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MODELING MARINE PALEOENVIRONMENTS OF THE ELLSWORTH PRODELTA DURING THE LATE DEVONIAN IN THE MICHIGAN BASIN

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ABSTRACT

The Antrim Formation is an organic-rich black shale that was deposited in the Michigan Basin during the Devonian. The overlying Ellsworth Formation is a turbiditic prodelta deposit of a river system draining from the nearby Wisconsin Arch. Although turbidite deposits in the distal part of an alluvial fan are expected to follow a binomial distribution, there is no data to visualize the sediment sorting in the Ellsworth Formation. This study modeled the paleoenvironments of the Ellsworth Formation in the St. Chester Welch #18 core (see Figure 3 of Zambito and Voice, this volume) by characterizing the lithologic and geochemical properties to delineate grain size variations at fine scale. Generalized linear models were used to evaluate high resolution lithologic and geochemical trends throughout the Ellsworth Formation, elucidating an overall coarsening upward sequence within the core consisting of smaller scale cyclicity at the millimeter scale. Elemental data collected using portable X-Ray Fluorescence (pXRF) was used as a proxy for clastic input. Characterizing the Ellsworth Formation provides new insights into how prodeltas formed during the Devonian.

INTRODUCTION

During the Devonian, substantial plate tectonic activity occurred with the collision of Avalonia and other microplates colliding with the eastern margin of North America during the Acadian Orogeny (Murphy and Keppie 2005). The Late Devonian was relatively warm, with higher CO_2 levels in the atmosphere and was associated with high sea levels and large organic deposits on anoxic seafloors which lithified into black shales (Brugger et al. 2019). The black shale deposited during the Upper Devonian consists of silt and clay sized sediment, and composed of minerals including quartz and clay minerals. The Michigan Basin, one of four depocenters in the northeast and upper Midwest United States, contains Late Devonian black shale of the Antrim Shale deposited under low-oxygen conditions.

The Ellsworth Shale interfingers with the Antrim Shale in the Michigan Basin and is a lesser studied marine formation that has had its stratigraphic position debated (Dellapenna et al. 1991; Gutschick and Sandberg 1991; Currie 2016). The Ellsworth is currently not assigned to any geologic group and consists of a silty gray and green shale. Deposited near the end of the Late Devonian, it represents the turbiditic deposits of a prodelta of a river system that drained into the Michigan Basin (Gutschick and Sandberg 1991). In a turbidite system, sediments are deposited from turbidity currents that flow down the delta slope into the basin. The sediments of turbidite systems are expected to follow binomial distributions, especially in more distal prodelta (Chen and Hiscott 1999). While Gutschick and Sandberg (1991) defined the depositional environment of the Ellsworth as a prodelta and Currie (2016) used pXRF to describe the Ellsworth's lithology, there is no existing high resolution lithostratigraphic data describing the historical development of the Ellsworth Prodelta.

METHODS

Lithostratigraphy

The core used in this study is the State Chester

Welch #18, (permit number #33875, Otsego Co., MI, latitude: 44.9091388, longitude: -84.49979) housed at the Michigan Geological Repository for Research and Education (MGRRE). The Ellsworth Formation is present between depths of 1,435 to 1,476 ft (437.4 and 449.9 m) as shown in Figure 1. There were visible laminations between dark colored clay and lighter silt throughout the core, so the thickness of each lamination was measured down to 0.01 ft (0.003m) using an engineering ruler. When there was difficulty discerning grain size visually, the grain size was estimated by rubbing the sediment to infer whether it was silty or clay-rich. The four classifications used along the core were clay (0), silt (1), unidentifiable rubble (2), if the rock was too shattered to determine the grain size, or missing (x) if there was missing core.

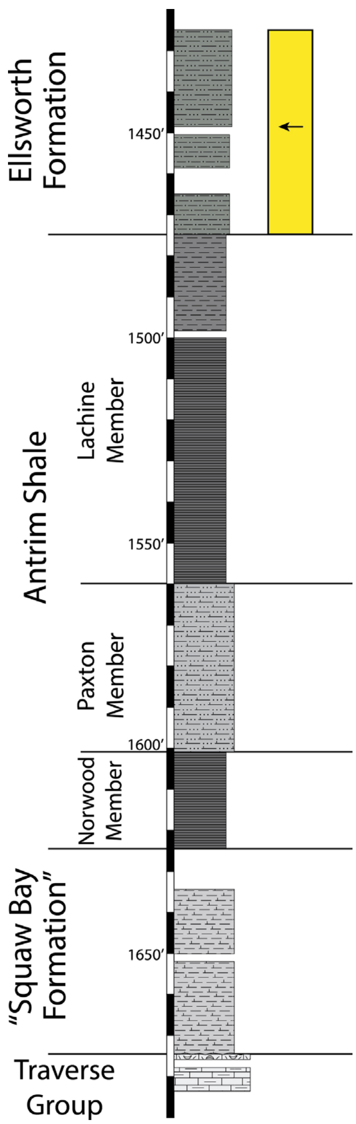

Figure 1. Stratigraphic column of the St. Chester #18 Welch Core with stratigraphic units labeled (adapted from Zambito and Voice, this volume). The yellow bar represents the interval of interest in this study.

