KECK Geology Consortium

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Published by the Keck Geology Consortium

Short Contributions
Keck Geology Consortium
Volume 36
May 2024
doi: 10.18277/AKRSG.2024.36.14

AN ANALYSIS OF STRATIGRAPHIC, PALEOECOLOGIC, AND GEOCHEMICAL VARIABILITY IN THE "SQUAW BAY FORMATION," MICHIGAN BASIN

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INTRODUCTION

Since being named by Warthin and Cooper (1935) nearly 100 years ago from a single, poorly exposed outcrop, the stratigraphic term "Squaw Bay Formation" has been used inconsistently to describe subsurface rocks by both drillers and researchers in the Michigan Basin. Along with problems in consistency of use, in November 2021 the Secretary of the Interior, Deb Haaland, issued Secretarial Order 3404 with the subject of declaring a series of terms, including 'squaw,' "a derogatory term and implementing procedures to remove the term from federal usage" (Department of the Interior, 2021). Since Secretarial Orders 3404 was released, Michigan geoscientists were acutely aware of naming protocols within the state and with the Department of Interior press releases. Collaborating together in a Keck Geology Consortium advanced summer project provided a vehicle for additional research in these Devonian-aged units, one of which is subject to renaming because it uses the derogatory term "squaw" in its name.

Principle Aims

This research will use lithostratigraphy, paleoecology, and pXRF to characterize and determine the variability of the "Squaw Bay" succession in the Krocker 1-17 core from the northern Michigan Basin, informing the renaming efforts within the rules of the North American Stratigraphic Code. It is also important to note that this paper uses one core, the Krocker core, that best represents all of the trends and interpretations found and discussed in Wiesner (2024). Analysis of XRD and magnetic susceptibility data conducted in Wiesner (2024) is also excluded from this paper.

According to the Stratigraphic Code, renaming a formation necessitates an additional justification for the name replacement beyond the renaming of the geographic feature itself (North American Commission on Stratigraphic Nomenclature, 2021). Justifications for a name change could include boundary changes or the discovery of a duplicate name. Thus, the research presented in this paper will assist in the effort to rename this formation by better describing the various characteristics of the rocks in the area. The primary objectives are to: 1) conduct a lithostratigraphic analysis of the Krocker core to determine facies and depositional models; and 2) use multiple datasets to help define formational boundaries and member boundaries associated with the newly renamed "Squaw Bay Formation," which has the name Birdsong Bay Formation proposed for it by the U.S. Geological Survey.

STUDY AREA

The Michigan Basin is a relatively undeformed and roughly circular intracratonic basin filled with approximately 4,000 m of Paleozoic rocks (Howell and van de Pluijm, 1999; Gutschick and Sandberg, 1991). Gutschick and Sandberg (1991) write that the Michigan Basin was likely located on the equator during the Late Devonian but shifted south during the Frasnian and north during the Famennian (Figure 1). The Michigan Basin is surrounded by the Wisconsin Arch to the west, the Wisconsin highlands to the north, the Canadian shield to the northeast, the Algonquin arch to the east, the Findlay arch to the southeast, and the Kankakee arch to the southwest (Figure 1; Ells, 1979; Currie, 2016). For further information on the geologic setting and basin history see Zambito and

