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INTEGRATED STRATIGRAPHIC AND PALEOENVIRONMENTAL STUDY OF THE MIDDLE-LATE DEVONIAN CARBONATE TO BLACK SHALE TRANSITION IN THE MICHIGAN BASIN

JAMES J. ZAMBITO IV, Beloit College
PETER J. VOICE, Western Michigan University

INTRODUCTION

Devonian climate trends have long been studied within the context of biological change. For example, the end-Devonian glaciation is typically thought to be related to CO_2-drawdown due to the evolution of forests during the Middle-Late Devonian (Algeo and Scheckler, 1998, and references therein). However, more recent paleoclimate reconstructions indicate that the Devonian climate story is more complex. Even though it has now been shown that the Middle Devonian was cooler than the end-Devonian and glacio-eustatic sea-level dynamics operated during the Middle Devonian (Fig. 1; Elrick et al., 2009, 2022; Joachimski et al., 2009), only Late and end-Devonian evidence for glaciation has been documented (Ettensohn et al., 2020). In order to better understand these long-term patterns, a current focus within the Devonian research community is the study of the repeated, short-duration, globally-recognized events that resulted in marine anoxia, extinctions, and carbon-cycle perturbations (Fig, 1; House, 2002; Becker et al., 2020; Brett et al., 2020), especially within the context of local environmental change and tectonics (Zambito et al., 2012; Chen et al., 2021).

This Keck Consortium project is focused on characterizing Middle-Late Devonian lithologies, geochemistry, and distribution of facies in the Michigan Basin in order to develop a local spatial and temporal framework within which future event stratigraphy can be undertaken. During this time interval, the overall depositional system transitioned from carbonate-dominated strata of the Traverse Group to siliciclastic-dominated strata, including organic-rich black shale, in the Squaw Bay Formation (herein "Squaw Bay Formation", a proposal for a formal name change to Birdsong Bay Formation is forthcoming, pers. comm. N. Stamm, 2024) and overlying Antrim Shale Formation and Ellsworth Shale Formation (Fig.

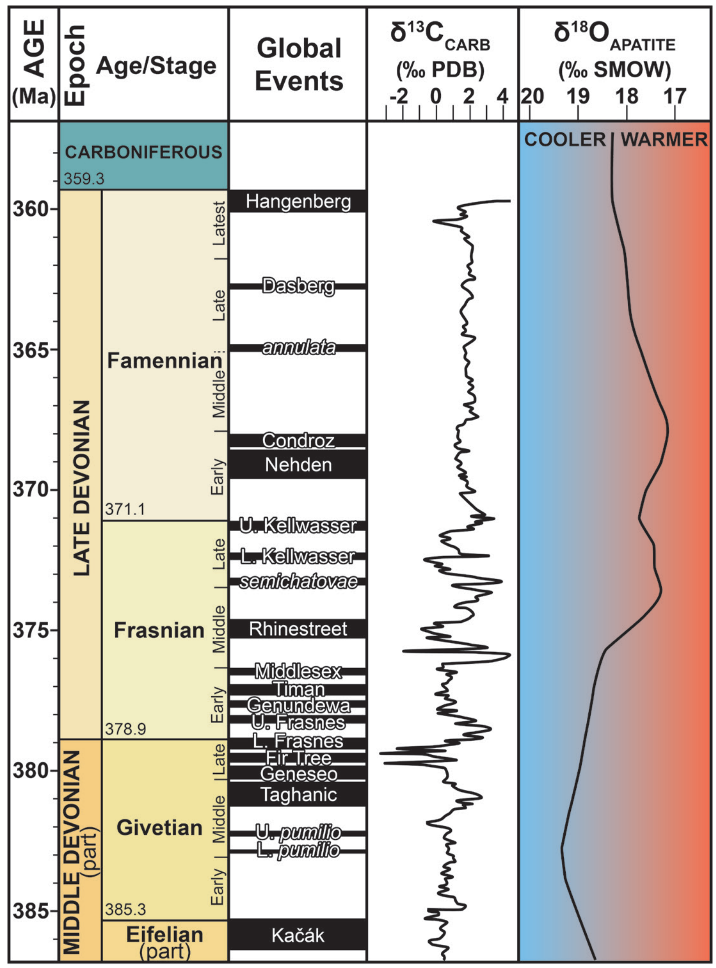

Figure 1. Middle (in part) and Late Devonian Time Scale showing the timing and duration of global events, carbonate carbon isotopic excursions, and generalized paleoclimate trends based on oxygen isotopic analysis of conodont apatite; Adapted from Becker et al., 2020.

2).

