigraphic obstacle to the parallel transmission of tectonic stress from the SE. Thinner, compressed Berea layers (as well as Ohio Shale) encountering this massive sandstone obstacle experienced differential compression, leading to a tight and exceptionally overturned anticline (Fig. 11). This also resulted in development of dextral shear and transpressional (oblique deformation of layers due to strike slip stress) (Harland 1971) stress during folding, and a change in layer orientation from NE–SW to NW–SE (Fig. 21). Berea on the crest and southern flank of the anticline was eroded and only the overturned layers of the northern flank remain and are exposed at both sides of the creek and in the creek bed.

- The Joppa anticline may have experienced similar deformation and change in fold trend following the Chappel Creek anticline-4 stratigraphic obstacle and transpression process, or may have been affected by the presence of unexposed locally thick sandstone layers similar to unnamed sandstone layers of Old Woman Creek (Figs. 5A and 5B) in the Bedford unit north of Joppa anticline.

- Most of the Berea layers of the folds were eroded. Uneroded remnants of the Berea are present in the core of synclines (Figs. 7, 10, and 11).

- A stratigraphic obstacle of the locally thick sandstone layer (Figs. 5A, 5B, and 17) in the Bedford within the syncline north of anticline OWC-5 (Fig. 13A) resulted in thrust faulting of Cleveland Shale on the south flank of the anticline over Bedford in the northern syncline (Figs. 16 and 17).

- Reconstruction of the folded layers along Chappel Creek (Figs. 11 and 21) shows that the