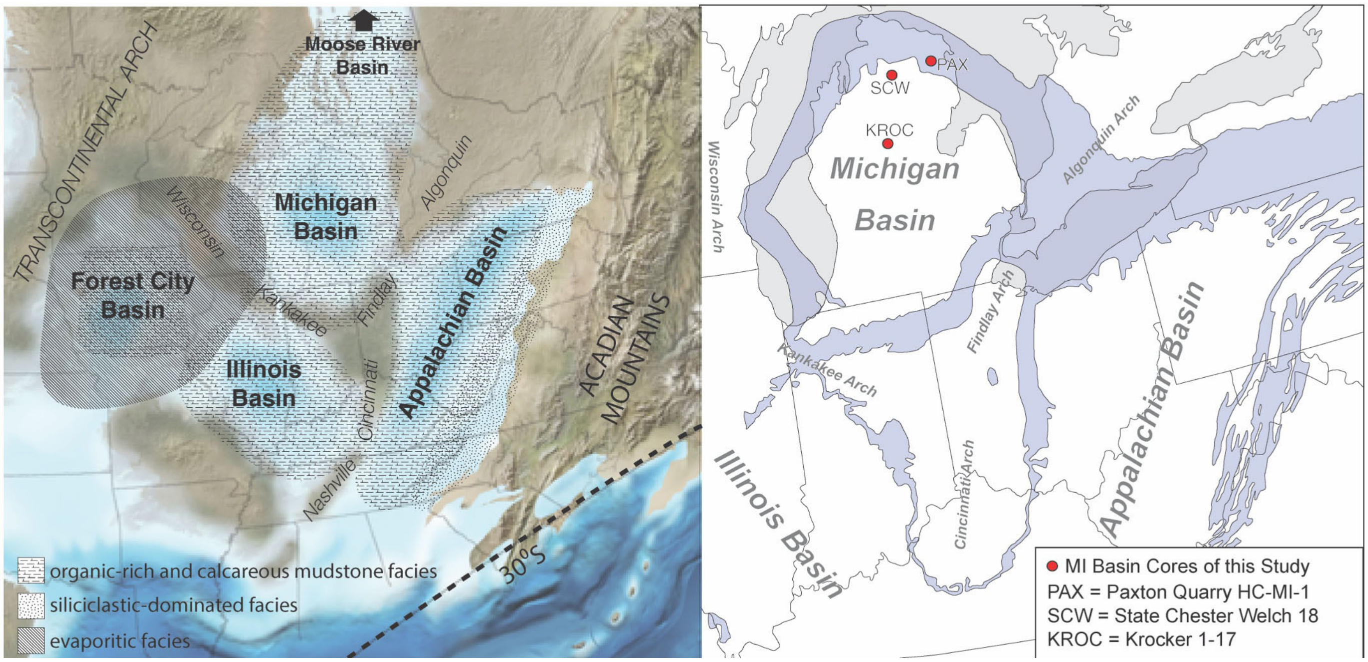

Figure 1. Left: Regional paleogeographic map showing the location of the Michigan Basin in relation to other tectonic basins of the Devonian. Right: Generalized map outlining the Devonian outcrop belt (purple) within the Michigan, Appalachian, and Illinois basins. The location of the three core localities (red dots) studied by Wiesner (2024), including the Krocker 1-17 core, are shown in the Michigan Basin. Paleogeographic maps are adapted from Blakey (2013) and Zambito and Voice (this volume). Devonian outcrop belt map adapted from Zambito and Voice (this volume).

Voice (this volume) and Wiesner (2024).

Data collection was conducted at the Michigan Geological Repository for Research and Education (MGRRE) at Western Michigan University in Kalamazoo, Michigan. This facility houses about 530,000 linear feet of drill core collected as a product of "oil, gas, and mineral exploration; environmental research; and geological mapping projects" (Western Michigan University, 2023).

Core Localities

Three cores, illustrated in Figure 1, were chosen not only because they encompass the entire "Squaw Bay Formation" in their respective areas, but also because they represent the observed variability in the lithologic facies from the center of the Michigan Basin to the margin. While Wiesner (2024) examines all three cores seen in Figure 1, this paper will only discuss the Krocker core. Additional information about the core localities can be found in Wiesner (2024).