GEOLOGIC SETTING

The Michigan Basin is one of three depocenters in the northeast and upper Midwest United States, the others being the foredeep Appalachian Basin adjacent to siliciclastic input from the Acadian Orogeny and the intracratonic Illinois Basin (Fig. 3). The intracratonic Michigan Basin contains ~5 km of strata that accumulated across a nearly-circular ~400 km diameter depocenter that is centered in the present-day state of Michigan (Gutschick and Sandberg, 1991a; Howell and Van Der Pluijm, 1999). There is little evidence for structural disruption in the Michigan Basin (Howell and van der Pluijm, 1999). Through the Middle to Late Devonian, the subsidence style in the Michigan Basin changed from basin-centered to eastward tilting (Howell and van der Pluijm, 1999), presumably due to substantial and renewed Acadian tectonism during the Middle-Late Devonian (see Ver Straeten, 2010, and references therein for detailed descriptions of Acadian tectophases). Along with these basin morphology changes, the Michigan Basin also shifted from carbonate-dominated deposition in the Middle Devonian Traverse Group to siliciclastic and organic matter dominated deposition in the Late Devonian (Fig. 2).

In the northern Appalachian Basin (New York State), Devonian strata are well exposed in an outcrop belt that is perpendicular to depositional strike of siliciclastic sediment input from the Acadian Mountains (Fig. 3); these strata are therefore not only better-studied than contemporaneous strata in the Michigan Basin, but New York strata are the type examples for which many global events are named (Fig. 1). However, the Appalachian Basin was also tectonically active at this time and local environmental change associated with basin subsidence and sediment supply often overprints global environmental changes (Fig. 1; Zambito et al., 2012). Conversely, the Middle-Upper Devonian transition from Traverse Group shallow marine carbonates through the transitional "Squaw Bay Formation" to the Antrim Formation anoxic black shale in the Michigan Basin is unlikely the result of continental-margin tectonism (Fig. 3), and more accurately reflects the signal of global environmental change (Fig. 1). The studies discussed herein will provide a critical stratigraphic and paleoenvironmental framework within which future workers can identify global events in the Michigan Basin.

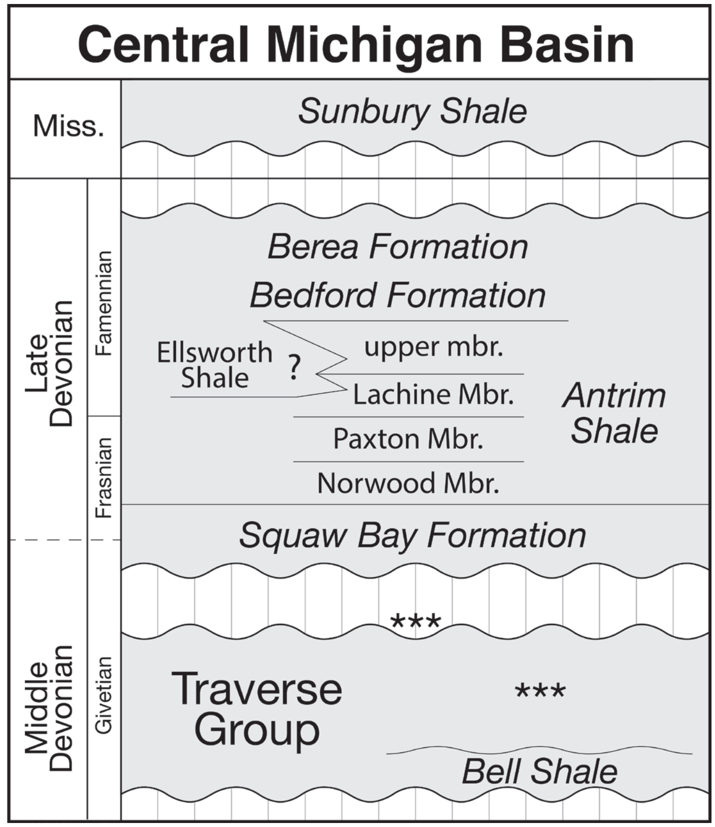

*Figure 2. Generalized lithostratigraphy of the Middle-Late Devonian stratigraphic succession, including the stratigraphic ranges of the cores studied (see Table 1; after Bultynck, 1976; Ells, 1978, 1979; Gutschick and Sandberg, 1991; Catacosinos et al., 2000; Wylie and Huntoon, 2003; Currie, 2016; Narkiewicz and Bultynck, 2016); *** Catacosinos et al. (2000) does not differentiate the Traverse Group in the subsurface, but see Wylie and Huntoon (2003) and Gutschick and Sandberg (1991a,b) for formation-level correlations in the subsurface and the interpretation that the age of the Traverse Group in the subsurface likely includes strata that are both older and younger than the strata of the Traverse Group at the Michigan Basin Margins.*