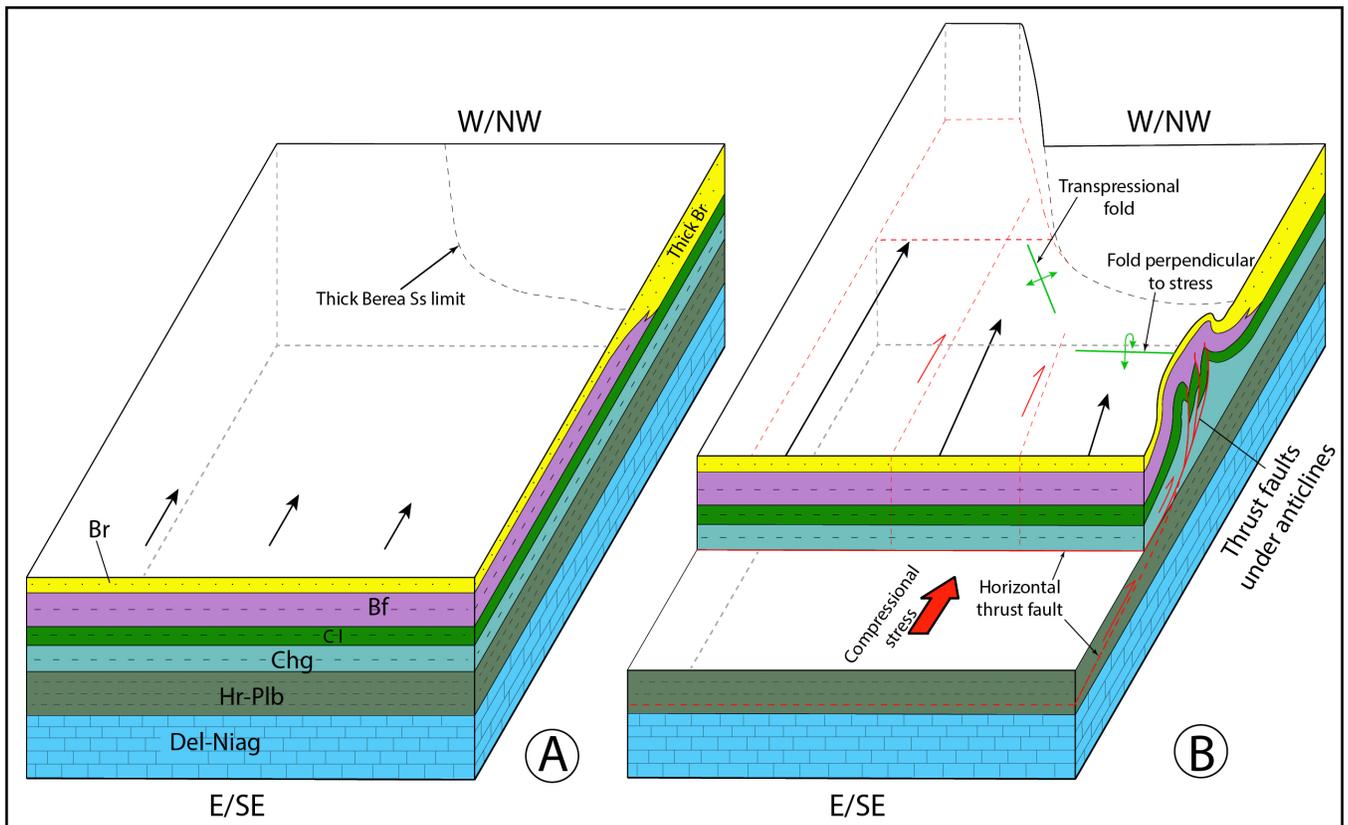


FIGURE 21. (A) Undeformed horizontal sedimentary layers in the Chappel Creek study area with thick Berea Sandstone deposited on Cleveland Shale at the upper right corner. (B) Schematic explanation of the development of a tight fold (Chappel Creek anticline-4), where moving layers (black arrows) reach the locally thick Berea Sandstone obstacle; a dextral shear zone develops at the obstacle's left edge, resulting in change of the orientation of the folding layers and fold axes.

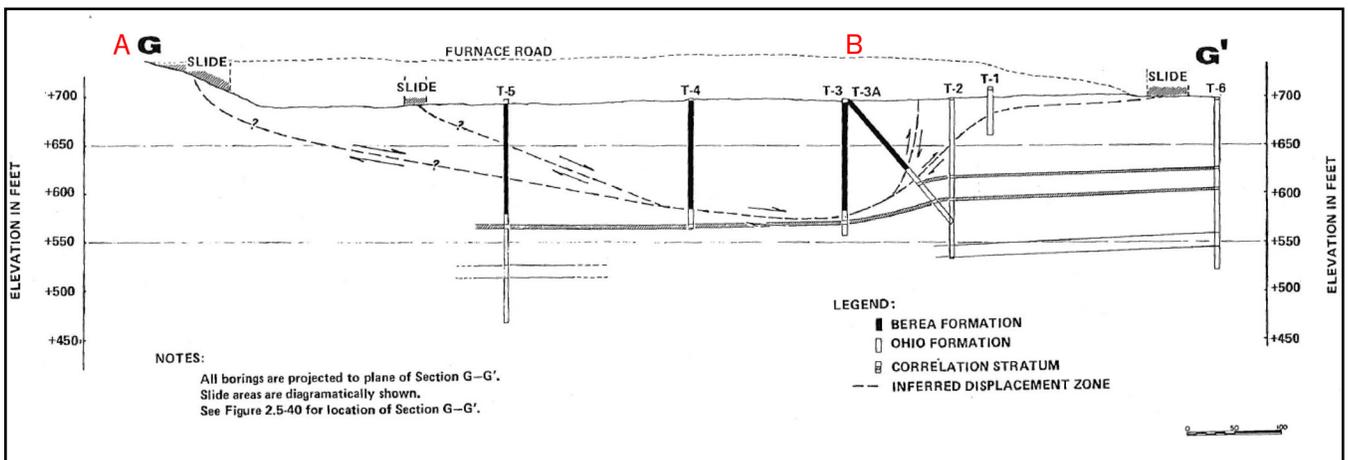


FIGURE 22. Ohio Edison Co. (1973), interpretation of displacement of horizontal Berea from point (A) southward to become overturned at point (B). Authors of the present study used Berea thickness data from the drilled cores T-3 to T-5 (Fig. 7B) in this section to create Chappel Creek structural cross-section (Fig. 11).

Chappel Creek and Joppa anticlines are tightly folded, with exposed faulted cores and about 30% spatial shortening. The northern folds along the creek, with older units of Ohio Shale exposed, are low-relief anticlines and have not been eroded down to the faulted core of the anticlines.