METHODS

Lithostratigraphy and Paleoecology

This project analyzes a core through the "Squaw Bay Formation" in the northern Michigan Basin, with a focus on lithostratigraphic and paleoecologic characteristics. The raw data was collected at MGRRE by taking detailed notes and measurements every foot of the Krocker 1-17 core (Figure 2). Observations were taken on the entire "Squaw Bay Formation," including a few feet of the underlying Traverse Group and the overlying Norwood Member of the Antrim Shale. Fossils were identified to the class level and where possible to the genus level. Facies descriptions were compiled and include observation of the distribution of fossils (isolated fossils floating in matrix versus shell beds), sedimentary structures, and other characteristics. For detailed methodology and data collected see Wiesner (2024) and Appendix A therein. With the notes taken while at MGRRE, a stratigraphic column was constructed using Adobe Illustrator.

pXRF

Additional chemostratigraphic data was collected by pXRF analysis (see methods in Zambito et al., 2016). This data was collected by T. Barker-Edwards, M. Giehler, J. Gugino, and I. Johnson at Beloit

College. Further information providing context and demonstrating the significance of each dataset to the stratigraphic interval of study can be found in Wiesner (2024). The relevant data points were graphed and compiled with the stratigraphic column. pXRF data can be found in Appendix B of Wiesner (2024).

RESULTS

Lithology and Paleoecology

The “Squaw Bay Formation” in the Krocker core is bracketed by the underlying Traverse Group limestone and the dominantly carbonaceous black shale of the overlying Norwood Member of the Antrim Shale. There are six distinct lithofacies present in the examined section of the Krocker core (Figure 3). General lithofacies trends can be divided into two units with the first unit, between the depths of about 3,497ft-3,470ft, being a gray calcareous shale with two fossiliferous beds. The second unit

Figure 2. An engineering ruler was used to measure the dimensions of fossils and fossil beds. In addition, changes in sediment color were described as well as the size and location of features, such as pyrite and concretions.

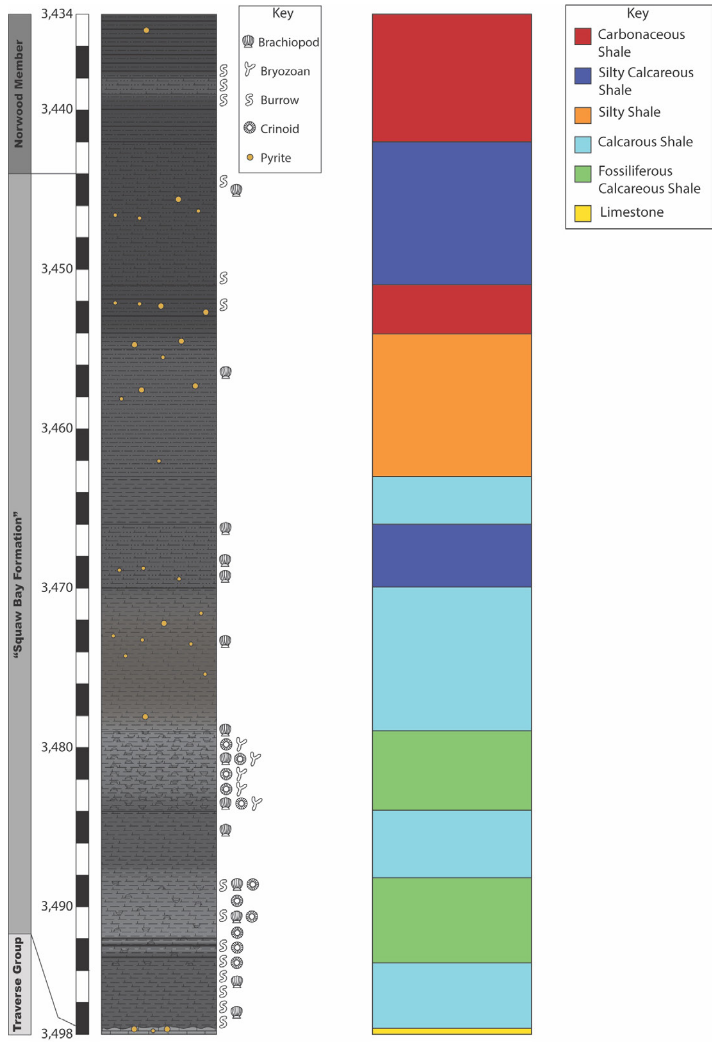

Figure 3. Stratigraphic column of the Krocker 1-17 core oriented next to a simplified column of the lithofacies present in the core. Lithologic symbols are taken from the FGDC Digital Cartographic Standard for Geologic Map Symbolization Section 37 (U.S. Geological Survey, 2006).