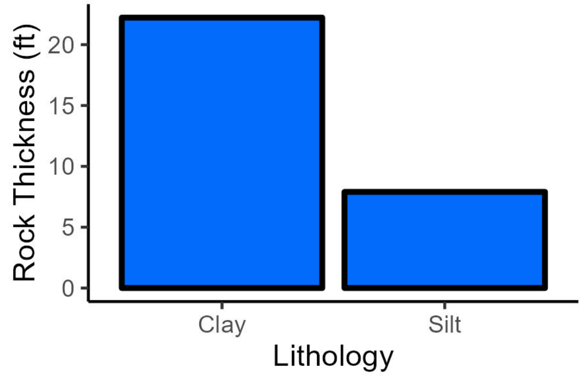

Figure 2. More clay than silt is observed throughout the Ellsworth Formation within the St. Chester Welch #18 Core.

Statistical Analysis

Statistical Analysis was undertaken in the statistics software, R. A total of 415 laminations were recorded over the 42 ft (12.8m) core. Of these measurements, 22.22 ft (6.8m) were made up of clay, 7.9 ft (2.41m) were made up of silt, 0.12 ft were core too broken up to determine laminations, and 11.76 ft (3.58m) were missing. The rubble was excluded because of the small amount of clay and silt.

To observe the amount of clay and depth across the core, a bar plot was created of the proportion of footage depth to account for the missing data (Fig. 2). To measure the change in clay and silt amounts, a clay to silt (c/s) ratio variable, cs_ratio, was derived by dividing the clay amount by the silt amount, per foot. If the c/s ratio was greater than 1, there was more clay found at a given depth, and if the c/s ratio was less than 1, then there was less clay. A linear regression was modeled between c/s ratio and the well depth.

To measure how the frequency of laminations changed with depth, a variable, num_oscilations, was created that summed the total changes from silt to clay per foot and modeled a Quasi-Poisson regression to predict the number of oscillations with well depth. A Poisson regression was also modeled to find patterns in the frequency of larger sediments (>0.04 in) associated with depth (Fig. 3).

Geochemical Analysis

To identify the presence of clastic sediments, pXRF data was used to detect elemental composition changes throughout the Ellsworth. The elemental data was

Table 1. Elemental relationships in Ellsworth, indicated with positive and negative directions.

Elemental comparison	Relationship (+/-)	P-value ($\alpha = 0.05$)	R^2
Si/Al & Ti	-	0.001	0.760
Si/Al & K	-	0.018	0.413
Si/Al & Ca	+	0.007	0.499

collected using a Thermo Fisher Scientific Niton XL3t GOLDD+ Handheld XRF Analyzer at Beloit College. The elements measured were aluminum and silicon as a proxy for quartz and clay minerals, calcium as a proxy for carbonates, and zirconium and titanium as proxies for detrital continental sediments (Tribovillard et al. 2006). Elements were analyzed to observe how they corresponded with depth, the relationship between other elements, and how the quantity of one element varied between the Ellsworth and underlying Lachine Member (Tables 1 and 2).

RESULTS

Lithostratigraphic Analysis

There were observable patterns from an empirical analysis of the Ellsworth Formation. The laminations alternated between clay and silt laminations with a coarsening upward sequence throughout the column and there was more clay found than silt in the Ellsworth. There was also an observable color shift from darker clay to lighter, green silts and that the frequency of laminations also decreased in the upper Ellsworth. There were also thick widths of silt at 1444 ft (440.13m) and 1467 ft (447.14m) in depth. When there were uniform grain sizes, there were still color variations in the clay (Figure 3).

Statistical Analysis

There were noticeable trends using the lithologic data from the Ellsworth Formation (Fig. 3). Looking at grain size distributions, there was a decreasing trend in the c/s ratio up section, meaning there was more silt present in the upper Ellsworth (coarsening upward). There was an increase in the number of laminations up section, meaning there were more shifts from clay to silt.