### Glacial Geology

Geological structures in the study area have been reviewed by numerous geologists since 1874. Some writers reported that folds and faults were created by soft-sediment deformation or folding by an unknown cause, but a primary explanation has been that these formed by the north–south movement of Pleistocene glaciers (Read 1878; Gilbert 1892, 1899; Prosser 1912; Wenberg 1938). Overturned Berea layers at Chappel Creek were studied in detail by Herdendorf (1963), Ohio Edison Co. (1973), and Wolfgang and Gardner (1977). They concluded that the Berea layers were deformed by the movement of glaciers during the Pleistocene. (Figs. 22 and 23).

However, the following issues must be considered if Pleistocene glaciation is proposed as the cause of the folded Berea at the Chappel Creek:

- The overturned beds of Berea are folded intact and solid without signs of rock crushing (Figs. 3A and 3B), whereas bedrock units typically deformed by glaciers are highly fractured and

crushed (Sardeson 1906; Glock 1929; Lamerson and Dellwig 1957; Dellwig and Baldwin 1965).

- The thickness and depth of bedrock layers deformed by glacial ice shove is usually very shallow, less than 10 m (Sardeson 1906; Glock 1929; Lamerson and Dellwig 1957; Dellwig and Baldwin 1965), whereas in Chappel Creek the structural deformation extends for more than 40 m vertically (Wolfgang and Gardner 1977).

- Layers deformed by glaciers are intermixed with glacial allochthonous boulders (Glock 1929; Lamerson and Dellwig 1957; Dellwig and Baldwin 1965), whereas there is no evidence of glacial material in the Paleozoic age deformed layers in Chappel Creek anticline-4.

- The sense of motion on the overturned beds at Chappel Creek is to the northeast. This contradicts the direction of Pleistocene glacial movement, which in the study area is from northeast to southwest (White 1982; Szabo et al. 2011).

- Mineralization of sharply fractured Bedford siltstone and sandstone beds (Fig. 24) indicates that folding and fracturing occurred after lithification.

The absence of well-known physical features—such as shallow deformation depth, sense of motion alignment, and crushed bedrock mixed with glacial particles of glacially deformed bedrock—proves Pleistocene glacial movement was not the cause of the Chappel Creek structures and overturned strata.