of the core, from about 3,470ft-3,444ft, illustrates a gradational change from gray calcareous shale to the black carbonaceous shale of the overlying Norwood Member. This second section of the core consists of mostly carbonaceous and silty black to dark gray shales. Additionally, there is an abundance of bioturbation at the bottom of the core below 3,488ft, with none in the middle of the core. Bioturbation reappears in the top 10ft of the “Squaw Bay” and continues into the Norwood Member.

The two concentrations of pyrite nodules consist of a group of generally smaller nodules (1cm or less in diameter) between 3,478-3,468ft, and a group of larger nodules (larger than 1cm in diameter) between 3,458-3,452ft. Additionally, the fossil distribution is dominantly within the bottom section of the core, with several isolated brachiopods throughout the middle section of the core.

pXRF

This paper examines Potassium (K), Aluminum (Al), Silicon (Si), Calcium (Ca), and Magnesium (Mg) concentrations from the interval between 3,435ft-3,497ft in the Krocker core. Trendlines in Figure 4 show general increasing amounts of K, Al, and Si up the core. Conversely, amounts of Ca and Mg show a general decreasing trend up section, with Ca having a more pronounced decreasing slope. It is also important to note that the shape of the graphs of K, Al, and Si are similar, and that the shape of the Ca graph is inversely related those elements. One characteristic that is shared by all five graphs is that below a depth of 3,470ft, the data tends to deviate from the trendline more, while above 3,470ft it tends to deviate less.

DISCUSSION

Lithostratigraphic Analysis

When looking at the "Squaw Bay Formation" in the lithofacies column in Figure 3, the underlying boundary with the Traverse Group is a sharp, easily identifiable contact featuring abundant pyrite nodules. Similar sharp boundaries with a drastic change in lithology and primary sedimentary structures, frequently indicate a significant change in water depth of the depositional environments (Adducci, 2015). The upper contact with the Norwood Member of the Antrim Shale is gradational, alternating between calcareous and carbonaceous shales. The change from