This project builds upon a long history of lithostratigraphic study and basin-wide correlation, though there is recognition that the stratigraphic nomenclature originally defined with the limited outcrops available at the northern basin margin is not easily applied to the subsurface (Fig. 2; Ehlers and Kesling, 1970; Kesling et al., 1974, 1976; Catacosinos et al., 2000; Wylie and Huntoon, 2003; Swezey et al., 2015). Furthermore, since Michigan Basin type-section outcrops are rare, stratigraphically short, and generally lack exposure of formation and member

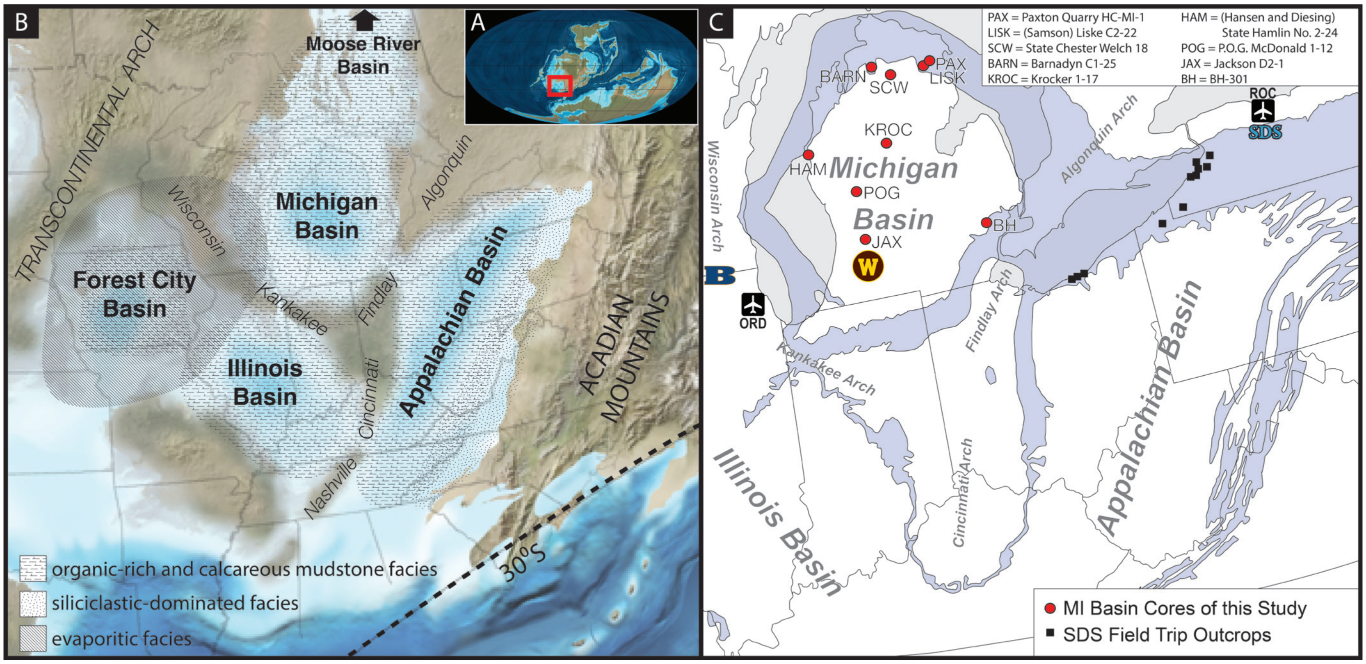

Figure 3. A) Devonian paleogeography (location of part B in red box). B) Paleogeography and generalized depositional settings of the Eastern and Midwest United States during the Middle-Upper Devonian. C) Outcrop belt (bluish gray) of Devonian strata in the study region (after Reed, 2004) and the location of Michigan Basin cores and SDS Field Trip stops examined as part of this study. Also shown is the location of sites where Keck research took place (Beloit College [B] and MGRRE at Western Michigan University [W]), the airports utilized, and the location of the SDS Meeting. Paleogeographic maps adapted from Blakey (2013).

contacts (Zambito and Voice, personal field notes), and a variety of cores exist as a result of active oil and gas exploration (Swezey et al., 2015), this project focuses on the study and sampling of the extensive drill core available at the Michigan Geological Repository for Research and Education (MGRRE) at Western Michigan University (see Figures 3 and 4 for details).