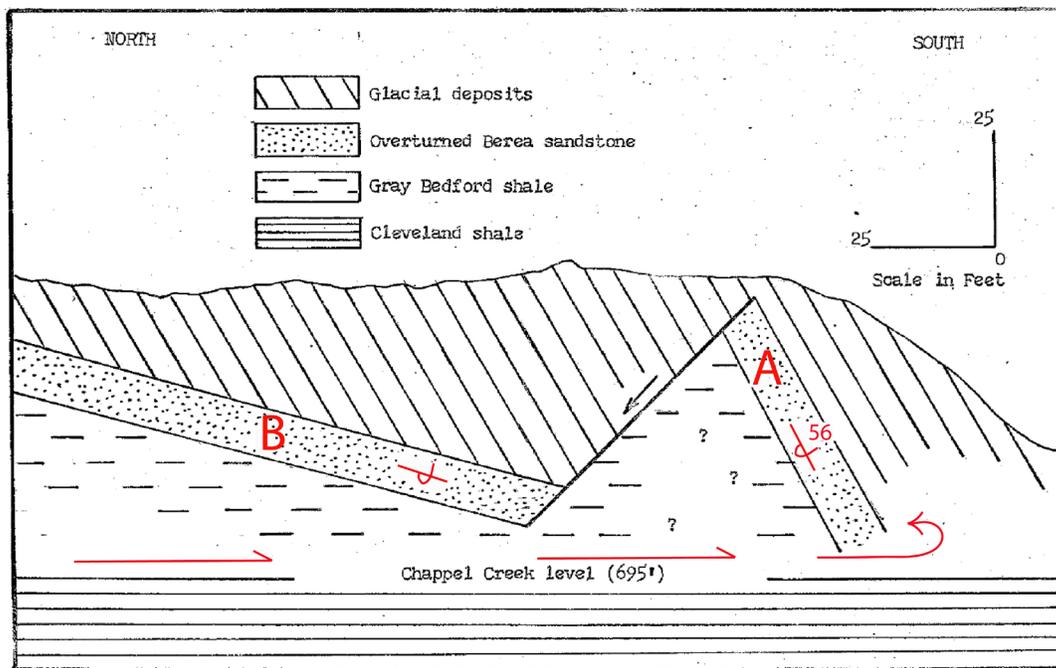


FIGURE 23. Modified from Herdendorf (1963) to explain deformation by glacial shove. Red arrows show displacement of Berea Sandstone layers from north to south above creek level and the changing of their primary horizontal position to 56° overturned (A); later, gravity sliding moves part of the overturned layers downward (B).



FIGURE 24. Sharply fractured and mineralized sandstone and silty mudstone layers of Bedford Shale in Chappel Creek (A) and Old Woman Creek (B). Displacement of the older joints (A) and ripple marks (B) indicates that they have been deformed and fractured after lithification of the layers. Scale divisions are 15 cm.

### Soft-sediment Deformation

Holocene, Mississippi Delta-style soft-sediment deformation (Morgan 1961; Morgan et al. 1968) was proposed as the cause of the structures at Chappel Creek and Old Woman Creek by Pashin and Ettensohn (1995) and Jones (2000). Pashin and Ettensohn (1995) concluded that “[Berea] sandstone bodies were not deposited in simple channels as proposed by Pepper et al. (1954), but...formed primarily by subsidence of sand into soft mud.” Baird (2017) proposed that Bedford deformations in Old Woman Creek were diapirs and ball-and-pillow structures controlled by sediment loading.

The following field observations, however, contradict the formation of folds, faults, or diapiric structures by soft-sediment deformation:

- Bedford thickness increases in Old Woman Creek (Fig. 14), resulting from southeast-dipping thrust faults. Sharp displacement of the faulted siltstone beds and the absence of smooth and rounded displacements on this outcrop indicates that faulting and thickening of the Bedford took

place after Berea Sandstone was lithified and Bedford Shale had been de-watered and compacted.

- Sharp and clear mineralization of fractures in Bedford Shale layers show that they were fractured in a brittle state (Fig. 24), indicating that fracturing took place post-lithification by compressional tectonic stress—possibly in the late Paleozoic but not during sediment deposition.

- Sedimentary structures (e.g., ripple marks) within the layers are intact with their fine details preserved (Figs. 3B, 5A, and 24), again indicating layers were lithified well before deformation occurred.

- Incompetent Bedford acted as a décollement zone and was thickened by displacement into the low-pressure zones of the folds during deformation, while thin brittle beds of the unit were sharply fractured or faulted.

- There are big, angular blocks of black Cleveland Shale within the Bedford just northwest of the OWC-4 anticline axis (Fig. 15). The reverse faults under the Cleveland Shale blocks are in contact with Bedford Shale. This shows that the apex of

the anticline in the Cleveland Shale horizon might be cut off by a horizontal thrust fault and relocated into the northwestern syncline within the Bedford Shale.

- The soft-sedimentary-deformed and convoluted layers sandwiched between undeformed Berea and Bedford layers were most likely created during (or soon after) deposition but prior to lithification. Their thickness is 0.5 to 1.5 m in the Berea (Figs. 4A and 4B) and up to several meters in the Bedford (Fig. 5B). Bedford and Berea layers, along with the convoluted beds, simultaneously participated later in the folding processes.

### Conclusion

A total of 17 small-scale exposed anticlines with deformed Ohio Shale were studied along Chappel Creek and Old Woman Creek in Erie County, Ohio. These low-relief anticlines trend mainly NE–SW, asymmetrically verging to the northwest, and formed by northwest-directed horizontal compressional stress.