The geochemical data provided insights for the mineralogic composition of the Ellsworth. Using the pXRF data of the Ellsworth Formation, silicon normalized to aluminum (Si/Al) ratio had a negative relationship with titanium and potassium, and positive relationship with calcium (Table 1). The aluminum, potassium, and silicon to aluminum ratio amounts were each greater in the Ellsworth than in the underlying Lachine Member, but the titanium, calcium, and silicon amounts did not differ (Table 2).

DISCUSSION

While characterizing rocks by their sediment sorting, grain size, color, and mineral composition is important for lithostratigraphic description, running statistical analyses are also important to learn more about depositional environments (Steiner, 1966). This exploratory data provides observations to how the St. Chester Welch #18 samples from the Ellsworth Formation were deposited in a submarine prodelta. The pXRF data showed that higher values of silicon and titanium present in younger portions of the Ellsworth suggest higher siliciclastic, continental input into the prodelta setting (Tribovillard et al. 2006). There was less quartz present when the rock exhibited higher concentrations of titanium and potassium. The decrease in calcium with younger rock is inferred as less calcium carbonate present up section. Including higher resolution data for the pXRF may help to elucidate geochemical trends and refine the Ellsworth's chronostratigraphic framework (Morgan, 2022). The pXRF powder samples were taken along 3 ft (0.91m) intervals, which may not have accounted

Table 2. Elements that are more abundant in the Ellsworth than the underlying Lachine.

Element	P-value ($\alpha = 0.05$)
Al	1.945e-06
K	1.046e-10
Si/Al	2.274e-07

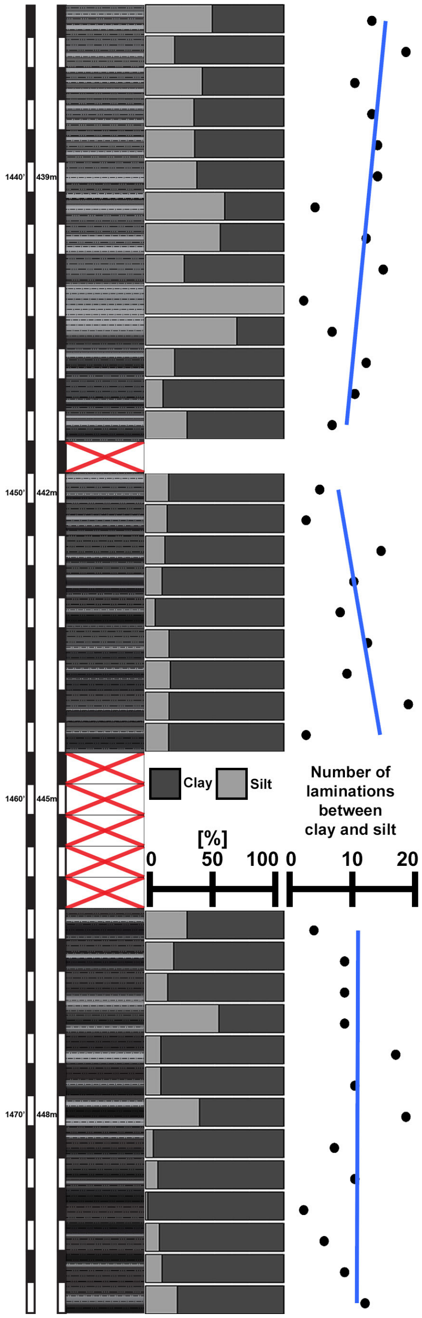

Figure 3. Reconstruction of the progradation of the Ellsworth delta into the MHigh resolution stratigraphic column of the studied interval of the St. Chester Welch #18 Core. Center track shows the percentage of rock present at each depth (middle), and number of laminations between clay and silt are seen on the right.

for geologic events occurring at higher resolutions.

Examination of crushed samples of the Ellsworth Formation using a low power binocular microscope showed that there were microlaminations present with thicknesses smaller than could be resolved with visual examination of the cores (Johnson, 2024). Future work could statistically analyze these microlaminations to better understand whether these microlaminations represent varves or tidally influenced deposits, which would provide higher resolution analysis for how prodeltas form.

CONCLUSIONS

The prodelta, as observed in the Ellsworth, prograded from the west to the east and included many environmental shifts through its development. A coarsening upward sequence within the succession studied was observed. This stratigraphic data presented herein can be used to inform research scientists and land managers for how prodeltaic environments developed during the Devonian and to understand how present deltaic environments may change.While only one well was measured at high resolution for this project, future work would require examination of other cores to show lateral variability in the Ellsworth deltaic system.

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