RESEARCH AND RESULTS

This Keck Consortium project involved research on core and outcrop as well as laboratory work (Fig. 3). The research group assembled at O'Hare International Airport and drove to the Michigan Geological Repository for Research and Education (MGRRE) at Western Michigan University for a project overview and to study and sample drill core. Then, the group traveled to Beloit College to conduct laboratory analyses. After initial laboratory work was complete, the research group drove to Cleveland where they joined a field meeting of the International Union of Geosciences Subcommission on Devonian Stratigraphy (SDS) to study the geologically contemporaneous Appalachian Basin Middle-Upper Devonian strata found in outcrops along the Lake Erie shoreline and creeks in Ohio, Pennsylvania, and New York State. This provided the opportunity to directly compare Michigan Basin subsurface observations to Devonian Global Event type example strata. Finally, this summer research experience culminated in a group poster presentation at the Subcommission on Devonian Stratigraphy Annual Meeting where students received constructive criticism from disciplinary experts on their project and preliminary data (Zambito et al., 2023). Students then departed from Rochester International Airport. Subsequent to the summer experience and after an academic year of research, group members presented the results of their research at the 2024 Joint North-Central and South-Central Section Meeting of the Geological Society of America on 21-23 April 2024 in Springfield, MO (Barker-Edwards et al., 2024; Giehler et al., 2024; Johnson et al., 2024; O'Bryan et al., 2024; Truong et al., 2024; Wiesner et al., 2024; Winget et al., 2024).

The lithostratigraphic successions studied, and the cores utilized in this project, are outlined in Figures 3 and 4 as well as Table 1. Most of the research conducted was on three cores: the basin margin State Chester Welch #18 core, the more basinal Krocker 1-17 core, and the Paxton Quarry core which was drilled at the stratigraphically important locality studied by Gutschick and Sandberg (1991b);

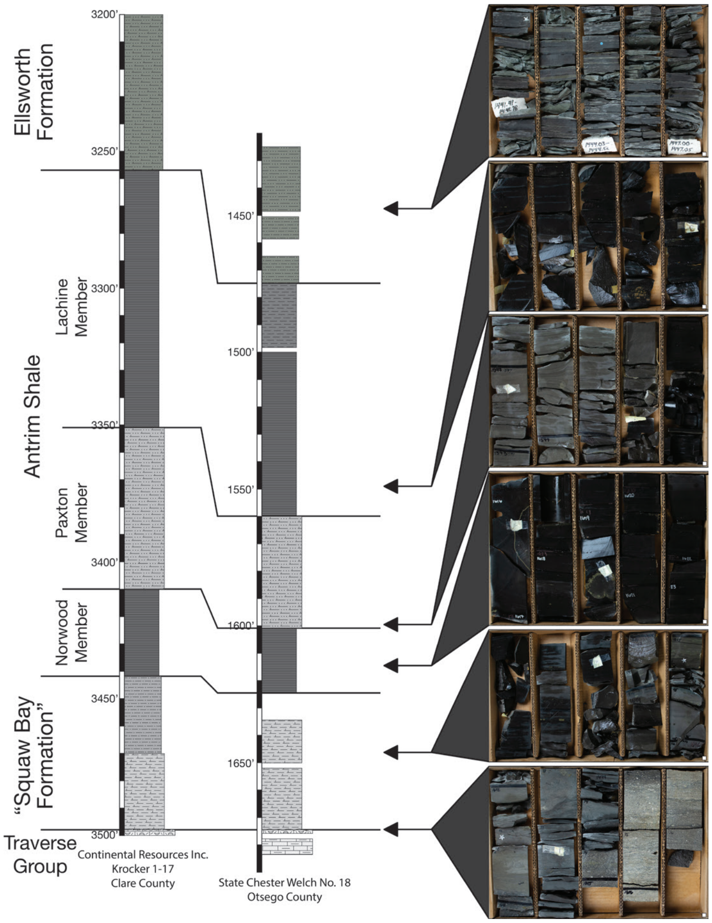

Figure 4. Lithostratigraphy and core photographs of the main studied successions. Lithostratigraphic columns for the Krocker 1-17 and State Chester Welch #18 cores are shown and correlated. Representative photographs of lithology for each unit studied are shown from the State Chester Welch #18 core.

unfortunately, the Paxton Quarry core was heavily sampled by previous researchers and therefore was not as ideal for geochemical sampling and the quarry itself has since flooded after decommissioning and is inaccessible. For this reason, most of the student projects undertaken focused on the State Chester Welch #18 and Krocker 1-17 cores.