The Chappel Creek anticline-4, with overturned Berea and deformed layers, is a tight overturned fold with its axis trending NW–SE. The overturned Berea layers make up the northeastern flank of this anticline. The Cleveland Member of the Ohio Shale is exposed at the core of the anticline. Increased Cleveland thickness is due to several south-dipping stacked thrust faults. Locally thick Berea in the syncline to the north constrained the harmonic movement of the layers during late Paleozoic folding, acting as a stratigraphic obstacle. This resulted in additional compressional stress on layers encountering this obstacle and the formation of a tight, overturned anticline. Furthermore, the locally thick Berea obstacle created a dextral shear stress zone to the west during folding. As a result, transpressional folding at Chappel Creek anticline-4 changed the fold orientation from the expected NE–SW to NW–SE.

Analysis of the geometry, wavelength, and amplitude of the folds shows up to 30% spatial shortening in comparison to the length of the folded layers. Expansion of lithified formations by postglacial rebound, or any other process, was unlikely to create these folds. The cemented fractures in the strata indicate that fracturing and deformation is much older than Pleistocene. Preserved and undeformed fine sedimentary structures like ripple marks, cross-beds, and thin convoluted (seismites)

beds sandwiched between Berea beds, indicate that the Berea was lithified prior to folding and overturning. Moreover, the time span for the deposition of the Ohio Shale through the Cuyahoga (?) Formation, including the major unconformity at the base of the Berea, is several million years. It is unlikely that all these Upper Devonian formations remained in a soft and plastic state only to be deformed after deposition of the Berea Sandstone.

Soft-sediment deformation features including flow rolls, ball-and-pillow structures, and load casts (all seismites) within the Berea and Bedford likely were created during and shortly after sedimentation, and are not the result of the compressional stress that led to folding. These features and accompanying strata were folded during later deformation.

Layer deformation by ice shove, particularly of the overturned Berea block, is ruled out for 3 reasons: (1) proven studies in Ohio, Kansas, Iowa, and other countries show that the thickness of bedrock units deformed by glacial movement is less than 10 m, whereas the thickness of deformed layers in the Chappel Creek anticline-4 is at least 30 to 40 m; (2) glacially deformed layers are folded or faulted verging in the direction of glacial movement, whereas the sense of motion on overturned Berea beds at Chappel Creek contradicts the general north–south movement of the ice sheets that encroached on northern Ohio; and (3) strata deformed by glaciers are typically highly fractured, crushed, and mixed with allochthonous glacial particles. This contrasts with Berea beds at Chappel Creek anticline-4 that are only moderately jointed by folding, with no evidence of crushing or mixing of glacially derived material with the bedrock. The only young structural features found in this study are the limited curved normal faults in the Berea, where sandstone layers in the east banks of the creeks locally slid down by gravity into adjacent valleys sometime during the Quaternary.

In summary, the overturned Berea layers—and all folds with northeast orientation in the stream cuts of Chappel Creek and Old Woman Creek—most likely were created during the Paleozoic by northwest-directed, Alleghenian tectonic compressional forces. There are few exceptions where the change in orientation of the fold axes resulted from localized variations in lithostratigraphic thickness. In all cases, folding occurred after lithification, rather than during sedimentation, and Pleistocene glacial movement could not be the cause.

## ACKNOWLEDGEMENTS

The authors thank the administration of the Ohio Department of Natural Resources (ODNR) and the Division of Geological Survey for their support of this study. We would like to express our appreciation to the ODNR Division of Geological Survey Chief, Michael P. Angle (retired), and Assistant Chief, James D. Stucker, for their support and assistance. The authors appreciate the Journal's anonymous reviewers for their time to review the manuscript and their insightful and beneficial comments. Thanks to Anthony Bresnen the ODNR Division of Geological Survey editor for his helpful contributions to this manuscript. Additional thanks go to the Stack, Bruce, and Peck families for providing site access.