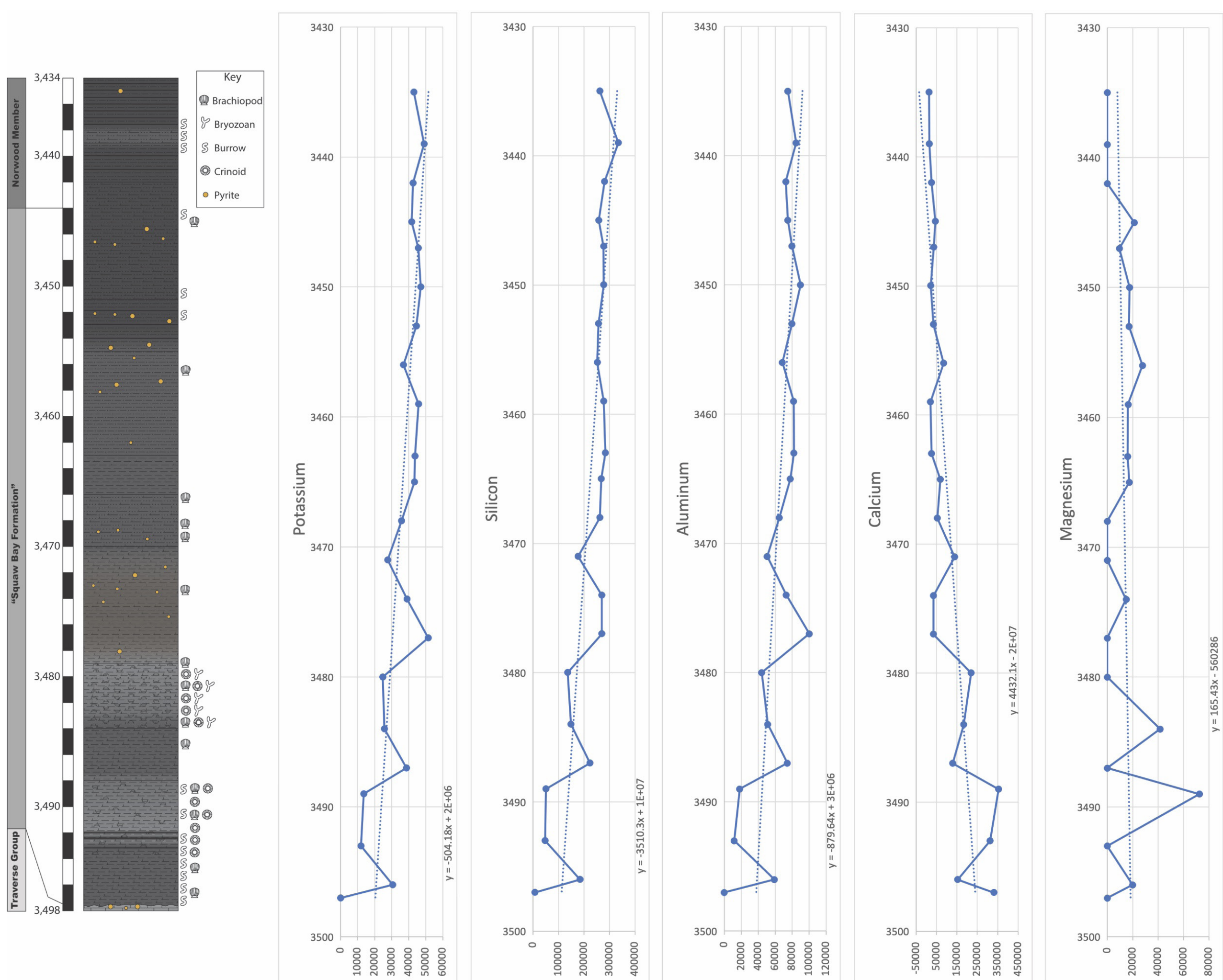

Figure 4. Stratigraphic column of the Krocker 1-17 core aligned with elemental profiles for key elements collected from pXRF analysis. Depth in the core is measured in feet and located on the Y-axis of the graphs, while concentrations of the elements are measured in ppm and located on the X-axis. Note that the trendlines in these graphs encompass most of the core, not just the "Squaw Bay Formation." All five graphs show a notable behavior change around the depth 3,470ft where they all transition from deviating more and frequently from the trendline, to following the trendline more closely.

calcareous to carbonaceous shale shows a deepening upward sequence, marking a transition in depositional environment from shallow marine carbonate deposition to deeper marine sedimentation (Currie, 2016).

A shallow marine carbonate environment interpretation for the lower half of the formation is further evidenced by more abundant fossils. The brachiopod, crinoid, and bryozoan fossils of the core were frequently broken but identifiable, indicating that the environment likely experienced moderate wave or current action that mechanically weathered the fossils (Adducci, 2015) and had sufficient energy and nutrients to sustain filter feeders. The top half of the "Squaw Bay Formation," while being a gradational contact, is mostly black carbonaceous shale. McGregor (1954) states that black shale depositional environments must allow for the preservation of organic matter with the deposited sediment and are often characterized by poor circulation and a lack of oxygen. This description supports a deep marine depositional environment.

The lithofacies patterns in the core also assist in potentially dividing the formation into two members. A division of the formation would feature a lower "Squaw Bay" that is characterized predominantly by gray calcareous shale and higher fossil content that both suggest a shallow marine depositional environment. An upper "Squaw Bay" member is characterized by predominantly black carbonaceous shale and fewer fossils that both suggest a deeper marine depositional environment that is less well circulated and is more dysoxic.