The strata studied are shown in Figures 2 and 4. The base of the studied succession is the Traverse Group. Unconformably overlying the Traverse Group is the “Squaw Bay Formation,” which transitions from a fossiliferous calcareous shale to a carbonaceous shale where it has a gradational contact with the black shale of the Norwood Member, the basal unit of the overlying Antrim Formation (Antrim Shale). The Norwood Member is relatively sharply overlain by the Paxton Member, a variably dolomitic, fossil-bearing gray mudstone. A sharp contact occurs between the Paxton and overlying Lachine Member, which is a black shale. The black shale of the Lachine gradationally transitions into the overlying Ellsworth Formation, which consists of interbedded light green-gray siltstone and dark gray to gray shale; the Ellsworth is the youngest unit observed in the cores studied. Regional gamma log correlation (Currie, 2016) suggests that the Ellsworth is overlain by the black shale of the upper member of the Antrim Formation across the basin, which is overlain by shale and sandstone of the Bedford and Berea formations and the Mississippian Sunbury Shale.

The research of **Winget** (this volume) was focused on the Traverse Group, specifically trying to identify the lithostratigraphic units described originally from scattered outcrops across the northern part of the lower peninsula within the cores studied herein. Winget (this volume) concluded that the strata of the Traverse Group in the State Chester Welch #18 core were most similar to previously collected hand samples from the type section of the Thunder Bay Formation.

The contact of the Traverse Group and overlying “Squaw Bay Formation” was studied petrographically and mineralogically by **O’Bryan** (this volume). Petrographic and scanning electron microscopy (SEM) and x-ray fluorescence scanning (µXRF) was used to decipher a complex paragenetic sequence of both early and late diagenetic mineralization (O’Bryan, this volume).

The lithology and paleontology of the “Squaw Bay Formation” was studied in detail by **Wiesner** (this volume). This study is an important step in the ongoing work of the USGS and the Michigan Geological Survey to better understand the subsurface expression of this unit in order to revise its inappropriate and hurtful name as well as lithologic characterization.

In order to gain a baseline understanding of detrital input into the Michigan Basin during the deposition of the “Squaw Bay” and Antrim formations to aid in interpretation of future organic carbon isotopic data within a global event stratigraphy framework (Fig. 1), **Giehler** (this volume) and **Gugino** (this volume) undertook chemostratigraphic analysis of the Krocker 1-17 and State Chester Welch #18 cores, respectively. Elemental proxies for detrital input were used to

Table 1. Sample Locations

NUMBER	NAME	LATITUDE	LONGITUDE
1	Paxton Quarry HC-MI-1	45.05346	-83.62996
2	(Samson) Liske C2-22	44.97927	-83.69924
3	State Chester Welch No. 18	44.90914	-84.49979
4	Barnadyn C1-25	45.05084	-84.87411
5	Krocker 1-17	43.95828	-84.82680
6	Hansen and Diesing State Hamlin No. 2-24	44.02325	-86.40055
7	Peninsular Oil and Gas McDonald 1-12	43.35304	-85.56642
8	Jackson D2-1	42.67055	-85.55842
9	BH-301	NA; Wayne County, Michigan	

constrain siliciclastic input into the basin, and how it changes across the basin and up section, through the “Squaw Bay” and the Antrim formations (Giehler, this volume; Gugino, this volume).

Another tool with implications for detrital influx as well as intra- and extrabasinal correlation is magnetic susceptibility. **Barker-Edwards** (this volume) utilized magnetic susceptibility of the “Squaw Bay” and Antrim formations to constrain detrital influx locally as well as correlate the strata of the Michigan Basin to a contemporaneous succession in the Illinois Basin that was studied previously.

The Ellsworth Formation is probably the least understood of the stratigraphic units addressed as part of this project. **Johnson** (this volume) undertook a detailed lithostratigraphic, chemostratigraphic, and mineralogical characterization of this unit in multiple cores, complemented by a high-resolution quantification and statistical analysis of Ellsworth Delta sedimentation (**Quiroz**, this volume).

Detailed study of multiple cores as part of this project, and a better understanding of the Michigan Basin stratigraphic framework (Fig. 2), meant that regional geologic mapping could also be revised. **Truong** (this volume) constructed a geologic map of Alpena County, Michigan that used lithologic observations from core to inform interpretation of driller’s logs. Importantly, Truong (this volume) demonstrates that subdivisions of the Antrim Formation can be mapped confidently in the subsurface of the map area.

SUMMARY

The following short contributions outline new research endeavors to better understand the lithologies, geochemistry, and distribution of facies in the Michigan Basin. The results provide critical revisions to our collective understanding of the spatial and temporal stratigraphic framework of the Middle-Late Devonian Michigan Basin within which future research can be undertaken.

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