## LITERATURE CITED

- Baird GC, Hannibal JT, Wicks JL, Laughrey CD, Mack EA. 2013. Stratigraphy and depositional setting of Upper Devonian Ohio Black Shale divisions and the overlying Bedford/Berea sequence in northeastern Ohio. Field trip guidebook for the AAPG 2013 Annual Convention & Exposition. Pittsburgh, Pennsylvania. 82 p.
- Baird GC. 2017. Old Woman Creek unit succession and structure (dynamically disrupted Cleveland Member – Berea Formation succession). Unpublished manuscript. Baird section No. 345.
- Blood DR, Baird GC, Danielsen EM, Brett CE, Hannibal JT, Lash GG. 2019. Upper Devonian paleoenvironmental, diagenetic, and tectonic enigmas in the western Appalachian Basin: new discoveries and emerging questions associated with the Frasnian-Famennian boundary and end-Devonian disturbances in central Ohio. Field trip guidebook for the 48th Annual Meeting of the Eastern Section of the American Association of Petroleum Geologists; 2019 Oct 12-16; Columbus, Ohio. 80 p.  
<https://www.researchgate.net/publication/339362901>
- Busk HG. 1929. Earth flexures. Cambridge (UK): Cambridge University Press. 106 p. ISBN 13: 9781107663190.
- Currie BC, Hannibal JT, Wicks JL, Swinford EM, Mott BE, Angle MP, Weis ME. 2014. Ohio Geological Survey, Core# 2739 (OHEE-2 well), (41°20'23.93"N, 82°25'20.87"W) gamma ray and core description. Ohio Geological Survey core workshop; 2014 Sep 19; Columbus, Ohio. Original wellsite description.
- Cushing HP, Leverett F, Van Horn FR. 1931. Geology and mineral resources of the Cleveland district, Ohio. Washington (DC): United States Department of the Interior, Geological Survey. Bulletin No.: 818. 138 p.  
<https://doi.org/10.3133/b818>
- Dahlstrom CDA. 1969. The upper detachment in concentric folding. *B Can Petrol Geol.* 17(3):326-346.  
<https://doi.org/10.35767/gscpgbull.17.3.326>
- De Sitter LU. 1964. Structural geology. 2nd ed. New York (NY): McGraw-Hill. 551 p.
- Dellwig LF, Baldwin AD. 1965. Ice-push deformation in northeastern Kansas. *Kans Geol Surv Bull.* 175, part 2.  
[http://www.kgs.ku.edu/Publications/Bulletins/175\\_2/](http://www.kgs.ku.edu/Publications/Bulletins/175_2/)
- Elizalde C, Griffith WA, Miller T. 2016. Thrust fault nucleation due to heterogeneous bedding plane slip: evidence from an Ohio coal mine. *Eng Geol.* 206:1-17.  
<https://doi.org/10.1016/j.enggeo.2016.03.001>
- Gilbert GK. 1892. Post-glacial anticlinal ridges near Ripley, N. Y., and near Caledonia, N. Y. [abstract]. In: Putnam FW, editor. Proceedings of The American Association for the Advancement of Science for the 40th meeting [Vol. 40]; August 1891; Washington, DC. Salem (MA): AAAS. p. 249-250.  
[https://www.google.com/books/edition/\\_/3iy\\_SZvwc2EC?hl=en&gbpv=0](https://www.google.com/books/edition/_/3iy_SZvwc2EC?hl=en&gbpv=0)
- Gilbert GK. 1899. Dislocation at Thirtymile Point, New York. *Geol Soc Am Bull.* 10(1):131-134.  
<https://doi.org/10.1130/GSAB-10-131>
- Glock WS. 1929. An example of sediments deformed by ice thrust. *Ohio J Sci.* 29(6):300-302.  
<http://hdl.handle.net/1811/2426>
- Harland WB. 1971. Tectonic transpression in Caledonian Spitzbergen. *Geol Mag.* 108(1):27-42.  
<https://doi.org/10.1017/S0016756800050937>
- Hartley RP. 1962. Relation of shore and nearshore bottom features to rock structure along Lake Erie. *Ohio J Sci.* 62(3):125-131.  
<http://hdl.handle.net/1811/4857>
- Herdendorf CE. 1963. The geology of the Vermilion Quadrangle, Ohio [master's thesis]. [Athens (OH)]: Ohio University. 182 p.  
<https://alice.library.ohio.edu:443/record=b2727395-S7>
- Herdendorf CE. 1966. Geology of the Vermilion West and Berlin Heights quadrangles, Erie and Huron counties, Ohio [geologic map]. Columbus (OH): Ohio Department of Natural Resources, Division of Geological Survey. Report of Investigations No.: 60. Scale 1:24,000, 1 sheet: color, accompanying text.  
<http://hdl.handle.net/1811/80304>
- Herdendorf CE (Center for Lake Erie Area Research [CLEAR], The Ohio State University, Columbus, OH). 1973. Geological investigations in the vicinity of the proposed Berlin Heights Nuclear Power Station. CLEAR Technical Report No.: 9. Prepared for Woodward-Garner & Associates, Inc., Philadelphia, PA. 35 p. Unpublished.  
<https://hdl.handle.net/2027/osu.32435002985752>
- Herdendorf CE (Center for Lake Erie Area Research [CLEAR], The Ohio State University, Columbus, OH). 1977. Evaluation of geologic structures in the vicinity of the proposed Erie Nuclear Plant. Addendum No.: 1 to CLEAR Technical Report No.: 9. Prepared for Woodward-Clyde Consultants, Plymouth Meeting, PA. 4 p. Unpublished.  
<https://hdl.handle.net/2027/osu.32435009586371>