Geochemical Analysis

The pXRF data gathered shows increasing trendlines upsection on the K, Si, and Al graphs and decreasing trendlines upsection on the Ca and Mg graphs (Figure 4). Not only do K, Si, and Al have the same general trendline, their graphs also behave similarly with synchronized excursions in the data. The pattern displayed by these three elements indicates a higher concentration of clay minerals in the cores. Abundances of Al can also be an important indicator of clastic supply to an area (Mastalerz et al., 2019). Thus the increasing levels of Al in the Krocker core indicate an increase in clastic input. Ca and Mg, on the other hand, are good indicators of the carbonate minerals present. There are slightly lower levels of Mg, pointing to higher levels of calcite than dolomite in the shales (Mastalerz et al., 2019). Additionally, the opposite fluctuations in the Ca and Si graphs could indicate that there is a repeating cycle of clastic and carbonate sedimentation in the basin (Currie, 2016).

Within the pXRF graphs for all elements, there is only one easily distinguishable boundary. While contacts between the "Squaw Bay" and the over- and underlying formations were fairly visible in the lithostratigraphic analysis, there is no obvious contact in the pXRF graphs either because there is no data for that section of the core or because there is simply no notable change in the behavior of the graph. However, at around 3,470ft in the Krocker core, the graphs transition from more frequent deviations from the trendline at the bottom of the formation, to more closely following the trendline at the top of the formation, indicating a place where the formation could be subdivided into members. The location of this division corresponds to the changes in lithology and the potential split of the formation proposed during the lithostratigraphic analysis.

CONCLUSIONS

The "Squaw Bay Formation" is not only poorly described, but also its name contains a derogatory term that, following a U.S. Department of Interior secretarial order in 2021, needs to be changed. The goals of the research were to help inform this renaming process by determining the variability of the formation and locating boundaries between over- and underlying formations through analysis of lithostratigraphic, paleoecologic, and geochemical data.

This research worked to determine facies and depositional models in the "Squaw Bay Formation." The combination of datasets available for this analysis indicates that the lower "Squaw Bay" was a shallow marine carbonate environment, further supported by the relatively higher concentrations of Ca and Mg. Up section these features change and K, Si, and Al concentrations all increase, indicating rising sea levels and a transition to a deep marine environment that is less oxygenated in the upper "Squaw Bay" and Antrim Shale.

This research also aimed to use all datasets to determine formational and member boundaries associated with the "Squaw Bay Formation." The lithostratigraphic analysis indicates a prominent and easily distinguished boundary between the Traverse Group and the "Squaw Bay Formation." This boundary is characterized by an abrupt transition from limestone to calcareous shale, with abundant pyrite nodules and crusts on this surface. However, no dataset examined in the research provided a clear delineation of the "Squaw Bay Formation" from the overlying Norwood Member due to the gradational nature of their contact.

Part of determining the contacts associated with the "Squaw Bay Formation" included determining any subdivisions in the member. Lithostratigraphic and pXRF data supports dividing the formation into two members around 3,470ft in the Krocker core. This division would split the rocks into a lower section of fossiliferous gray calcareous shale with pXRF values that vary more frequently with respect to the trendline, and an upper section of predominantly black calcareous shale with few fossils and pXRF values that more closely follow the trendline of the core. Results discussed in Wiesner (2024) further examine the ways in which XRD and magnetic susceptibility data could support the potential subdivision of the "Squaw Bay Formation."

Further research into the "Squaw Bay" is necessary to definitively locate the boundary between it and the Norwood Member, and is also necessary to determine how the formation could be subdivided. More detailed data collection and analysis specifically in geochemical fields, like XRD, could be useful in these determinations.

ACKNOWLEDGEMENTS

This material is based upon work supported by the Keck Geology Consortium and the National Science Foundation under Grant No. 2050697. Additional thanks to the College of Wooster Geology Department; the Michigan Geological Repository for Research and Education; the Beloit College Geology Department; Drs. Shelley Judge, James Zambito, Peter Voice, and Meagen Pollock; my Keck internship group; and, my friends and family.

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