- Hull DN, chief compiler. 1990 (rev. Larsen GE, 2000; Slucher ER, 2004). Generalized column of bedrock units in Ohio [geologic column map]. Columbus (OH): Ohio Department of Natural Resources, Division of Geological Survey. 1 sheet. [https://ohiodnr.gov/static/documents/geology/Column\\_Slucher\\_2004.pdf](https://ohiodnr.gov/static/documents/geology/Column_Slucher_2004.pdf)
- Jones DM. 2000. The development of complex joints and associated infillings and alterations in two late Paleozoic formations in Ohio [master's thesis]. [Kent (OH)]: Kent State University. 151 p. [http://catalog.ohiolink.edu/iii/encore/record/C\\_\\_Rb20140557](http://catalog.ohiolink.edu/iii/encore/record/C__Rb20140557)
- Lamerson PR, Dellwig LF. 1957. Deformation by ice push of lithified sediments in south-central Iowa. *J Geol.* 65(5):546-550. <https://doi.org/10.1086/626456>
- Morgan JP. 1961. Genesis and paleontology of the Mississippi River mudlumps. Baton Rouge (LA): Department of Conservation, Louisiana Geological Survey. *Geological Bulletin No.*: 35, part 1. 116 p. <https://www.lsu.edu/lgs/publications/products/geological-bulletins.php>
- Morgan JP, Coleman JM, Gagliano SM. 1968. Mudlumps: diapiric structures in Mississippi Delta sediments. In: Braunstein J, O'Brien GD, editors. Diapirism and diapirs: a symposium. *Memoir No.*: 8. Tulsa (OK): American Association of Petroleum Geologists. p. 145-161. ISBN 13: 9781629812304. <https://doi.org/10.1306/M8361C10>
- Murphy JL. 1974. Glacially deformed bedrock in Erie County, Ohio. Cleveland (OH): Case Western Reserve University, Department of Geology. 14 p.
- Newberry JS. 1874. Surface geology [of Ohio]. In: Newberry JS, chief geologist. Report of the Geological Survey of Ohio. Vol. 2, pt. 1, sec. 1, chap. 30. Columbus (OH): Legislature of Ohio. p. 1-80. <https://hdl.handle.net/2027/mdp.39015005149060>
- Ohio Edison Co. 1973. Outcrop map and stratigraphy section. In: Wolfgang JL, Gardner WS. 1977. Near-site faulting evaluation Erie Nuclear Plant, Erie County, Ohio. Woodward-Clyde Consultants. Open file unpublished report.
- Ohio Geological Survey Core #734, (41°23'45.49"N, 82°32'44.07"W) Well record and formation description, Ohio Geological Survey, drilled for Nickel Plate Development Co. in city of Huron. Unpublished.
- Pashin JC, Etensohn FR. 1995. Reevaluation of the Bedford-Berea sequence in Ohio and adjacent states: forced regression in a foreland basin. Bolder (CO): Geological Society of America. *GSA Special Paper* 298. 69 p. ISBN 13: 9780813722986. <https://doi.org/10.1130/SPE298-p1>
- Phillipson SE. 2005. Effects of late Paleozoic foreland deformation on underground coal mine ground instability, Illinois and Appalachian Basins. *Int J Coal Geol.* 64(1-2):3-19. <https://doi.org/10.1016/j.coal.2005.03.002>
- Pepper JF, De Witt W Jr, Demarest DF. 1954. Geology of the Bedford Shale and Berea Sandstone in the Appalachian Basin. Washington (DC): United States Department of the Interior, Geological Survey. *Professional Paper No.*: 259. 111 p. <https://doi.org/10.3133/pp259>
- Prosser CS. 1912. The Devonian and Mississippian formations of northeastern Ohio. Columbus (OH): Geological Survey of Ohio. *Forth Series; Bulletin No.*: 15. 574 p. <https://hdl.handle.net/2027/osu.32435026429464>
- Ragan DM. 1968. Structural geology: an introduction to geometrical techniques. New York (NY): John Wiley & Sons. 602 p. ISBN 13: 9780471704805.
- Read MC. 1878. Report on the geology of Huron County. In: Newberry JS, chief geologist. Report of the Geological Survey of Ohio. Vol. 3, pt. 1, sec. 2, chap. 65. Columbus (OH): Legislature of Ohio. p. 289-309. <https://hdl.handle.net/2027/mdp.39015063418753>
- Sardeson FW. 1906. The folding of subjacent strata by glacial action. *J Geol.* 14(3):226-232. <https://www.jstor.org/stable/30055841>
- Schumacher GA, Mott BE, Angle MP. 2013. Ohio's geology in core and outcrop: a field guide for citizens and environmental and geotechnical investigators. Columbus (OH): Ohio Department of Natural Resources, Division of Geological Survey. *Information Circular No.*: 63. 191 p. [https://ohiodnr.gov/static/documents/geology/IC63\\_Schumacher\\_2013.pdf](https://ohiodnr.gov/static/documents/geology/IC63_Schumacher_2013.pdf)
- Szabo JP, Angle MP, Eddy AM. 2011. Pleistocene glaciation of Ohio, USA [chapter 39]. In: Ehlers J, Gibbard PL, Hughes PD, editors. Quaternary glaciations - extent and chronology: a closer look. Amsterdam (NL): Elsevier. p. 513-519. ISBN 13: 9780444534477. [https://roccopoetic.files.wordpress.com/2015/04/szabo\\_2011\\_pleistocene\\_glaciation\\_ohio.pdf](https://roccopoetic.files.wordpress.com/2015/04/szabo_2011_pleistocene_glaciation_ohio.pdf) <https://doi.org/10.1016/B978-0-444-53447-7.00039-8>
- Van Horn FR. 1910. Local anticlines in the Chagrin shales at Cleveland, Ohio [abstract]. *Bull Geol Soc Am [now Geol Soc Am Bull]*. 21(1):771-773. [https://archive.org/stream/bulletinofgeolog21191geol/bulletinofgeolog21191geol\\_djvu.txt](https://archive.org/stream/bulletinofgeolog21191geol/bulletinofgeolog21191geol_djvu.txt) <https://doi.org/10.1130/GSAB-21-753>
- Wenberg EH. 1938. The Paleozoic stratigraphy of Lorain County, Ohio [master's thesis]. [Oberlin (OH)]: Oberlin College. 114 p. [http://rave.ohiolink.edu/etdc/view?acc\\_num=obgrad1427290443](http://rave.ohiolink.edu/etdc/view?acc_num=obgrad1427290443)
- White GW. 1982. Glacial geology of northeastern Ohio. Columbus (OH): Ohio Department of Natural Resources, Division of Geological Survey. *Bulletin No.*: 68. 75 p. <http://hdl.handle.net/1811/78538>
- Wolfgang JL, Gardner WS. 1977. Near-site faulting evaluation Erie Nuclear Plant, Erie County, Ohio. Woodward-Clyde Consultants. Open file unpublished report. 51 p.